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Systematic Mapping of the Literature on Vertiport Location in Urban Environments

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ABSTRACT

To map and synthesize research on locating urban vertiports for vertical takeoff and landing aircraft, including electrically powered variants. A systematic mapping review used a predefined protocol with research questions, selection criteria, and structured data extraction. In 2025, searches covered five themes: urban air mobility, location-allocation, optimization, network and routing, and vertical takeoff and landing aircraft across major scientific databases. From 1,056 records, duplicates were removed, and screening yielded 31 studies. Most studies propose mathematical optimization models, predominantly integer linear programming formulations solved with commercial optimization tools. Some incorporate vertiport capacity and socio-environmental criteria such as noise, land use, and equitable access, while others address only operational factors. Applications on real networks with observed demand data are common; specialized simulation is less frequent. Evaluations mainly report travel time, demand coverage, and costs, and often include sensitivity analyses and limited validation procedures. Research is progressing in modeling vertiport networks, but validation remains weakly standardized, and uncertainty treatment is still limited. Comparable evaluation protocols and stronger socio-environmental robustness are needed to better support planning decisions in advanced air mobility.

Keywords: Advanced air mobility; Electric vertical take-off and landing; Urban aviation; Location optimization; Systematic mapping review.

INTRODUCTION

Urban densification, recurrent congestion, and the limited capacity of ground transport systems have intensified interest in mobility architectures capable of expanding accessibility with lower marginal pressure on urban land. In this context, urban air mobility (UAM), now more frequently framed as advanced air mobility (AAM), has been understood not merely as an aircraft-centered innovation, but as a multimodal system whose feasibility depends on the coordination of aerial operations, digital traffic management, and distributed ground infrastructure (ANAC 2023).

Recent peer-reviewed studies, therefore, frame this transition as a network design problem in which infrastructure siting, transfer performance, and operational coordination must be addressed jointly (Bridgelall *et al.* 2023; Rahman *et al.* 2023; Rohrmeier *et al.* 2025).

Within this system, vertiports constitute the principal interface between aerial operations and urban mobility. Their location affects access time, multimodal integration, fleet utilization, noise exposure, land-use compatibility, and distributive equity. For that reason, recent studies on equitable access, multimodal integration, and infrastructure-selection criteria treat vertiport siting not as a purely geometric task, but as an integrated decision problem shaped by spatial, operational, and regulatory constraints (Mercan *et al.* 2025; Volakakis and Mahmassani 2024; Zhao and Feng 2024).

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This interpretation is reinforced by studies that treat vertiports as multimodal infrastructure rather than isolated facilities. GIS-based screening methods identify candidate sites connected to public transit (Rahman *et al.* 2023), while hierarchical and multimodal network models relate hub structure to feeder accessibility (Peksa *et al.* 2023; Peng *et al.* 2022).

Case studies in São Paulo and Beijing show that accessibility, land-use compatibility, and network integration materially influence siting outcomes (Ribeiro *et al.* 2023; Zhao and Feng 2024). Taking together, these studies indicate that vertiport planning is not only an infrastructure and intermodal coordination problem, but also a formal modeling problem, since these dimensions must be translated into computational assumptions and network structures.

The literature, however, remains fragmented across only partially connected strands. Planning-oriented syntheses and criteria-based studies clarify key siting dimensions, including social acceptance, land-use compatibility, multimodal connectivity, and equity (Mercan *et al.* 2025; Rohrmeier *et al.* 2025; Volakakis and Mahmassani 2024).

In parallel, application-driven studies formulate specific optimization and network-design problems for airport access, metropolitan hub structure, adaptive discretization, and integrated demand network settings (Mandava and Karatas 2024; Rath and Chow 2022; Wang *et al.* 2022; Willey and Salmon 2021; Wu and Zhang 2021). What remains lacking is a study that systematically maps how these strands connect at the computational level, particularly through the articulation of models, algorithms, datasets, validation strategies, and uncertainty treatment across the field.

Two methodological axes stand out in recent research. The first comprises classical location-allocation and network-design formulations, predominantly solved through mixed-integer linear programming (MILP), including extensions that incorporate user behavior and operational range constraints, such as the eUnit-based formulation discussed by Kitthamkesorn and Chen (2024). The second comprises data-driven and hybrid approaches that combine clustering techniques, metaheuristics, and simulation environments in real urban case studies, such as New York City (Senthilnathan *et al.* 2025).

Despite this methodological progress, four structural limitations persist. First, the integration of socio-environmental constraints such as noise, land use, and equity remains uneven. Second, explicit uncertainty modeling is still limited. Third, validation procedures remain weakly standardized and often rely on sensitivity analysis. Fourth, heterogeneous reporting and evaluation practices continue to restrict direct comparability across studies. As a result, cumulative comparison remains difficult, and methodological convergence is only partially visible.

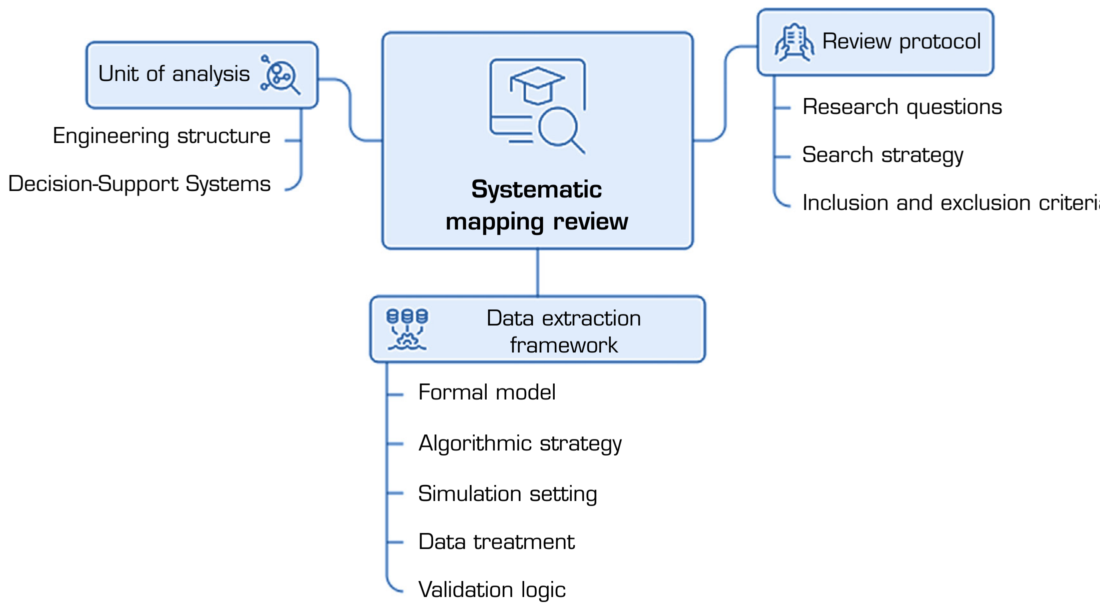
This study addresses that gap through a systematic mapping of the literature on vertiport location for vertical take-off and landing/electric vertical take-off and landing (VTOL/eVTOL) operations in urban environments. The review protocol is grounded in the evidence-based guidelines of Kitchenham and Charters (2007) and in the research methodology principles for computer science described by Wazlawick (2021). These references are appropriate because the evidence base is fundamentally computational: the selected studies formalize location, allocation, network design, simulation, and evaluation as algorithmic artifacts. Accordingly, the review does not seek to estimate a pooled transport effect; rather, it classifies modeling paradigms, experimental designs, and validation practices in a reproducible manner.

By organizing the state of the art across four analytical dimensions context, computational methodology, experimental design and data usage, and evaluation and validation this study systematizes prevailing computational practices, identifies recurrent methodological patterns, characterizes the technical maturity of the field, and establishes the basis for a computational taxonomy of research on vertiport location.

METHODOLOGY

This study adopts a systematic mapping review to organize and classify the existing body of knowledge on vertiport location and allocation for VTOL/eVTOL operations in urban contexts. Unlike traditional systematic literature reviews, which focus on synthesizing evidence to test specific hypotheses, systematic mapping provides a structured overview of research trends, methodological approaches, and knowledge gaps in emerging and heterogeneous fields, particularly when the objective is taxonomic rather than effect-oriented (Petersen *et al.* 2015).

As illustrated in Fig. 1, the review is structured around three core components: the unit of analysis (engineering structure of decision-support systems), the review protocol (research questions, search strategy, inclusion and exclusion criteria), and the data extraction framework (formal model, algorithmic strategy, simulation setting, data treatment, and validation logic).



Source: Elaborated by the authors.

Figure 1. Conceptual framework of the systematic mapping review (visual design support from Napkin AI).

The protocol follows the evidence-based guidelines proposed by Kitchenham and Charters (2007) and aligns with methodological principles for computer science research (Wazlawick 2021). This approach is appropriate because the unit of analysis is the computational solution proposed by each study. Accordingly, the review focuses on the engineering structure of decision-support systems rather than on estimating intervention effects. The protocol was defined prior to data collection, ensuring consistency and transparency in study selection and analysis.

Planning and research questions (RQs)

This systematic mapping seeks to identify the state of the art in solutions for vertiport allocation in urban contexts involving vertical takeoff and landing operations, with particular emphasis on VTOL/eVTOL aircraft and the UAM networks in which they operate. The goal is to build a structured view of the field, capable of highlighting gaps and trends and deepening the understanding of associated methods, technologies, and challenges. The scope covers studies that propose or apply methods, techniques, and/or algorithms to allocate, optimize, and/or simulate VTOL/UAV networks intended for passenger and/or cargo transportation in urban environments.

Four RQs guide the investigation:

- RQ1 – Context: in what operational, urban, and regulatory context is the proposed vertiport locating system situated? Justification: to delimit the operational, urban, and regulatory context that conditions the feasibility of the system.
- RQ2 – Methodology: which datasets, scenarios, and simulation environments are adopted in the process of defining vertiport locations? Justification: to identify the methods adopted to assess the robustness of the models and position them with respect to the state of the art in operations research and UAM.
- RQ3 – Experimental design: which scenarios, data sets, and simulations were considered in the design and testing of the vertiport location system? Justification: to characterize the degree of realism and applicability of studies in different urban contexts based on the data and simulations used.

- RQ4 – Evaluation: how are system performance evaluation and validation of the vertiport location system conducted? Justification: to verify the effectiveness of the system, identify limitations, and ensure the reliability of the results through the evaluation procedures adopted.

These RQs enable the classification of studies along contextual, computational, experimental, and validation dimensions.

Search strategy

An exploratory scan identified the study by Senthilnathan *et al.* (2025) as a methodological baseline. Their multi-objective approach to eVTOL vertiport deployment in New York City informed the definition of the search string, which was structured around five thematic axes: air mobility, location-allocation, optimization, route, and VTOL. Air mobility provides the general context of the literature analyzed, location-allocation delimits studies on vertiport allocation/location, optimization directs the search toward maximization/minimization studies, route focuses on the formation of networks/routes among optimized locations, and VTOL emphasizes vertical takeoff and landing vehicles.

The search string combines the five components through AND operators and uses OR to incorporate synonyms, thereby ensuring broad and conceptually consistent coverage. These axes represent the general context, vertiport allocation, optimization objectives, route networks, and VTOL aircraft. This structure was refined via Parsif.al (2025) and calibrated against Scopus to incorporate relevant synonyms. The semantic core of the query was preserved across all databases, while field tags, quotation rules, and searchable metadata fields were adjusted only when required by each interface to maintain retrieval equivalence. In practical terms, the adaptation criterion was conservative: the syntax could vary, but the conceptual coverage of the five axes could not. The final search string was applied to the following databases: Scopus, IEEE Digital Library, ACM Digital Library, EI Compendex, and ISI Web of Science.

No publication-year filter was applied at the database query stage. All searches were conducted in the early morning of May 2025 to minimize temporal discrepancies across databases. This procedure yielded an initial set of 1,056 records, from which the following final search string was defined: ("Air Mobility" *OR* "AAM" *OR* "Advanced Air Mobility" *OR* "Aerial Mobility" *OR* "Air Taxi" *OR* "Air Travel" *OR* "UAM" *OR* "Urban Aerial Mobility" *OR* "Urban Air Mobility") AND ("Location-Allocation" *OR* "Allocation" *OR* "Location" *OR* "Modeling" *OR* "Placement" *OR* "Planning" *OR* "Relocation") AND ("Optimization" *OR* "Maximization" *OR* "Maximize" *OR* "Minimization" *OR* "Minimize" *OR* "Multi objective" *OR* "Multi-Objective" *OR* "Optimal" *OR* "Optimality" *OR* "Optimize" *OR* "Optimizing") AND ("Route" *OR* "Connection" *OR* "Mesh" *OR* "Network" *OR* "Routing") AND ("VTOL" *OR* "Vertical Take-Off and Landing").

Before being applied to the remaining databases, the search string was calibrated in Scopus through an exploratory and iterative procedure. An initial scan in Google Scholar helped identify representative terminology in the field, including the study by Senthilnathan *et al.* (2025), which served as a methodological reference for refining the initial vocabulary. Based on this step, the strategy was structured around five thematic axes air mobility, location-allocation, optimization, route, and VTOL – and subsequently refined in Parsif.al through its integration with Scopus. The purpose of this calibration was to verify whether the selected terms effectively appeared in relevant titles, abstracts, and keywords while preserving the conceptual boundaries of the protocol.

For transparency, the refinement of the search string was guided by the principle of maximizing semantic coverage without introducing unnecessary noise. Air mobility included AAM, UAM, and air taxi, so as to capture both technical terminology and recurrent expressions used in the field. Location-allocation grouped terms such as allocation, location, modeling, placement, planning, and relocation to retrieve studies on siting and facility location across transportation, GIS, and operations-research vocabularies. Optimization included forms such as optimize, optimal, maximize, minimize, and multi-objective, thereby capturing studies structured around explicit objective functions. Route incorporated terms such as network, routing, connection, and mesh to recover studies that model vertiports as elements of a network rather than as isolated facilities. Finally, VTOL explicitly included the expanded form vertical take-off and landing, ensuring retrieval of studies that do not rely on the acronym alone. In all cases, synonym selection followed a conservative criterion: terms were retained when they expanded conceptual coverage and excluded when they introduced disproportionate ambiguity. This refinement favored broader initial recall, followed by manual screening under the inclusion/exclusion criteria (IC/EC criteria) (Senthilnathan *et al.* 2025).

After calibration in Scopus, the search strategy was extended to the other selected scientific databases, namely the ACM Digital Library (http://portal.acm.org), El Compendex (http://www.engineeringvillage.com), IEEE Digital Library (http://ieeexplore.ieee.org), and ISI Web of Science (http://www.isiknowledge.com), in addition to Scopus itself (http://www.scopus.com). The semantic core of the query remained unchanged across all databases. Only syntactic elements such as quotation rules, field tags, and searchable metadata fields were adapted when required by each interface in order to preserve retrieval equivalence. The searches were executed in a standardized manner, on the same day and within the same collection period, during the early morning of May 2025. This procedure yielded 1,056 studies, distributed as follows: Scopus (681), IEEE Digital Library (316), EI Compendex (38), ACM Digital Library (21), and ISI Web of Science (zero relevant records).

Selection criteria and screening process

This section describes the selection criteria applied to the studies identified in the databases, with the purpose of guiding the identification of those most relevant to the proposed systematic mapping.

Screening was conducted in sequential phases to ensure methodological rigor, transparency, and internal consistency. Duplicate records were first identified and removed to eliminate redundancy. Next, titles were screened to exclude clearly unrelated studies, followed by an analysis of abstracts and keywords to verify adherence to the predefined inclusion criteria. When ambiguity remained, full-text assessment was performed to confirm eligibility and methodological relevance to vertiport allocation in urban VTOL/eVTOL contexts. Decisions at each stage were guided strictly by the predefined inclusion and exclusion criteria, thereby ensuring the traceability of selection outcomes. To improve reliability and reduce classification bias, a pilot screening phase was conducted to calibrate interpretation standards, and ambiguous cases were re-evaluated through structured discussion, reinforcing consistency in study selection and evidence synthesis. This documentation logic is also consistent with contemporary principles of transparency in systematic review reporting (Page *et al.* 2021).

The predefined criteria, summarized in Table 1, were applied consistently throughout the screening phases.

Table 1. Inclusion Criterion (IC) and Exclusion Criterion (EC) criteria.

ID	Criteria
IC1	Apply methods, techniques, and/or algorithms to allocate, and/or optimize, and/or simulate VTOL/UAV network scenarios for the transportation of people and/or cargo in urban environments.
EC1	Non-algorithmic studies do not apply methods, techniques, and/or algorithms to allocate and/or optimize and/or simulate VTOL/UAV network scenarios for the transportation of people and/or cargo in urban environments.
EC2	Secondary, tertiary, conceptual, opinion, review, editorial, or normative studies.
EC3	Publications written in languages other than English or Portuguese.
EC4	Abstract only or promotional material for a work.
EC5	Duplicate records.
EC6	Publications older than 5 years.
EC7	Lack of full-text access.
EC8	Studies exclusively focused on routes.
EC9	Studies exclusively focused on collision.

Source: Elaborated by the authors.

Inclusion criterion 1 (IC1) required the application of computational or algorithmic methods for vertiport allocation, optimization, or simulation in urban VTOL/UAV contexts. Exclusion criterion 1 (EC1) was formulated as the direct negation of IC1, ensuring mutual exclusivity and greater precision in identifying studies effectively related to vertiport allocation in urban contexts.

The remaining EC2–EC9 were established independently, covering types of publication, language, availability of full-text access, temporal recency, and thematic adequacy (for example, studies focused exclusively on routes or on collisions).

The recency criterion (EC6) was applied during screening rather than retrieval. This decision avoided database-specific distortions caused by inconsistent year filters and prevented the premature exclusion of borderline studies before full eligibility assessment. The final restriction to the last 5 years is also substantively justified.

Research on vertiports has concentrated in the most recent phase of AAM development, and, after 2020, the field entered a more clearly defined technological and regulatory cycle, marked by the European Union Aviation Safety Agency (EASA 2022) vertiport design specifications, the FAA's AAM Implementation Plan (2023), and updated FAA–EASA certification guidance for eVTOL aircraft (2024) (FAA 2024).

Restricting the final sample to this period, therefore, improves methodological coherence because it preserves comparability among studies developed under broadly similar assumptions regarding VTOL/eVTOL operations, infrastructure requirements, digital traffic management pathways, and current certification and integration constraints. After screening, 31 studies remained for structured analysis.

Data extraction and coding procedure

Data extraction was performed using a structured form, as shown in Table 2. Each focused RQ (FRQ) was defined to operationalize the four mains RQs (RQ1–RQ4) and to generate structured evidence for answering them. The correspondence between FRQs and RQs was established *a priori* as follows: FRQ1–FRQ4 address RQ1 (contextual dimension); FRQ5–FRQ9 address RQ2 (methodological dimension); FRQ10–FRQ13 address RQ3 (experimental-design dimension); and FRQ14–FRQ17 address RQ4 (evaluation and validation dimension). This hierarchical organization ensured analytical traceability between the higher-level research objectives and the evidence extracted from the primary studies.

Table 2. Questions from data extraction.

FRQ	Questions
FRQ1	In what type of urban/regional environment is the study applied?
FRQ2	What is the focus of transport integration in the context analyzed?
FRQ3	Were regulatory/environmental constraints considered?
FRQ4	What is the maturity level of the system analyzed?
FRQ5	What was the main approach used?
FRQ6	What computational method was adopted?
FRQ7	What optimization algorithm was adopted?
FRQ8	Did the study consider vertiport capacity variables?
FRQ9	Were social/environmental criteria used in the decision model?
FRQ10	What type of scenario was modeled?
FRQ11	What data were used?
FRQ12	Was there integration with ground traffic data?
FRQ13	What simulator was adopted?
FRQ14	Which performance metrics were used?
FRQ15	Was there a comparison between different scenarios/methods?
FRQ16	How was validation conducted?
FRQ17	Did the study consider uncertainties (demand, traffic, costs)?

Source: Elaborated by the authors.

Beyond answering the RQs individually, the extraction framework was deliberately designed to support a multidimensional classification of studies across contextual, computational, experimental, and evaluative attributes. By organizing the evidence along these four analytical axes, the framework enables not only descriptive synthesis but also the identification of recurrent methodological configurations and structural patterns within the field.

Standardized response categories were progressively consolidated throughout the review process, as summarized in Table 3. These categories were derived from recurrent modeling and evaluation practices identified across the selected studies and were refined to ensure conceptual clarity and, whenever feasible, mutual exclusivity. The adoption of predefined response options enabled the consistent classification of heterogeneous approaches, reduced interpretive variability, and supported cross-study comparison.

Table 3. Responses from the extraction data.

FRQ	Responses
FRQ1	Megacity; Medium-sized city; Metropolitan region; Inter-municipal corridor; National; Not specified.
FRQ2	Airport–downtown connection; Multimodal connection (with metro, bus, etc.); General urban network; Logistics network; Other; Not specified.
FRQ3	Land use; Noise; Air safety; Equity of access; Not specified.
FRQ4	Conceptual; Academic simulation; Real strategic planning; Pilot project; Implementation in progress.
FRQ5	Mathematical optimization (MILP, MPEC, p-hub, etc.); Heuristics/metaheuristics; GIS/multicriteria; Clustering; Agent-based simulation; Other.
FRQ6	Exact optimization; Genetic algorithms; Machine learning; Integer linear programming; Stochastic simulation; Discrete choice models; Variable neighborhood search; Tabu search; Other; Not specified.
FRQ7	Solver; CPLEX; Integer linear programming; Greedy local search; Gurobi; Tabu search; Genetic algorithm; Not specified.
FRQ8	Yes; No; Partially.
FRQ9	Yes; No; Not specified.
FRQ10	Synthetic urban simulation; Real transport network (real traffic/Google/OD data); National scenario; Fictitious scenario; Other.
FRQ11	Real (OD, urban mobility); Synthetic (generated by models); Both; Not specified.
FRQ12	Yes (Google/real roads); Yes (traffic models); No; Not specified.
FRQ13	SIMIO; AEDT (Aviation Environmental Design Tool); MANTA (Microsimulation Analysis for Network Traffic Assignment); CAST Simulator; MATSim; AirSim; OpenAI Gym; V-HATT (Vertiport Human-Automation Teaming Toolbox); Other; Not specified;
FRQ14	TP; CD; Cost or profit; Congestion reduction; Equity of access; Noise/environmental impact; Not specified; Other.
FRQ15	Yes; No; Partially.
FRQ16	Comparison with the literature; Sensitivity analysis; Calibration with real data; Partial validation; No validation; Not specified.
FRQ17	Yes; Partially (limited sensitivity); No; Not specified.

Source: Elaborated by the authors.

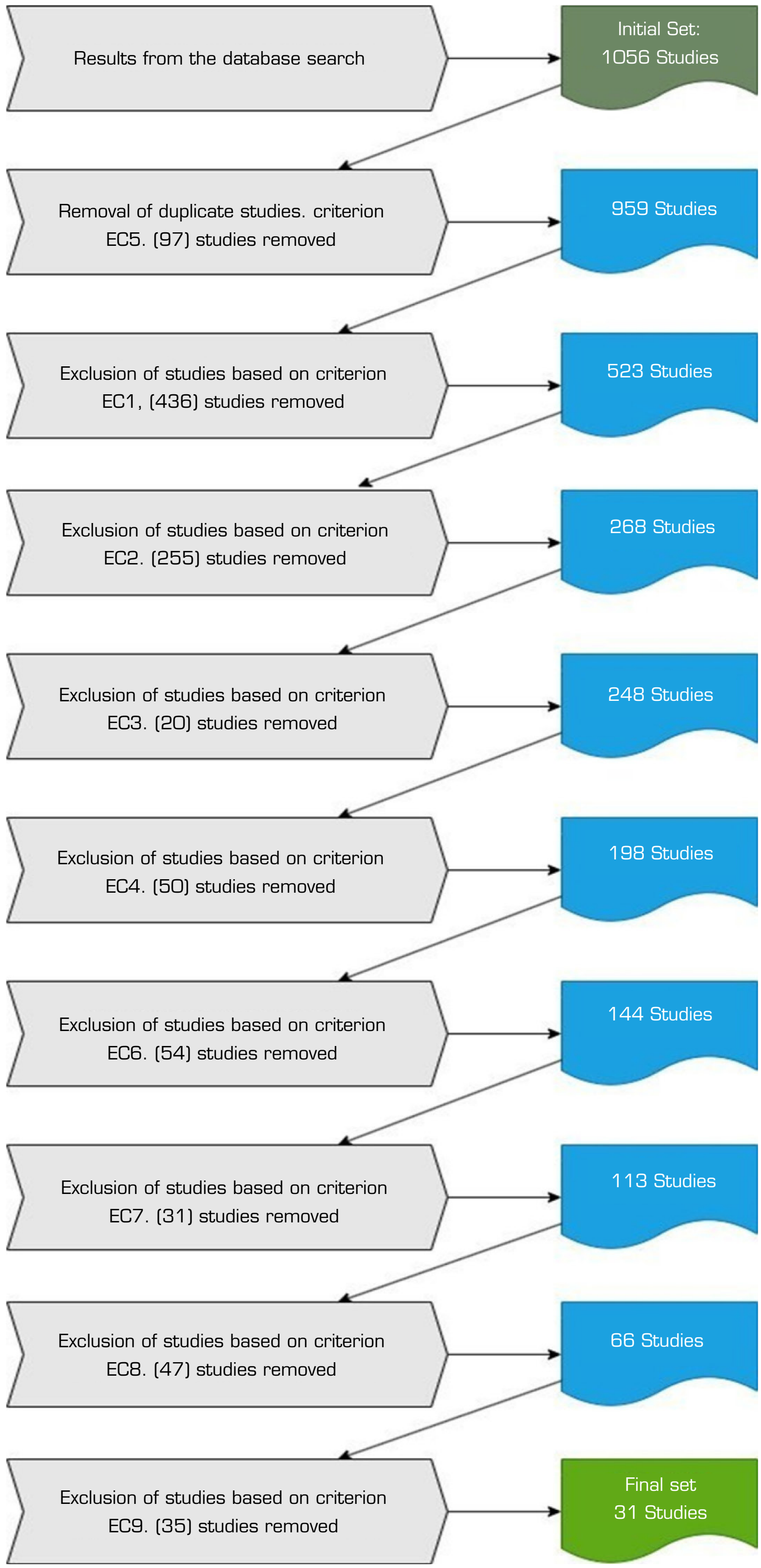
The extraction procedure followed the FRQ1–FRQ17 criteria within a structured methodological workflow. A pilot extraction cycle was conducted to calibrate interpretation standards and refine category definitions before full-scale coding. Senthilnathan *et al.* (2025) was adopted as a methodological baseline during this calibration stage because of its comprehensive modeling and evaluation structure. Each selected study then underwent full-text analysis, and the data were manually coded according to a standardized response scheme. Periodic review rounds were carried out to resolve ambiguities and ensure internal consistency in classification decisions.

By systematically organizing modeling approaches, computational methods, data usage, validation strategies, and uncertainty treatment, the extraction design provides the analytical basis for identifying dominant computational paradigms and assessing the structural maturity of vertiport location research. This structured categorization, in turn, supports the subsequent development of a consolidated computational taxonomy grounded directly in the extracted evidence.

Conduct

Figure 2 presents the study selection flow following the initial retrieval of 1,056 records. Scopus (681 records) and the IEEE Digital Library (316 records) emerged as the primary repositories, while EI Compendex (38 records) and the ACM Digital Library (21 records) provided complementary coverage; ISI Web of Science yielded no relevant results within the defined scope. This distribution highlights the central role of Scopus and IEEE as dominant indexing platforms in the field, with other databases contributing broader but comparatively limited coverage.

After duplicate removal, 959 studies remained. The sequential application of EC1–EC9 progressively refined the corpus, reducing it from 523 records after EC1 to 66 after EC8, culminating in 31 studies selected for structured data extraction. This multi-stage filtering process ensured strict alignment between the final evidence base and the vertiport allocation objectives defined in the protocol. Table 4 lists the selected studies and their publication years, illustrating the temporal distribution of research activity.



Source: Elaborated by the authors.

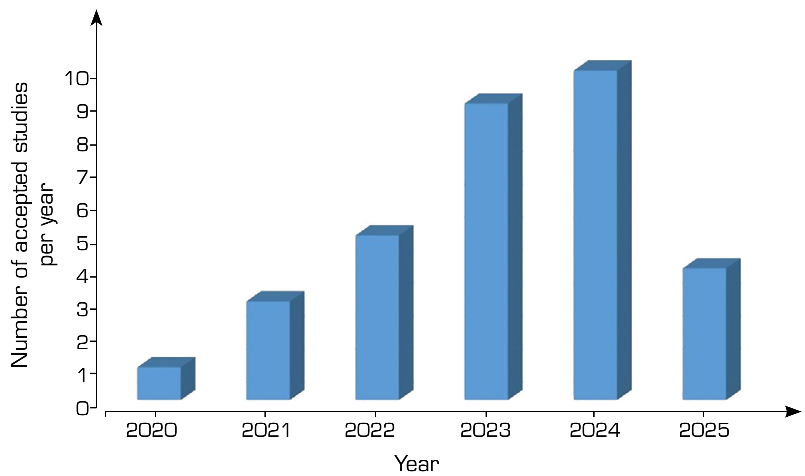
Figure 2. Study selection procedure.

Table 4. Studies resulting from systematic filtering.

ID	Title
1	A clustering-metaheuristic-simulation approach to determine air taxi operating site location Senthilnathan *et al.* (2025)
2	Vertiport Design Optimization using Integer Programming Park and Kim (2022)
3	A method for urban air mobility network design using hub location and subgraph isomorphism Willey and Salmon (2021)
4	Vertiport infrastructure location optimization for equitable access to urban air mobility Volakakis and Mahmassani (2024)
5	Vertiport location for eVTOL considering multidimensional demand of urban air mobility: an application in Beijing Jiang *et al.* (2025)
6	Vertiport location selection criteria for urban air mobility Mercan *et al.* (2025)
7	Maximum capture problem for urban air mobility network design Kitthamkesorn and Chen (2024)
8	User base estimation methodology for an eVTOL business airport shuttle air taxi service Roy *et al.* (2020)
9	Selection of vertiports using K-means algorithm and noise analyses for urban air mobility (UAM) in the Seoul metropolitan area Jeong *et al.* (2021)
10	Hierarchical vertiport network design for on-demand multi-modal urban air mobility Peng *et al.* (2022)
11	Vertiport planning for urban aerial mobility: an adaptive discretization approach Wang *et al.* (2022)
12	Scalable vertiport hub location selection for air taxi operations in a metropolitan region Chen *et al.* (2022)
13	Air taxi skyport location problem with single-allocation choice-constrained elastic demand for airport access Rath and Chow (2022)
14	Integrating urban air mobility into a public transit system: A GIS-based approach to identify candidate Locations for Vertiports Rahman *et al.* (2023)
15	Repurposing urban air mobility infrastructure for sustainable transportation in metropolitan cities: a case study of vertiports in São Paulo, Brazil Ribeiro *et al.* (2023)
16	Simulation-based assessment of airside operations and airspace capacity at vertiports Biemann and Wille (2024)
17	Integrated optimization of strategic planning and service operations for urban air mobility systems Jin *et al.* (2024)
18	Analysis of cost-efficient urban air mobility systems: optimization of operational and configurational fleet decisions Husemann *et al.* (2024)
19	Strategic integration of vertiport planning in multimodal transportation for urban air mobility: a case study in Beijing, China Zhao and Feng (2024)
20	Multi-objective vertiport location optimization for a middle-mile package delivery framework: case study in the South Holland Region Petit and Ribeiro (2025)
21	Integrated network design and demand forecast for on-demand urban air mobility Wu and Zhang (2021)
22	Vertiport design of urban air mobility for eVTOL aircraft Xiong *et al.* (2023)
23	Vertiport locations optimization in discrete search space Chae *et al.* (2023)
24	Integrated arrival and departure management for urban air mobility vertiport operations in the New York City airspace Chen *et al.* (2024)
25	A maximal covering approach for vertiport location problem Hess *et al.* (2024)
26	A method for air route network planning of urban air mobility Li *et al.* (2024)
27	Vertiport selection in hybrid air-ground transportation networks via mathematical programs with equilibrium constraints Yu *et al.* (2023)
28	Preliminary study of nation-wide urban air mobility demand and vertiport network study in Germany Lippoldt *et al.* (2023)
29	Fast decision support for air traffic management at urban air mobility vertiports using graph learning KrisshnaKumar *et al.* (2023)
30	Hierarchical vertiport network for an urban air mobility system: Munich metropolitan area case study Peksa *et al.* (2023)
31	Designing skyport networks: a hub location approach for urban air mobility Mandava and Karatas (2024)

Source: Elaborated by the authors.

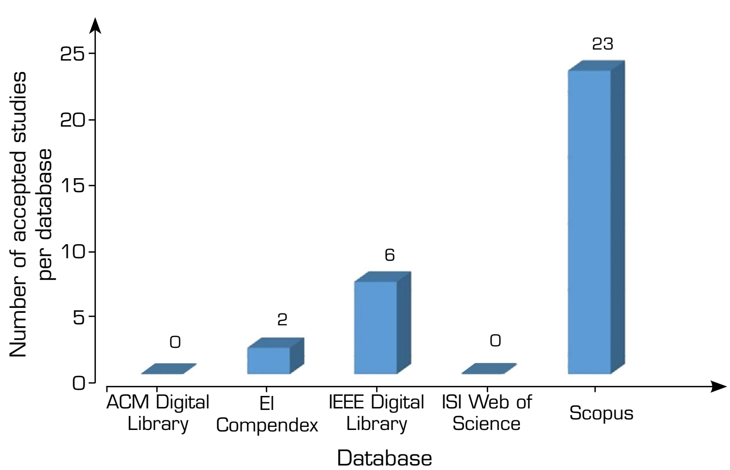
As shown in Fig. 3, publications exhibit steady growth up to a peak in 2024, with 2023 and 2024 being the most productive years, accounting for nine studies (28.12%) and 10 studies (33.33%), respectively. Earlier years display intermediate values, with an upward trend from 2021 to 2023 and a slight decrease in 2025, consistent with the search cutoff date (May 2025). This temporal pattern suggests an expanding and consolidating research domain.



Source: Elaborated by the authors.

Figure 3. Accepted studies per year.

Figure 4 presents the distribution of accepted studies by indexing database. Scopus predominates with 23 studies (71.9%), followed by IEEE Digital Library with seven studies (21.9%) and EI Compendex with two studies (6.2%); ACM Digital Library and ISI Web of Science did not contribute selected publications within the timeframe. This distribution reinforces the centrality of Scopus and IEEE in disseminating research on vertiport location, while other databases play a complementary role.



Source: Elaborated by the authors.

Figure 4. Accepted studies by the indexing database.

Computational paradigms and structural maturity

The systematic mapping indicates that vertiport location research has reached a relevant level of methodological development, but it still remains transitional in terms of systemic integration, validation maturity, and uncertainty treatment. By jointly synthesizing the evidence extracted across RQ1–RQ4, it becomes possible to derive a computational taxonomy of the field, understood as a structured classification of modeling paradigms according to their computational logic, scope of integration, and robustness of evaluation. These categories are not defined as *a priori*; rather, they emerge from recurrent methodological configurations identified across the analyzed studies.

Dominant modeling structures

The field is predominantly structured around mathematical optimization. Half of the studies adopt it as their primary modeling strategy, and 44% explicitly employ integer linear programming, most often implemented with Gurobi or C Programming Language Simplex (CPLEX). This pattern is consistent with canonical formulations of network design and location allocation, such as those proposed by Chen *et al.* (2022), Kitthamkesorn and Chen (2024), Rath and Chow (2022), Wang *et al.* (2022), and Willey and Salmon (2021). Hub-based and maximal-covering formulations (Hess *et al.* 2024; Mandava and Karatas 2024) further reinforce the predominance of combinatorial optimization structures. Collectively, these findings establish deterministic optimization as the dominant computational core of the field.

Within this deterministic core, recent extensions incorporate multidimensional demand (Jiang *et al.* 2025), adaptive discretization (Wang *et al.* 2022), and equilibrium constraints (Yu *et al.* 2023), signaling growing formal sophistication. This advance, however, has not been accompanied by a comparable expansion in systemic representation: capacity modeling appears explicitly in only 41% of the studies, and uncertainty treatment remains limited (23% explicit, 16% partial). Computational rigor is therefore high, but systemic robustness remains uneven. Even when applied to real metropolitan datasets, most models still operate under static or quasi-deterministic assumptions.

This pattern defines the first layer of the computational taxonomy: a deterministic optimization paradigm characterized by high formal rigor, predominant reliance on integer programming, and only partial incorporation of operational constraints.

Hybrid and data-integrated configurations

Beyond the deterministic core, a second layer of the taxonomy is defined by hybrid configurations that combine optimization with clustering, heuristics, simulation, or other data-driven components. Senthilnathan *et al.* (2025) exemplify this arrangement by integrating clustering, metaheuristics, and simulation to evaluate air-taxi operating-site performance in New York City. Jeong *et al.* (2021) similarly combine k-means clustering with noise analysis in vertiport selection, whereas KrisshnaKumar *et al.* (2023) extend this data-driven frontier by introducing graph learning for operational decision support in vertiport air traffic management.

These contributions correspond to the 22% of studies classified under heuristics/metaheuristics, as well as to the smaller subset that incorporates machine learning, stochastic simulation, or agent-based approaches. Although secondary in numerical terms, they indicate a methodological shift toward greater scalability, spatial realism, and more adaptive decision-support architectures.

The field also exhibits a strong empirical orientation. Fifty-nine percent of the studies are applied to real transport networks using observed traffic or origin-destination (OD) data, and 63% explicitly incorporate ground-traffic information. In parallel, works such as Bridgelall *et al.* (2023), Peksa *et al.* (2023), Peng *et al.* (2022), Rahman *et al.* (2023), and Zhao and Feng (2024) reinforce a multimodal and system-integration perspective, indicating that vertiports are generally modeled as nodes embedded in broader transport networks rather than as isolated infrastructure.

Despite this empirical grounding, 75% of the studies do not employ specialized simulation platforms. Even operationally oriented contributions, such as integrated arrival and departure management (Chen *et al.* 2024) or airside-capacity simulation (Biemann and Wille 2024), remain only partially connected to strategic vertiport siting models. This pattern indicates that, although the field has advanced in the use of real data and multimodal representations, a persistent gap remains between network-design optimization and operational simulation.

This second layer can therefore be understood as a hybrid, data-integrated paradigm in which optimization remains the dominant structuring logic, while heuristic, learning-based, and simulation components are incorporated to enhance scalability, empirical grounding, and operational representation.

Systemic integration

The third analytical dimension concerns evaluation maturity and systemic embedding. The mapped corpus remains overwhelmingly academic: 94% of the studies are classified as academic simulations, while the remaining 6% are conceptual. No cases of real strategic planning, pilot projects, or implementation in progress were identified. Accordingly, vertiport location research remains largely at a pre-operational stage.

Within this predominantly academic setting, performance evaluation is generally structured around combinations of cost/profit (CL), demand coverage (CD), and average travel time. Scenario comparison is widespread (91%), suggesting a relatively strong concern with internal comparative design. Validation procedures, however, remain heterogeneous: sensitivity analysis predominates (44%), benchmarking is still limited, and 31% of studies do not clearly specify their validation procedures. Explicit uncertainty modeling is likewise not predominant, reinforcing the still transitional character of the field's methodological maturity.

Regulatory and socio-environmental dimensions reinforce this transitional maturity. Nearly half of the studies do not explicitly formalize regulatory or environmental constraints. When such dimensions are incorporated, air safety, noise, and land use appear in heterogeneous combinations, while equity of access remains marginal, despite being explicitly addressed in Volakakis and Mahmassani (2024) and discussed in planning-oriented analyses (Mercan *et al.* 2025; Rohrmeier *et al.* 2025). This partial formalization is consistent with the broader literature, which shows that feasible vertiport configurations depend not only on geometric or cost-based criteria, but also on planning acceptability, multimodal accessibility, and operational constraints that are often modeled separately rather than in an integrated manner (Rahman *et al.* 2023; Ribeiro *et al.* 2023; Zhao and Feng 2024).

The same fragmentation is also evident in the treatment of operational uncertainty. Studies focused on strategic siting frequently adopt static or quasi-deterministic assumptions, whereas operationally oriented contributions show that pad capacity, sequencing, arrival-departure coordination, and airspace interactions materially condition system performance (Chen *et al.* 2024; Biemann and Wille 2024).

Likewise, demand-sensitive and equilibrium-based formulations show that siting outcomes are shaped by demand structure, user-allocation behavior, and network interdependencies, rather than by geometric configuration alone (Jiang *et al.* 2025; Rath and Chow 2022; Yu *et al.* 2023).

This evidence demonstrates that uncertainty, operational constraints, and regulatory conditions are intrinsic components of the modeling problem, as they directly redefine the feasible solution space and, consequently, the external validity of siting results.

Accordingly, the third layer of the taxonomy is characterized as a transitional stage of methodological and systemic maturity, combining strong optimization-oriented formulations with limited uncertainty formalization, heterogeneous validation practices, and only partial integration of regulatory and socio-environmental constraints.

Consolidating the computational taxonomy

The computational taxonomy of vertiport location research comprises three interrelated structural layers (Fig. 5), each associated with distinct methodological patterns and empirical prevalence:

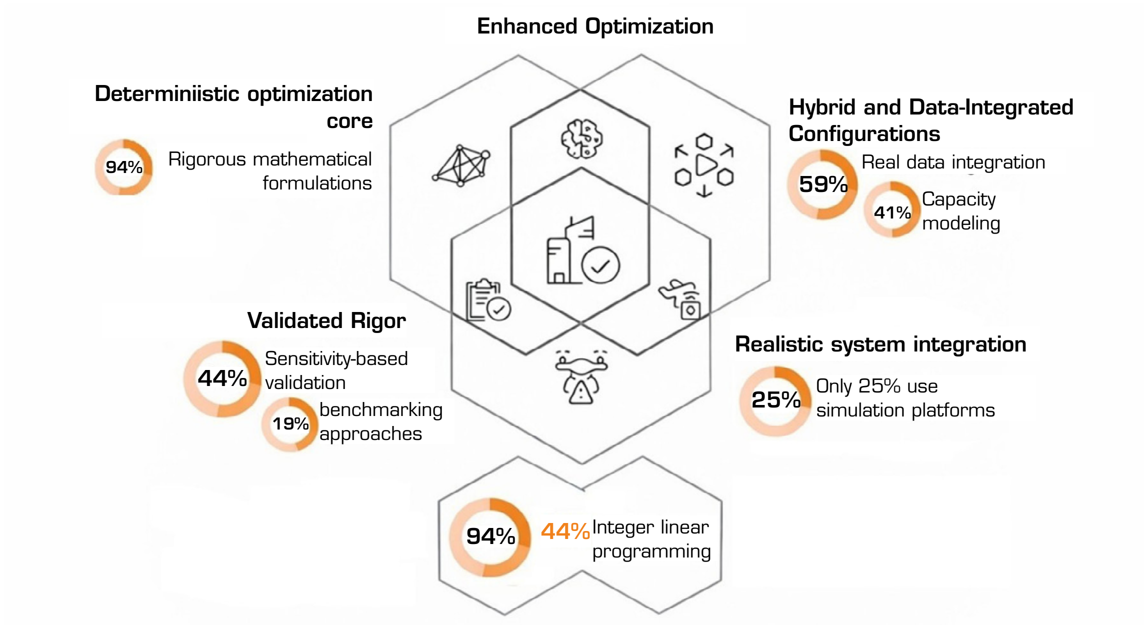
Deterministic optimization core: dominated by mathematical optimization approaches, particularly MILP-based formulations, representing approximately 50% of the analyzed studies. This layer is characterized by high mathematical rigor, although with limited integration of real-world operational constraints.

Hybrid and data-integrated configurations: incorporating real data, capacity modeling, and multimodal integration, with 59% of the studies using real-world data and 38% explicitly modeling capacity constraints. This layer reflects a transition toward more scalable and operationally grounded approaches.

Transitional systemic maturity: characterized by emerging integration of validation, simulation, and uncertainty, yet still limited in scope. While 94% of studies remain at a pre-operational, academic simulation stage, only 22% explicitly model uncertainty and just 25% incorporate simulation platforms, indicating a gap in systemic robustness and real-world applicability.

Figure 5 was visually organized with the support of generative artificial intelligence tools, while its conceptual structure derives from the authors' synthesis of mapped literature. The three layers are not mutually exclusive, but reflect recurrent structural tendencies observed across the studies. Together, they clarify the computational organization of the field and its current trajectory of methodological evolution.

The taxonomy indicates that vertiport location research has reached a solid level of formal development, although it remains systemically incomplete. Recent studies point to a clear movement toward methodological convergence: operational-management research incorporates airside and sequencing constraints more explicitly (Biemann and Wille 2024; Chen *et al.* 2024),



Source: Elaborated by the authors.

Figure 5. Computational taxonomy and structural maturity of vertiport location research (visual design support from Napkin AI).

multimodal-planning approaches deepen accessibility and transfer integration (Rahman *et al.* 2023; Peng *et al.* 2022; Zhao and Feng 2024), and demand-responsive or equilibrium-based models capture more realistic interactions between demand and network configuration (Jiang *et al.* 2025; Rath and Chow 2022; Yu *et al.* 2023).

Overall, the field is advancing toward models that more effectively integrate uncertainty, simulation, and operational realism, providing a more consistent basis for decision-making in vertiport planning within AAM systems.

RESULTS

RQ1: context of vertiport location systems

The spatial scope of the analyzed systems (FQ1) (Freitas *et al.* 2026) demonstrates a strong predominance of metropolitan regions (74%) as the primary application scale. Megacities represent 7% of cases, national-scale studies account for 3%, and 13% do not explicitly specify spatial scope. This distribution confirms that vertiport planning is predominantly framed within dense urban agglomerations where multimodal articulation and network integration are critical.

Regarding transport integration (FQ2) (Freitas *et al.* 2026), system design favors multimodal connections (42%), followed by general urban network integration (26%) and airport-downtown connections (16%). Logistics-oriented networks remain rare (3%), and 13% of studies do not specify integration focus. The prevailing context, therefore, positions vertiports as articulated nodes within broader transport ecosystems, either through comprehensive modal integration or through strategic airport connectivity.

Regulatory and environmental constraints (FQ3) (Freitas *et al.* 2026) remain heterogeneously incorporated. Almost half of the studies (48%) do not explicitly formalize constraints. When included, air safety appears in isolation in 16% of studies and, when combined with noise and land use, reaches 40%. Noise considerations appear in 3% of cases in isolation and 14% in combination (17% total), while land use appears in 3% alone and 15% in combination (21% total). Equity of access appears in only 3% of cases. These findings indicate that although regulatory and environmental dimensions are acknowledged, their computational formalization remains non-consolidated.

System maturity (FQ4) (Freitas *et al.* 2026) further reinforces this profile: 94% of studies are classified as academic simulations and 6% as conceptual. No instances of real strategic planning, pilot projects, or operational implementations were identified.

Conclusion (RQ1): vertiport location systems are predominantly situated in metropolitan settings and are commonly structured around multimodal integration or airport-downtown connectivity. Regulatory and socio-environmental constraints remain only partially formalized, while the maturity of the analyzed systems is still predominantly academic. Within this context, the problem is generally formulated as a network-design or location-allocation optimization task.

RQ2: methodologies and techniques

The methodological landscape (FQ5) (Freitas *et al.* 2026) is clearly optimization-driven. Mathematical optimization accounts for 48% of approaches, heuristics/metaheuristics for 22%, GIS/multicriteria methods for 7%, agent-based simulation for 3%, and other approaches for 9%. This confirms the dominance of classical optimization-based location-allocation modeling.

In terms of computational methods (FQ6) (Freitas *et al.* 2026), integer linear programming is the most frequent technique (45%). Genetic algorithms appear in 10%, Mathematical Programs with Equilibrium Constraints (MPEC) and exact optimization in 7% each, while machine learning, clustering, variable neighborhood search, local search, discrete choice models, and stochastic simulation each account for 3.17%. One study is classified as none (3.17%). Overall, integer linear programming constitutes the structural backbone of computational modeling.

Solver usage (FQ7) (Freitas *et al.* 2026) further confirms this structure: Gurobi (23%) and CPLEX (20%) predominate. Not specified appears in 20% of studies and none in 16%, with occasional use of genetic algorithms, tabu search, local search, k-means, and deep reinforcement learning (3% each), as well as other solvers (6%).

Capacity modeling (FQ8) (Freitas *et al.* 2026) is explicitly addressed in 38% of studies and partially in 3%, while 56% do not clearly incorporate capacity variables. Social/environmental criteria (FQ9) (Freitas *et al.* 2026) are included in 39% of works, whereas 61% do not explicitly formalize them.

Conclusion (RQ2): vertiport location research remains predominantly structured around deterministic optimization, particularly MILP-based formulations supported by commercial solvers. Heuristics and complementary techniques contribute to scalability and computational flexibility, but capacity modeling and socio-environmental criteria are still not systematically incorporated. As a result, important opportunities remain to increase the operational realism and systemic robustness of current models.

RQ3: scenarios, data, and simulation

Modeled scenarios (FQ10) (Freitas *et al.* 2026) show a preference for realism: 58% rely on real transport networks calculated with observed data, 13% on synthetic urban simulations, 23% fall into other classifications, and fictitious or unspecified cases each represent 3%.

Demand datasets (FQ11) (Freitas *et al.* 2026) are real in 45% of studies, synthetic in 29%, both in 3%, and not specified in 23%.

Integration with ground traffic (FQ12) (Freitas *et al.* 2026) appears in 61% of cases, confirming a multimodal evaluation approach linking aerial and ground performance.

Despite this realism, 74.4% of studies do not employ dedicated simulation platforms (FQ13) (Freitas *et al.* 2026), and simulator usage does not converge toward any standardized environment. This suggests that most analyses rely on static or semi-static modeling structures rather than fully dynamic simulation-based architectures.

Conclusion (RQ3): vertiport location design and evaluation are predominantly grounded in real datasets and multimodal integration, but they are still generally developed without the consolidated use of specialized simulation platforms.

RQ4: performance evaluation and validation

Performance metrics (FQ14) (Freitas *et al.* 2026) are predominantly multi-objective. Cost/profit (CL), CD, and average time (TP) each appear in 52% of studies, often in combination. Congestion reduction and environmental impact appear in 9% each, equity of access in 3%, "other" metrics in 27%, and 7% do not specify metrics.

Scenario comparison (FQ15) (Freitas *et al.* 2026) is widely adopted, supporting relative performance analysis.

Validation (FQ16) (Freitas *et al.* 2026) is primarily conducted through sensitivity analysis (45%), with benchmarking appearing in isolation in 6.5% and combined in 10% (16.5% total). Thirty-one percent do not specify validation procedures, and 6.5% report none.

Uncertainty modeling (FQ17) (Freitas *et al*. 2026) is explicit in 23% of studies, partial in 16%, and not specified in 3%. Thus, only a minority formally incorporates variability in demand, traffic, or costs.

Conclusion (RQ4): performance evaluation is predominantly structured around multi-metric objective functions and comparative scenario analysis; however, validation practices remain heterogeneous, and explicit uncertainty modeling is still limited across the literature.

CONCLUSION

This study mapped recent research on decision-support systems for vertiport location across contextual, methodological, experimental, and evaluative dimensions (RQ1–RQ4). The results confirm that vertiport siting is being treated as a multimodal network-design problem rather than as a purely geometric task. However, the mapped corpus remains predominantly academic and pre-operational, concentrated in metropolitan scenarios and only partially formalizing regulatory and socio-environmental constraints such as noise, land use, and equity (Mercan *et al.* 2025; Peksa *et al.* 2023; Rahman *et al.* 2023; Rohrmeier *et al.* 2025; Volakakis and Mahmassani, 2024; Zhao and Feng, 2024).

From a computational standpoint, the field is dominated by deterministic optimization, especially MILP-based formulations supported by commercial solvers (Chen *et al.* 2022; Kitthamkesorn and Chen 2024; Wang *et al.* 2022). Although many studies use real demand and ground-transport data, recurrent weaknesses remain: limited explicit representation of capacity and operational dynamics, low incorporation of specialized simulation, and still restricted treatment of uncertainty (Chen *et al.* 2024; Jiang *et al.* 2025; Senthilnathan *et al.* 2025). In addition, validation remains heterogeneous and is still centered largely on sensitivity analysis, which restricts comparability and weakens external validity.

The evidence suggests that these results support a computational taxonomy composed of a dominant optimization core, emerging hybrid and data-integrated configurations, and a transitional layer marked by partial systemic integration, heterogeneous validation, and limited uncertainty treatment. Because the mapped corpus is recent and overwhelmingly pre-operational, this taxonomy should be understood as a synthesis of recurrent structural tendencies rather than as a definitive maturity sequence.

Future research should prioritize models that jointly incorporate siting, multimodal accessibility, operational capacity, regulatory constraints, and uncertainty within more standardized validation frameworks. Greater integration between strategic location models and operational simulation, as well as stronger treatment of robustness and socio-environmental criteria, is necessary for vertiport planning to progress from formally rigorous but still partial models to decision-support systems better aligned with the practical requirements of AAM (Biemann and Wille 2024; Volakakis and Mahmassani 2024; Yu *et al.* 2023; Zhao and Feng 2024).

CONFLICTS OF INTEREST

Nothing to declare.

AUTHOR CONTRIBUTIONS

Conceptualization: Freitas JH; **Methodology:** Freitas JH; **Software:** Freitas JH and Costa RM; **Validation:** Costa RM and Bandeira MCGSP; **Formal Analysis:** Freitas JH and Bandeira MCGSP; **Investigation:** Freitas JH, Costa RM, and Bandeira MCGSP; **Resources:** Freitas JH and Bandeira MCGSP; **Data Curation:** Freitas JH and Bandeira MCGSP; **Writing – Original Draft:** Freitas JH and Bandeira MCGSP; **Writing – Review & Editing:** Freitas JH, Bandeira MCGSP, and Costa RM; **Visualization:** Freitas JH and Bandeira MCGSP; **Supervision:** Bandeira MCGSP and Costa RM; **Project Administration:** Bandeira MCGSP and Costa RM; **Final approval:** Bandeira MCGSP.

DATA AVAILABILITY STATEMENT

The data are available on Zenodo https://doi.org/10.5281/zenodo.20753929

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

During the preparation of this work, the authors used (i) Napkin AI (Napkin Inc.) to generate preliminary visual layouts that informed the design of Figs. 1 and 5 and (ii) Grammarly (Grammarly Inc.) for grammatical revision, language refinement, and translation support of the manuscript. The AI tools were not used for generating original scientific content, for conducting literature searches, for screening or extracting study data, for performing analysis or interpretation of the systematic mapping results, or for any decision affecting the scientific content of the article. After using these tools, the authors reviewed and edited all outputs and take full responsibility for the content of the publication.

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