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Urban Air Mobility: Systematic Review of Scientific Publications and Regulations for Vertiport Design and Operations

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Abstract: Novel electric aircraft designs coupled with intense efforts from academia, government and industry led to a paradigm shift in urban transportation by introducing UAM. While UAM promises to introduce a new mode of transport, it depends on ground infrastructure to operate safely and efficiently in a highly constrained urban environment. Due to its novelty, the research of UAM ground infrastructure is widely scattered. Therefore, this paper selects, categorizes and summarizes existing literature in a systematic fashion and strives to support the harmonization process of contributions made by industry, research and regulatory authorities. Through a document term matrix approach, we identified 49 *Scopus*-listed scientific publications (2016–2021) addressing the topic of UAM ground infrastructure with respect to *airspace operation* followed by *design*, *location and network*, *throughput and capacity*, *ground operations*, *cost*, *safety*, *regulation*, *weather* and lastly *noise* and *security*. Last listed topics from *cost* onwards appear to be substantially under-represented, but will be influencing current developments and challenges. This manuscript further presents regulatory considerations (Europe, U.S., international) and introduces additional noteworthy scientific publications and industry contributions. Initial uncertainties in naming UAM ground infrastructure seem to be overcome; *vertiport* is now being predominantly used when speaking about vertical take-off and landing UAM operations.

Keywords: urban air mobility; UAM; eVTOL; vertiport; literature review

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1. Introduction

"To take off, flying vehicles first need places to land" [1]

The interest in suitable VTOL ground infrastructure is rising due to the growing amount of small UAS applications and the thriving topic of UAM introducing a new mode of passenger transport and on-demand deliveries inside urban areas. UAM is striving for revolutionizing the status quo of ground transportation, aircraft design, ATM processes and the principles of multi-modality. Furthermore, UAM seeks to connect residential areas and airports to city centres, to attract as many residents as possible by promising immense time savings under affordable conditions. UAM is setting the scene for new approaches, new technologies and new potential markets. However, UAM is describing a new mode of aerial transportation which will be implemented in very challenging urban environment in which VTOL capabilities and early considerations of infrastructure design specifications are expected to be crucial. This is supported by EASA "Study on societal acceptance of Urban Air Mobility in Europe" which concluded with infrastructure being the biggest challenge for UAM [2].

These days, the topic of UAM is thriving, the number of published contributions is large, but those who focus specifically on UAM ground infrastructure are widely scattered and are addressing different business cases, time horizons and technological readiness. This manuscript provides a detailed and systematic review of 49 *Scopus*-listed, scientific publications about ground infrastructure in the context of UAM and published between the years 2016 and 2021 (including). The publications were selected through a text mining approach: if the abstract of a publication contained both "urban air mobility" and at least one keyword related to ground infrastructure (see the list of keywords in Section 1.1) it was included in the selection. The various text mining techniques used in the analysis are explained in Sections 1.2 and 1.3. These encompass database overlap analysis, document term matrix and document classification. All scripts were written by the authors using the following *Python 3.8* packages: *pandas*, *nltk*, *stop_words* and *statistics*. A comprehensive introduction into the text mining approaches used in this review can be found in [3].

The review predominantly focuses on VTOL operations and subsequently calls UAM ground infrastructure: *vertiports*. Furthermore, additional noteworthy contributions made by research, regulatory authorities and industry are presented. This review complements already existing UAM review publications of Garrow et al. [4] and Straubinger et al. [5] and contributes thereto by focusing explicitly on ongoing research, regulatory and industrial contributions as well as intermediate achievements in the field of UAM VTOL ground infrastructure. We are aware that the term "urban air mobility" indicates a limited view compared to "advanced air mobility" (AAM) as proposed by NASA [6]. Yet NASA continues to use the term UAM as a subset of AAM, as do comprehensive reviews of the field [4,5]. For this reason we will use the term UAM, but we do not intend to exclude other applications of AAM, such as regional or rural air mobility.

Throughout the review, eleven research topics were identified: *airspace operation*, *design*, *location and network*, *throughput and capacity*, *ground operations*, *cost*, *safety*, *regulation*, *weather*, *noise* and *security* (sequence: descending prominence), which shaped the following structure of the manuscript. Section 1 provides an overview and a systematic trend analysis (text mining) of already used UAM ground infrastructure terminology and classifications. Section 2 elaborates a summary of current heliport design guidelines and introduces first drafts and prototypes of vertiport design specifications focusing mainly on European and American contributions. The subsequent Sections 3–5 summarize and discuss the contributions of 49 publications based on the trend analysis introduced in Section 1. Additional noteworthy scientific, regulatory and industry contributions are discussed. Section 3 examines the development of vertiport networks considering different operating environments and groups of customer. Section 4 summarizes vertiport design proposals, analyzes different approaches of developing vertiport airside air and ground operations and collects initial investment estimations for specific vertiport designs. Section 5 concludes the review by providing initial evaluations of weather impacting UAM and vertiport operations. Finally, Section 6 conducts a critical evaluation of all sighted contributions and highlights pending and under-represented research questions.

1.1. Taxonomy of UAM Ground Infrastructure

One might ask the question, why is there a need to define a new class of ground infrastructure specifically for UAM when we already have a distinct set of thoroughly practiced design guidelines covering aerodromes, airports and heliports?

Assuming affordable access to UAM flights is targeted, high numbers of throughput need to be achieved which will require larger and probably more complex ground infrastructure topology and access management as it is currently available for helicopter/heliport operations [7]. This may include ground taxiing of VTOL aircraft, reduced separation, simultaneous/automatic/autonomous operations as well as steep/vertical approach and departure profiles in order to operate in densely populated and built-up urban environment. For comparison, basic flight maneuvers for rotorcraft address a typical descent profile of 8 to 12 degrees whereas a steep approach is defined by approx. 15 degrees descent angle [8]. Moreover, UAM being considered on-demand, following high dispatch frequencies and mainly operating in urban scenery with shortly changing flight phases are characteristics of significant difference compared to current aviation operations.

As to understand with what UAM ground infrastructure is associated with and what considerations are stated in terms of classification and definition, the following Sections 1.1.1 and 1.1.2 will provide an overview of historic and current developments.

1.1.1. Regulatory and Standardization Context

Both well-established and novel aircraft manufacturers, research facilities, local and public authorities, regulatory agencies, CNS providers, air navigation service providers, consulting companies and many more all around the world are currently contributing to the development of UAM. A considerable inconsistency was found in the classification of such UAM VTOL ground infrastructures throughout different (scientific) publications addressing UAM.

Starting with already familiar aviation ground infrastructure and according to ICAO, the *aerodrome*, is "a defined area on land or water (including any buildings, installations and equipment) intended to be used either wholly or in part for the arrival, departure and movement of aircraft" [9]. In the European certification specification for aerodrome design *CS-ADR-DSN*, EASA follows ICAO's guidelines but added the specification of being located "on land or water or on a fixed offshore or floating structure" [10]. This also includes small general aviation airfields, heliports, commercial airports and military airbases [11]. A distinct version for rotorcraft, the *heliport*, is defined by ICAO's *Annex 14* and EASA's *CS-HPT-DSN* as "an aerodrome or a defined area on a structure intended to be used wholly or in part for the arrival, departure and surface movement of helicopters" [9,12]. For completion, an airport has terminal(s) and car parks additional to the infrastructure used by the aircraft itself, thus the aerodrome is part of an airport [11]. Consequently, the heliport extends the characteristic of an aerodrome by the definition of an area on structure which includes the possibility of elevated areas. Also, the heliport is exclusively used by helicopters, whereas the aerodrome can be used by both vehicles. It needs to be highlighted that EASA's *CS-HPT-DSN* only provides design certification specification for heliports located at aerodromes that fall under scope of *Regulation (EU) 2018/1139*.

Transitioning from "traditional" aviation towards initial serious considerations of inter-city aerial transportation, in 1983, the National Rotorcraft Program analyzed how the national inter-urban transportation market in the U.S. can be improved [13]. Among others, the report determined that conventional helicopters did not satisfy the stated requirements due to lack of capacity, high operational costs and high noise levels. The recommendation of considering tiltrotor aircrafts offered higher speed and range and vertical take-off and landing capabilities.

Followed by this recommendation, in 1985, the FAA, NASA and the Department of Defense conducted a joint civil tiltrotor study in order to identify the potential of the commercial tiltrotor transport market [13] . Several studies followed covering the topics civil tiltrotor missions and applications, potential risk areas, market evaluations, ground infrastructure planning and development, air traffic control and public acceptance (see [13–16]).

Driven by those civil tiltrotor developments generated by industry, military and government, in 1991, the FAA developed an *AC 150/5390-3* guiding vertiport design [17]. The terminologies *vertiport* and *vertistop* were first introduced describing respectively "an identifiable ground or elevated area, including any buildings or facilities thereon, used for takeoff and landing of tiltrotor aircraft and rotorcraft" and "a vertiport intended solely for takeoff and landing of tiltrotor aircraft and rotorcraft to drop off or pick up passengers or cargo". This AC paved the way for the term vertiport and the general idea of creating classes of ground infrastructure to describe different characteristics and operational capabilities. Those considerations were never put into practice since military tiltrotor technologies were never used commercially therefore causing the cancellation of *AC 150/5390-3* in July

2010 [18]. However, years later, those former developments serve as important precedent being now adjusted and refined for modern UAM operations.

First, the generic term *UAM aerodrome* was introduced by FAA's first version of a UAM ConOps [19] addressing foundational principles, roles and responsibilities, scenarios and operational threats. It describes "a location from which UAM flight operations depart or arrive. [. . .] UAM aerodrome is used explicitly when the context indicates functionality to support UAM operations that is not present in NAS [National Airspace System] operations" [19].

NASA is following FAA's approach by using the term *UAM aerodrome* in the first version of the published UAM Vision ConOps in 2020 [6], addressing a UAM operation of medium density and complexity. The term *UAM aerodrome* is further specified by addressing operational UAM characteristics such as VTOL capabilities and ground movement leading into the definition of a "specifically defined area that is intended for the arrival, departure, and ground movement of UAM aircraft. Because of the VTOL nature of many UAM aircraft, most UAM aerodromes look more like today's heliports with landing pads as opposed to long runways" [6]. In a follow-up ConOps addressing high-density automated vertiports [20], NASA again further specified the classification and defined the term *vertiport* in correspondence to the aircraft design (VTOL and rotorcraft) and its propulsion unit (eVTOL). Also, the physical location of a vertiport (ground-based or elevated) is now part of the definition which resulted into "an identifiable ground or elevated area, including any buildings or facilities thereon, used for the takeoff and landing of eVTOL and rotorcraft".

Responding to the rising requests claiming for a consolidated UAM ground infrastructure design guideline, in March 2022 the FAA published an engineering brief on the subject of vertiport design limited to piloted and VFR VTOL operations in order to capture early UAM VTOL operations [18]. In [18], UAM ground infrastructure is now following the initial classification of [17], but clearly stating propulsion characteristics, VTOL capabilities and the specific use of co-located buildings for passenger handling and other UAM services. Consequently, the *vertiport* is defined as "an area of land or a structure, used or intended to be used, for electric, hydrogen, and hybrid VTOL landings and takeoffs and includes associated buildings and facilities" and the *vertistop* as "an area similar to a vertiport, except that no charging, fueling, defueling, maintenance, repairs, or storage of aircraft are permitted" [18].

Transitioning to European UAM applications, EASA introduced the term *vertiport* in the first draft of the SC SC-VTOL-01 [21] in 2019. It provides an initial description naming the vertiport "an area of land, water, or structure used or intended to be used for the landing and take-off of VTOL aircraft". There is no specific requirement attached to that definition addressing the VTOL aircraft's propulsion unit, passenger handling and service facilities providing e.g., charging/refuelling and maintenance. This rather generic definition was picked-up by EASA's Prototype Technical Specification *(PTS-VPT-DSN)* for VFR Vertiports [22] published in 2022.

Since regulatory authorities are working closely together with standardization bodies, it is noteworthy mentioning them in this context. The EUROCAE, operating as a non-profit organization, is dedicated to the elaboration of aviation standards since 1963. The development of UAM operations is incorporated in working group 112 "Vertical Takeoff and Landing" which is developing several standards such as vertiport operations (ED-299 currently under development [23]), and VTOL aircraft ConOps (ED-293 [24]). Important groundwork for [22] was provided by EUROCAE. In [24], EUROCAE makes use of the term *vertiport* following the definition stated in EASA's SC-VTOL-01.

On an international standardization level, the International Organization for Standardization *ISO*, is currently developing a vertiport standard *ISO/AWI 5491* under the technical committee *ISO/TC 20/SC 17 Airport Infrastructure* [25]. A publication is still pending. Further, *ASTM International* initiated already in 2017 the work item of "New Specifications for Vertiport Design" which also indicates the usage of *vertiport* and *vertistop* and providing the following, sofar most precise definition: "Vertiport means a generic reference to the area of land, water, or structure used, or intended to be used, for the landing and takeoff of VTOL aircraft together with associated buildings and facilities. Vertistop means a minimally developed VTOL aircraft facility for boarding and discharging passengers or cargo. The vertiport/vertistop relationship is comparable to a bus terminal-bus stop relationship with respect to the extent of services provided or expected" [26]. It is also highlighted that vertiports are expected to serve both civil VTOL aircraft and civil helicopters and the extension for electric driven VTOL aircraft should be considered carefully [26].

1.1.2. Commercial and Research Context

In 2016, when *UBER Elevate* published the whitepaper "Fast-Forwarding to a Future of On-Demand Urban Air Transportation" [27], the topic short range metropolitan air transportation including the vertiport "came back to life". Several whitepapers followed addressing among others "The Roadmap towards scalable urban air mobility" [28], "The New Digital Era of Aviation" [29] and a "Concept of Operations: Autonomous UAM Aircraft Operations and Vertiport Integration" [30].

Ref. [27] picks up the terminologies introduced by [17] but focusses on layout and charging characteristics. The infrastructure which supports urban VTOL operations is defined as *vertiports*, described as "VTOL hubs with multiple takeoff and landing pads, as well as charging infrastructure" and as *vertistops* "a single TLOF pad with minimal infrastructure". This whitepaper together with the following *UBER Elevate* Summits in the years 2017, 2018 and 2019 received considerable attention and significantly pushed forward the topic of UAM. This trend is also depicted by the number of publications related to the topic UAM ground infrastructure in Figure 1. When investigating all publications listed in the online database *Scopus* from the year 2000 onwards, which are displaying a connection to the keyword UAM ground infrastructure, it appears that the number of publications is increasing explicitly with the year 2016.

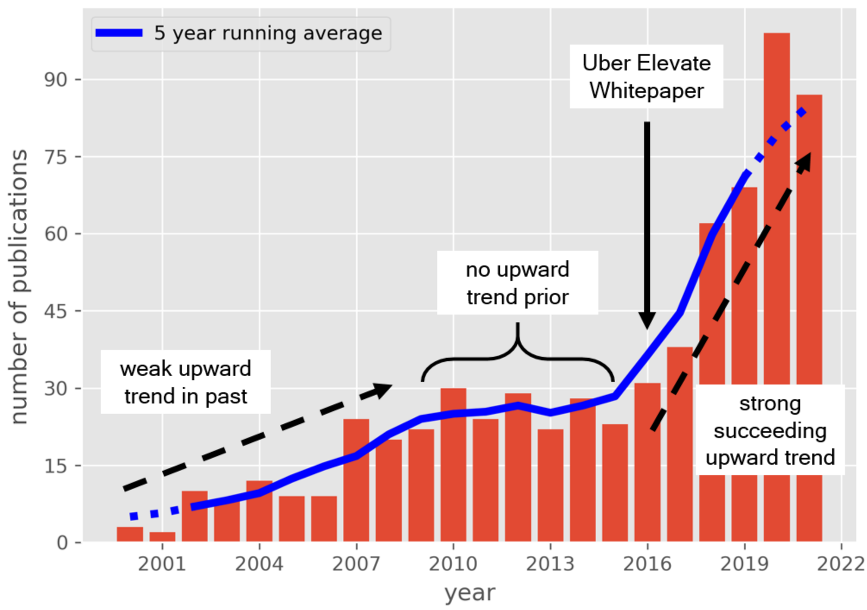


Figure 1. Publications related to UAM ground infrastructure as listed in *Scopus* after the year 2000 and in relation to the publication of *UBER*'s whitepaper in 2016 [27].

The consulting companies *Deloitte* [31] and *McKinsey and Company* [1] both established a UAM ground infrastructure classification with multiple sub-categories addressing varying features, capabilities and local implementation. The generic term of the physical infrastructure is termed as *vertiplaces* [31] and *VTOL ports* [1], respectively. The largest archetype is defined by both as *vertihub*. Ref. [31] describes it as small airports for eVTOL aircraft, mainly located on the periphery of urban or suburban areas because of their large footprint including the availability of MRO infrastructure, whereas, ref. [1] envisions it as a stand-alone building implemented in central and high-traffic areas providing charging/refueling capabilities for VTOL aircraft and distinct services for passenger. The second archetype is termed as *vertiport* and *vertibase*, respectively. Based on [31], the *vertiport* is located at points of interests ideally integrated with other modes of ground transportation. Multiple eVTOL aircraft can be accommodated, fast-charging, refueling and minor MRO services are provided. Security check-points, passenger waiting lounges, systems for fire safety and real-time surveillance are highlighted as well. According to [1], *vertibases* are medium size, located at medium-traffic areas and are either newly built or retro-fitted. As third archetype depicting the smallest footprint, Refs. [1,31] use the term *vertistation* and *vertipad* respectively. On the one hand a *vertistation* provides only one or two pads for which the use of existent helipads can be considered. On the other hand, *vertipads* are assigned to a "spoke" in a hub-and-spoke network. Both share the characteristic of smaller footprints and lower costs which could enable an easy implementation as peripheral infrastructure in suburban or rural locations.

Following the approach of multiple archetypes but based on aircraft performance and UAM ground infrastructure capabilities, ref. [7] uses the term *UAM aerodrome* by [19] as hypernym for UAM ground infrastructure. With regard to a UAM aircraft's performance, VTOL or STOL capabilities are distinguished resulting into different UAM aerodrome classes. The term *vertidrome* was used for VTOL operations and *stoldrome* for STOL operations only. Two additional flavors of vertidromes are used, *vertiport* and *vertistop*, in order to distinguish between operational and technical capabilities like charging, refueling, MRO and passenger handling.

Numerous terms for novel take-off and landing ground infrastructure were found by [32], such as *vertiport*, *vertipad*, *pocket airport*, *skypark*, *sky node* and *sky port*. To avoid the definition of a specific term and therefore limiting ground infrastructure to a specific characteristic, ref. [32] uses the generic term *TOLA*, take-off and landing area, for on-demand mobility operations, which describes any location an aircraft, VTOL or STOL aircraft, can depart from or arrive at. Additional terms were found such as *Verti-X* [33], *skyports* [34] and *airpark* [35] if super STOL (SSTOL) and STOL aircraft are being considered to serve metropolitan areas and intra-city operations.

But towards what terminology is the UAM community trending? The next section will run a systematic analysis of what terminologies are used in the scientific context, based on the set of *identified terms* introduced in this section.

1.2. Trends in Research and Scientific Publication

In this section, the use and prominence of the above-mentioned terms or keywords (both words used synonymously) will be analyzed. The goal is to illuminate the usage of different keywords in the past and present and help the community become more aware of current developments in the field of UAM ground infrastructure. As hinted in the title of this paper, we believe "vertiport" to be the most prominent keyword and it is therefore used throughout this manuscript.

In Section 1.1, a total of 19 keywords were discussed. A search in the publication database *Scopus* (find the *Scopus* publication portal under https://www.scopus.com/; accessed on 11 July 2022) yielded that 11 of 19 keywords were used at least once in the listed scientific literature (equals database "ground infrastructure"); this means 8 keywords were not used at all. A limitation of this approach was that the keywords needed to occur in the title or abstract of the publication, as *Scopus* only searches the meta data of publications. This database was chosen as a compromise between a wide range of publications (e.g., *Web of Science* does not list conference proceedings) and quality of publications (e.g., *Google Scholar* has no transparent mechanism of selecting papers).

To gain a feeling for the trend of each keyword (see Table 1), three time spans and sub-databases were looked at in particular: the last two decades, the last 10 years, and the years after 2016 which marked a turning point due to the publication of the UAM white paper by *UBER Elevate* [27] (see Figure 1). The number of publications in each sub-database is shown as well in Table 1. The size of the database does not have to match the sum of the occurrences of all keywords for various technical reasons: for example, one paper could contain multiple keywords from the list.

Table 1. Prominence of "ground infrastructure" related keywords.

Keyword	*Scopus* All Years	Past Two Decades (2000–2021)	Past 10 Years (2012–2021)	Since *UBER Elevate* (2016–2021)
aerodrome	662	536	383	296
airpark	30	27	12	9
pocket airport	2	2	2	1
skynode	23	23	13	8
skypark	6	5	5	4
vertidrome	1	1	1	1
vertihub	2	2	2	2
vertipad	4	6	6	6
vertiport	82	63	62	60
vertistop	2	2	2	2
verti-x	1	1	1	1
ine				
Size of database without duplicates	**810**	**689**	**500**	**396**

As the focus of this review is ground infrastructure in the context of UAM, the same search was then applied to the keyword of "urban air mobility" (equals database "urban air mobility"). The goal of this analysis is to find the best-fitting keyword for ground infrastructure in the context of UAM, which is done by comparing the two databases derived from *Scopus*. In Figure 2, the overlap of these two databases is visualized. Set A and B represent the UAM and ground infrastructure database, respectively. The comparison of two sets is conducted by looking at DOIs as unique identifier. As not all listed entries carry a DOI, these entries are removed, yielding the sets C and D representing the cleaned databases for UAM and ground infrastructure, respectively.

Entries in *Scopus* that do not carry a DOI number can be proceedings, workshop summaries or other material, but also conference papers and articles. There are other ways of comparing entries such as using the title, but this might lead to problems with consistency. Excluding all entries that do not carry a DOI number is therefore a way of dataset quality control, while we acknowledge that this might create a bias within the dataset.

The combination of both databases is labeled as set E, the papers exclusively occurring in the urban air mobility database as set F and the papers exclusively occurring in the ground infrastructure database as set G. Our set of interest are those papers shared by both databases, which are labelled as set H. In Table 2, a brief description of all sets is given, including the size of each set and their relation to one another. Comparing the databases of both searches showed that only 8 keywords (see Table 3) of the 11 keywords shown in Table 1 are used in the context of UAM throughout 49 scientific publications listed by *Scopus*.

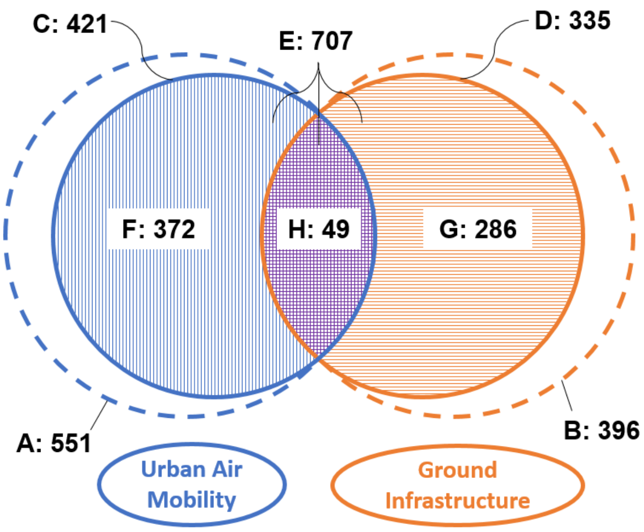


Figure 2. Overlap between databases derived from the keyword "urban air mobility" and 11 keywords related to "ground infrastructure".

Table 2. Size of sets from database overlap analysis: 49 shared papers including keyword "urban air mobility" (UAM) and keywords related to "ground infrastructure" (GI).

Set	Descripton	Size	Mathematical Relation of Sets
A	UAM all publications	551	$A \supseteq C \supseteq F$
B	GI all publications	396	$B \supseteq D \supseteq G$
C	UAM only publications with DOI	421	-
D	GI only publications with DOI	335	-
E	UAM and GI combined	707	$E = C \cup D$
F	UAM exclusive	372	$F = C \setminus H$
G	GI exclusive	286	$G = D \setminus H$
H	UAM and GI shared	49	$H = C \cap D$

Table 3. Keyword occurrences describing UAM ground infrastructure (set H).

Keyword	Hits
aerodrome	1
airpark	4
vertidrome	1
vertihub	1
vertipad	4
vertiport	40
vertistop	1
verti-x	1
total hits	**49**

Applying a document term matrix approach, the number of occurrences of each keyword in the final database can be highlighted (see Table 3). A document term matrix shows how often each keyword occurs in each publication. The number of hits shown are the sum of occurrences across all 49 publications. It can be seen that "vertiport" occurs in 40 of the total 49 publications and therefore covers over 80%. *Vertiport is the most prominently used term or keyword to describe UAM ground infrastructure*. This is in direct contrast to the wider field of aerospace research where "aerodrome" (296 occurences in the last 6 years) appears to be the more prominent keyword while "vertiport" is used less often (60 occurences in the last 6 years) as can be seen in Table 1. Yet, the keyword "aerodrome" has negligible relevance in the UAM community (1 occurence in the context of "urban air mobility", see Table 3). The process of selecting keywords describing ground infrastructure and finding the overlap with the body of research concerned with UAM is summarized in Figure 3.

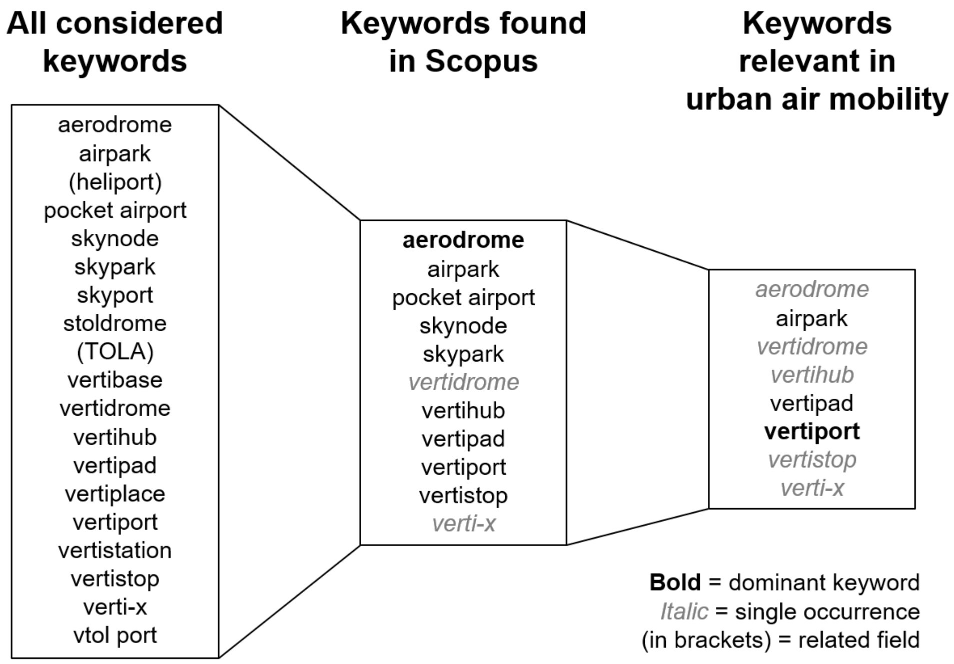


Figure 3. Selection process of keywords used to describe "ground infrastructure" in the context of "urban air mobility".

An analysis of the full UAM database (set A displayed in Figure 2) shows, that only two papers have been published before 2016, wherefore the assumption to start our analysis with the publication of *UBER*'s whitepaper [27] in 2016 is justified. We are aware that searching for the keyword "urban air mobility" may neglect former UAM-like contributions covering intra-city air travel. The focus of this manuscript, however, is to specifically cover the recent trend of UAM addressing novel eVTOL aircraft and airspace designs as well as the concept of on-demand and multi-modal mobility.

An exponential growth in UAM related publications can be seen after the year 2018. Analyzing the vertiport database (set H displayed in Figure 2) also shows a rising trend in publications. Both trends are visualized in Figure 4. Using a data analytics approach the most frequent authors are listed in the Appendix A. Similarly, the conference proceedings and journals which published most often about the topic of vertiports are identified (see Figure A1a and Figure A1b, respectively). Finally, a list of the top ten papers with the highest impact according to number of citations is shown in the Appendix A in Table A1. This overview is supposed to give the reader an idea of which publications and authors impacted the research community; and where to search for articles and submit personal contributions to.

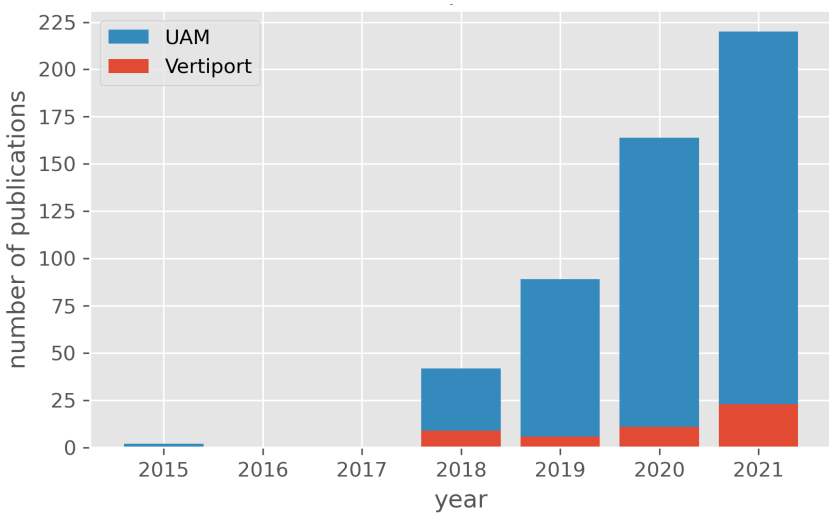


Figure 4. Trends of publication in the fields of UAM and vertiports.

1.3. Classification of Vertiport-Related Topics

Reading through the 49 scientific publications extracted from *Scopus* as explained in Section 1.2, we identified eleven topics which will be proposed as a classification of the current vertiport research. The topics and their prominence across those 49 publications are displayed in Figure 5. The sizes of the rectangles correspond to the weight of each topic. The larger the area of a topic the more attention it received so far. The weight of a topic was determined via weighted sum analysis. First, for each publication it was analyzed if the topic played no role (0 points), a minor role (1 point), or a major role (2 points). This was applied for all topics giving each publication a sum of points. Second, the amount of points for the topic was divided by the sum of all points of that particular publication to create a normalized point-score (so that the sum of point-scores for each publication is 1). Third, the normalized point-scores of the topic were added up across all publications.

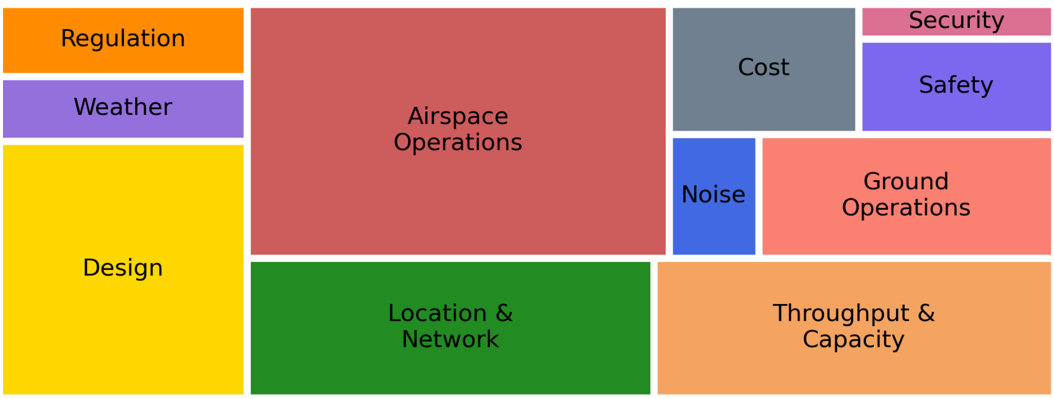


Figure 5. Classification of vertiport-related topics and their weight in the reviewed scientific literature (49 publications); size of rectangle corresponds to prominence of the topic.

1.4. Summary

Reviewing different publications addressing the description of UAM ground infrastructure resulted into a collection of various approaches, classifications and terminologies used for UAM ground infrastructure (cf. Section 1.1). UAM ground infrastructure is often classified based on the operating vehicle's performance (VTOL, STOL, civil helicopter), propulsion characteristics (electric, hybrid, hydrogen, LNG), operational features (charging, refueling, MRO), entertainment services (passenger, residents) and training capabilities. Additionally, the overall footprint (large, middle, small), the way of implementation (newly built, retro-fitted) and the location where UAM ground infrastructure is going to be placed (city-center, urban, sub-urban, periphery, connected to other modes of transport) play an important role when establishing UAM ground infrastructure and its specific services. Based on the individual perspective, 19 different terms have been identified. Searching in the database *Scopus* for "ground infrastructure" in connection to "urban air mobility" and trough database overlap analysis, we found 49 publications building the basis for this manuscript (cf. Section 1.2). Using a document term matrix, we were able to show that "vertiport" is the most commonly used term occurring in over 80% of the sighted publications. Additionally, we found a rising trend of vertiport publications starting in the year 2018; this affirms our assumption to only include recent years in our analysis. Lastly in Section 1.3, we identified eleven research areas in the vertiport domain presently addressed with varying significance. This includes airspace operation, design, location and network, throughput and capacity, ground operations, cost, safety, regulation, weather as well as noise and security.

2. Heliport and Vertiport Design Guidelines

> *"Heliports provide the most analogous present-day model for VTOL vertiports. However, despite the similarities between the two types of aircraft, there are design differences between traditional helicopters and VTOL aircraft. VTOL aircraft come in varied configurations and propulsion systems, with and without wings, and with varied landing configurations."* [18]

Merging aerial transportation with our daily lives would often require vertiports to be located in densely populated areas and inside city boundaries which is currently more a vision than a reality. If future vertiports are going to play an eligible part of a multi-modal transportation network already following certain standards, they have to be additionally aligned with aviation safety standards in order to operate in the first place. *Skyports*, a globally acting developer of UAM ground infrastructure, demands that "national and international aviation rules and industry standards must be changed rapidly to enable the introduction of new VTOL aircraft and associated ground infrastructure" [36]. Driven by these demands, national aviation agencies who are responsible for providing and regulating safe flight conditions are now working on adjusting current design guidelines and regulations, and where necessary, to develop and implement new ones. Since the UAM community is still lacking a comprehensive understanding of how VTOL operations are changing ground infrastructure design specifications and requirements, it is frequently referred to already existent heliport and rotorcraft terminologies, approaches and procedures. Figure 6 depicts the terminology typically used in the context of UAM and vertiports.

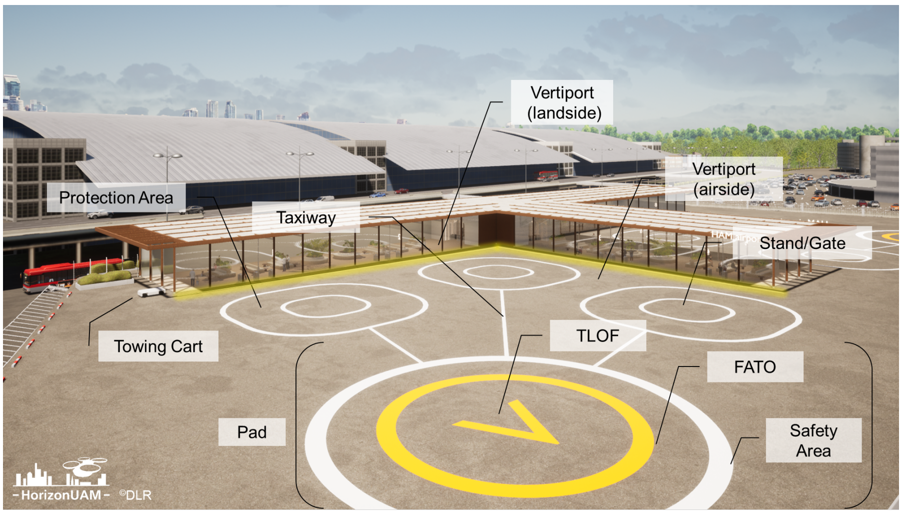


Figure 6. Vertiport topology terms used in the context of UAM.

Depending on different time horizons, maturity levels and traffic densities, vertiports can differ in elements, capability, size and throughput. One key element is the TLOF of specific size, pavement, marking, load-bearing and drainage, etc. in order to withstand dynamic forces during touchdown. At the TLOF, the VTOL aircraft initiates take-off and conducts final touchdown. The FATO is a defined area of specific size over which the VTOL aircraft is completing its final phase of approach or initial phase of departure. A dedicated safety area surrounds the FATO to specific extent and provides an extended obstacle free area. Additional stands of specific size and protection area can be used for parking and passenger handling. They are connected by a taxi route in order to provide a safe transition from one element to another. Taxi routes must follow pre-defined requirements and have to provide protection areas to ensure a safe operation. Various operational modes of taxiways can be considered, such as moving the vehicle through air or on the ground resulting into different size and safety margins (see Section 4.2.2).

In the following two sections, a summary of historic and current regulatory design guidelines will be provided with the focus on European and American contributions.

2.1. Europe

Ongoing vertiport research and regulatory work is driven by EASA's drone and VTOL operation initiative.

In 2020, a first issue of a proposed means of compliance *MOC SC-VTOL* was published focusing primarily on basic VTOL aircraft design topics such as minimum handling qualities and CFP [37]. A thorough definition of a vertiport's role and minimum requirements was missing. EASA's second publication of proposed *MOC-2 SC-VTOL* [38] started to address the airside operation of a vertiport such as approach and departure paths, operating volumes, FATO dimension and climb gradients, for which a final publication is expected in 2022.

Based on those developments, a Prototype Technical Specification for the design of VFR vertiports accommodating manned eVTOL aircraft, *PTS-VTP-DSN*, was published in March 2022 and is leading the way for a first European regulatory framework [22].

2.1.1. Operation Classes

In Europe, UAS operations are grouped in different operation classes based on the performance involved and the operational risk addressed. Its categories are *open*, *specific* and *certified*. Operations in the open and specific category address (leisure) operations with low and medium level of risks for which we already have a European regulatory framework for (Open: [39], Specific: [40]). Lastly, the certified category caters for the highest level of risk, therefore asking for the highest safety standards compared to other operation classes. According to [41], certified operations need to meet aircraft standards for manned aviation requiring a type certificate and a certificate of airworthiness. The dependency between type certificate, risk-levels and operational requirements including the use of designated UAM ground infrastructure was developed in the first issue of *SC-VTOL-01* in 2019 [21]. "VTOL aircraft that are certified in the Category Enhanced would have to meet requirements for continued safe flight and landing, and be able to continue to the original intended destination or a suitable alternate vertiport after a failure. Whereas for Category Basic only controlled emergency landing requirements would have to be met, in a similar manner to a controlled glide or auto-rotation" [21]. In order to better understand the European approach of classiyfing UAS operations, a structured overview of its setup is depicted in Figure 7. European regulation for certified UAS operations is currently under development under the rule making task *RMT.0230(C)* which initially defines three types of operation [42]. Operation type #1, IFR cargo UAS operations in class A-C airspace. Operation type #2, UAS operation in congested environment in *U-space* airspace including unmanned passenger and cargo transport. Completed by operation type #3 following characteristics of type #2 but with pilot on-board and considering also operations outside of *U-space* airspace. For further description of the topic *U-space*, please visit Section 2.1.5.

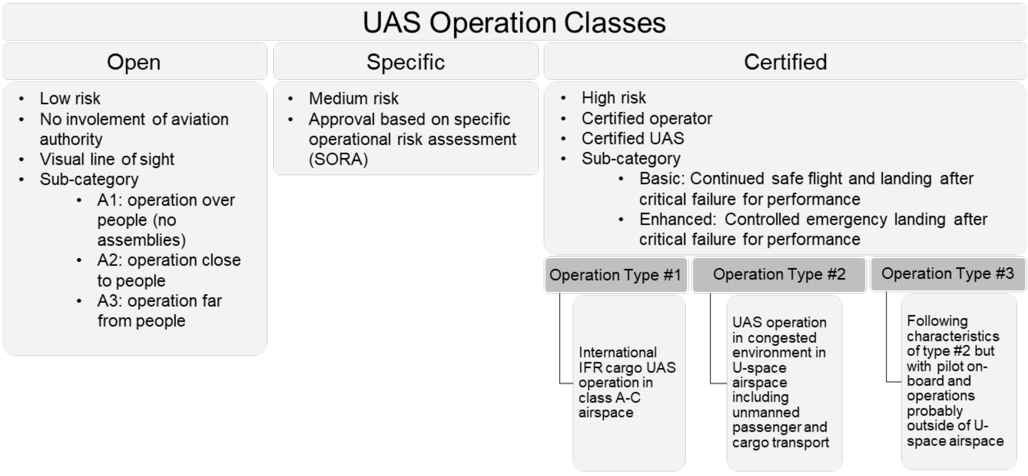


Figure 7. European UAS operation classes, subcategories and types based on [41,43,44].

Later on, when operating volumes and contingency procedures at vertiports are being defined, the corresponding operation class and operation type will determine performance and therefore vertiport footprint requirements.

2.1.2. D-Value

Following former heliport design guidelines such as [12], the D-value has been used to dimension a heliport's airside topology, safety margins and operating constraints. The D-value defines "the largest overall dimension of the helicopter when rotor(s) are turning measured from the most forward position of the main rotor tip path plane to the most rearward position of the tail rotor tip path plane or helicopter structure" [12]. Comparing novel VTOL aircraft designs (cf. [45]), ref. [46] found that the smallest enclosing circle being equally to the D-value for rotorcraft can be off by 15%. A thorough mathematical derivation is provided in Appendix 1 of [22]. In order to secure sufficient obstacle clearance, EASA re-defined the D-value for VTOL aircraft by changing it into "the diameter of the smallest circle enclosing the VTOL aircraft projection on a horizontal plane, while the aircraft is in the take-off or landing configuration, with rotor(s) turning if applicable. [. . .] If the VTOL aircraft changes dimension during taxi or parking (e.g., folding wings), a corresponding D_{taxi} and $D_{parking}$ should also be provided" [38].

2.1.3. Vertiport Design Guidelines

Taking into account the new D-value definition specifically fitting VTOL aircraft designs, key elements of a vertiport (airside ground) can be dimensioned in order to establish an operating environment. Please re-visit Figure 6 to refresh specific heliport/vertiport design elements and terminologies used.

According to [22], a vertiport has to offer at least one FATO, in order to provide a designated area free of obstacles and with sufficient surface and load-bearing qualities. The dimension of a FATO is driven by the vehicle with the largest D-value intending to operate on the designated ground infrastructure. Furthermore, at least one TLOF needs to be provided at a vertiport. It can be located within a FATO or co-located with a stand. An additional safety area (solid/non-solid) exceeding the FATO and a protection side slope should protect the operation from penetrating obstacles. The vertiport might also offer taxiways and stands for additional operation. Both can be designed to meet either ground or hover movement capabilities of the VTOL aircraft resulting in higher footprints for the latter. Stands can be used simultaneously, sequentially, by turning in a hover or by taxiing-through without a need to turn. Depending on the intended operation, different requirements need to be met. Furthermore, EASA's *PTS-VTP-DSN* proposes a lightning vertiport identification marking of a letter "V" inside a blue circle, a D-value marking to clearly state those aircraft designs being able to be accommodated at the vertiport, a FATO identification number, as well as a marker for the maximum allowable mass. Additional proposals for approach lighting systems and flight path alignment guidance markings and lights were elaborated, defining the location, characteristics, and configurations of each system. It is expected, as a second step, that a full regulatory framework will be developed in the context of the rule making task *RMT.0230* "Introduction of a regulatory framework for the operation of unmanned aircraft systems and for urban air mobility in the European Union aviation system" [42] in the near-term.

For further details, the reader is pointed to EASA's certification specification for VFR heliports *CS-HPT-DSN* [12] and VFR vertiports *PTS-VTP-DSN* [22].

2.1.4. Proposed Reference Volume for VTOL Procedures

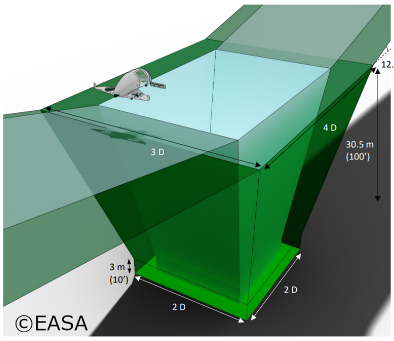
After examining the design requirements for a vertiport's airside ground topology, the airspace directly attached to the vertiport accommodating among others approach and departure paths (airside air) needs to be structured. Reviewing different regulatory proposals and guidelines, in the second publication of the proposed *MOC-2 SC-VTOL* [38], VTOL take-off and landing procedures are building on existing regulations for helicopters of category A. "Category A with respect to helicopters' means a multi-engined helicopter designed with engine and system isolation features specified in the applicable airworthiness codes and capable of operations using take-off and landing data scheduled under a critical engine failure concept that assures adequate designated surface area and adequate performance capability for continued safe flight or safe rejected take-off in the event of engine failure" [47]. Novel VTOL aircraft designs are expected to offer advanced vertical take-off and landing capabilities in order to meet the needs of emerging VTOL operations in urban environment. Therefore, a novel take-off path was elaborated addressing explicitly vertical take-off. It consists of a significant vertical climb segment until the take-off decision point is reached. Additionally, at least two take-off/climb and approach surfaces with a separation of at least 135° (ideally 180°) should be provided. Furthermore, obstacle clearance in terms of protection surfaces apply with respect to the virtual elevated vertiport which describes the top of the vertical climbing segment until positive rate of climb is achieved and the VTOL aircraft is starting the acceleration into forward flight. VTOL aircraft can either follow conventional landing or a newly developed vertical landing procedure while complying with the requirements of obstacle separation. For this purpose, vehicle performance as well as navigation and communication performance requirements need to be elaborated in order to define the maximum allowed deviation from the nominal landing path. The required landing distance provides a safe environment if a CFP event is recognized at the landing decision point (LDP). For additional details please refer to Figures 1 and 2 of [38].

Due to the variety of VTOL designs, a first "Reference Volume Type 1" was proposed by *MOC-2 SC-VTOL* providing standardized parameter values for vertical take-off and landing procedures [38]. This proposed reference volume for VTOL procedures led into EASA's so called obstacle free volume (OFV) proposed in [22]. It describes a protection volume above take-off/landing pads in order to create a safe environment for UAM operations especially in congested and obstacle-rich environment (see left visualization in Table 4). In order to qualify as a OFV, certain criteria and dimensions must be met. Considering different accumulations of approach and departure surfaces to fit different obstacle characteristics can lead into bi-directional or omni-directional OFVs. A standardized reference volume Type 1 was developed and is displayed in Table 4. Manufacturer of VTOL aircraft may voluntarily comply with the reference volume type 1, and if required, additional reference volumes can be defined. It needs to be highlighted that the reference volume type 1 displayed in *PTS-VPT-DSN* [22] was enlarged compared to what was proposed initially in *MOC-2 SC-VTOL* [38].

Next to the design dimensions of a VTOL-specific operating volume, VTOL aircraft manufacturer and certification authorities need to agree jointly on an operating procedure and minimum performance requirements. This also includes strategies and measures if non-nominal situations occur during different flight phases.

During the flight, ref. [22] introduced the concept of alternate vertiports assigned to the flight prior take-off in cases of a critical failure. Whereas, if an individual take-off procedure needs to be aborted, the vertiport needs to provide a suitable FATO extension (rejected take-off distance) for the VTOL aircraft to complete a rejected take-off under a CFP at the take-off decision point. This results into bigger vertiport footprints in order to accommodate those contingency procedures. Similar to the aborted take-off procedure, a vertiport needs to offer a safe operating volume when balked landing is conducted due to CFP and a go-around procedure needs to be in place guiding the VTOL aircraft from LDP back to LDP in order to start a second approach.

Table 4. VTOL reference volume type 1 according to *PTS-VPT-DSN* [22]; visualization (left) extracted from [22], ©EASA.



Parameter	Short Description	Reference Volume Type 1
D	D-Value	VTOL aircraft specific
h_1	Low hover height	3 m
h_2	High hover height	30.5 m
TO_{width}	Width at h_2	3 D
TO_{front}	Front distance at h_2	2 D
TO_{back}	Back distance at h_2	2 D
$FATO_{width}$	Width of the FATO	2 D
$FATO_{front}$	Front distance of the FATO	1 D
$FATO_{back}$	Back distance of the FATO	1 D
α_{app}	Slope of approach surface	12.5%
α_{dep}	Slope of departure surface	12.5%

2.1.5. Airspace Structure and Traffic Management

Latest European UAM development show, that urban passenger-carrying operations are considered to operate first under current ATM procedures and most probably under visual flight rules, but are targeting an operation inside the European UTM system *U-space* in the mid- and long-term. *U-space* was elaborated initially in form of a ConOps (see [48,49]) providing a first set of operational practices and rules, predominantly addressing drones and small UAS. Those insights contributed to the recent regulation describing the *U-space* framework, its foundational structure and mandatory services [50]. Furthermore, a corresponding draft of acceptable means of compliance and guidance material was developed in accordance with the *U-space* framework [51]. However, the peculiarities of passenger-carrying operations were not considered during the initial *U-space* ConOps, consequently a vertiport's role, responsibility and participation in *U-space* is not defined yet on a ConOps or regulatory basis. In addition, *U-space* is currently limited to very low-level airspace up to 500 ft (150 m) AGL which might be re-evaluated considering passenger-carrying UAM traffic. As UAM is considered to grow over time, the *U-space* system is assumed to mature in levels of connectivity and automation as well (*U-space* services U1 to U4). Starting from foundational services like e-identification and traffic information, it targets a full set of strategic and tactical operating *U-space* services in order to accommodate the complexity and dynamic behaviour of UAM including passenger-carrying VTOL operation. The basis of the *U-space* framework and its corresponding ConOps asks for a detailed analysis of stakeholders, roles, required services and a thorough ground and air risk evaluation. In 2021, the European standardization organisation *EUROCAE* published the second volume of an eVTOL ConOps *ED-293* [24], in which the vertiport was highlighted as an essential stakeholder and operational procedures such as ground handling processes were proposed. Further details including the distinct definition of roles and responsibilities within a vertiport's organisation are currently finalized in ED-299 [23] and are expected to be published this year.

For vertiport operations, a thorough traffic management analysis is still pending. What information is required by the *U-space* community during the course of different flight phases? How is a vertiport integrated into urban airspace? Who is responsible for the air traffic management at a vertiport and how do multiple *U-space* service provider interact in the vicinity of a vertiport In the next years, *U-space* will be re-evaluated and expanded in order to fit UAM demands in the mid-and long-term. The completion of several European *U-space* research projects including but not limited to CORUS-XUAM developing an extended *U-space* ConOps [52], TINDAiR investigating the safe integration of UAM as an additional airspace user [53], DACUS developing demand and capacity balancing strategies [54] and PJ34-W3 AURA developing a ATM *U-space* interface [55]) will support essentially this development.

2.2. USA

In the U.S., heliport design guidelines have an extensive history and impacted regulatory efforts worldwide. According to the World Factbook of the Central Intelligence Agency, over 80% of all heliports worldwide are located in the U.S. [56]. The current FAA heliport design guideline published in *AC 150/5390-2C* in 2012 [57] is building the basis for most ongoing vertiport research.

2.2.1. Heliport Design Guidelines

The FAA heliport design guidelines describe the dimensions of the airfield elements, approach and departure paths, safety related questions and the heliport facility as a whole. In the current version, general aviation heliports, transport heliports and hospital heliports are treated individually. As general aviation heliports are most closely related to anticipated early UAM operations, the following descriptions will focus on this application. The dimensions for TLOF, FATO and safey area of pads are defined, as well as widths of taxiways and safety zones around parking positions. The slope of approach and departure operations should be 8:1 and two FATOs need to be at least 200 ft (61 m) apart to be operated simultaneously. The safety area of the pad needs to be obstruction free, but can expand over the rim of a building for elevated heliports. In Figure 8, two key figures from FAA's vertiport engineering brief can be seen.

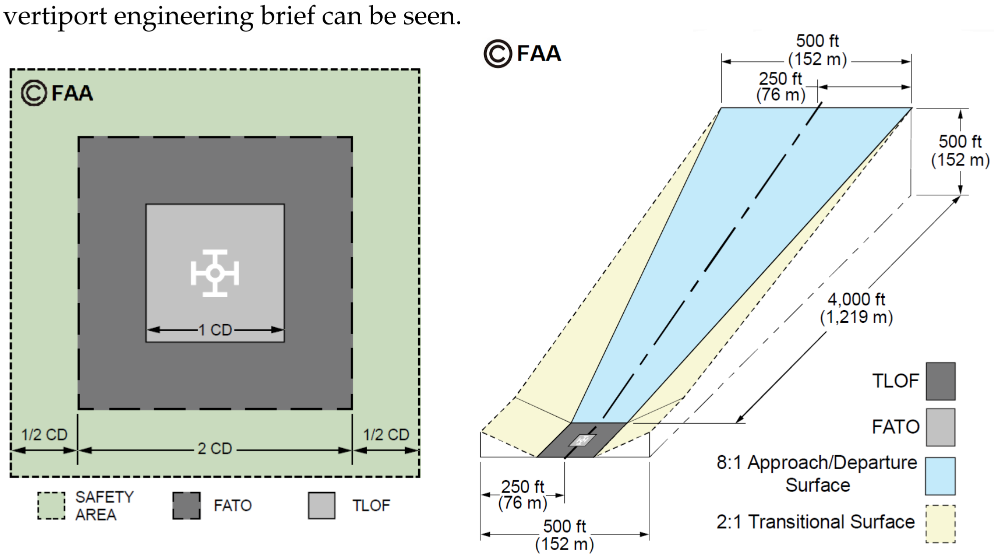


Figure 8. Dimensions of pad and approach/departure slope according to FAA engineering brief on vertiport design [18], ©FAA.

Various reports have been published containing considerations for updating heliport guidelines to fit future vertiport requirements. As there are no vertiport guidelines in effect today, heliport guidelines are the closest scenario. An update of the FAA heliport design guidelines, *AC 150/5390-2D*, is currently drafted [58]. The National Air Transportation Association published a review of UAM related literature in 2019 and finds that "there is no comprehensive canon of policy guidance or regulatory mandates governing vertiport operations" [59]. The report goes on to address regulatory gaps in passenger facilitation, ground handling, security, (ground) marking, design and planning and first response. A similar view on regulatory aspects, but with a stronger focus on building codes is taken in an article written by Zoldi [60]. Here, building codes around fire, health, safety, electricity, plumbing, air circulation and sustainability standards are listed, which are not heliport specific, but must be considered in the process of designing the facilities. A more operations-related perspective is taken by [61], who describes a safe helicopter approach path to be at a slope of 500 ft (150 m) per nautical mile for helicopter-carrying sea vessels.

In 2020 the FAA published a ConOps for UAM with an emphasis on novel airspace structures in the national airspace [19]. Vertiports are viewed as "location[s] from which UAM flights arrive and depart". New "corridors" or tubes in the air are established through which eVTOL aircraft travel. This airspace is designed to be shared by manned and unmanned transport.

Lastly, NUAIR has recently published a ConOps for high-density automated vertiport operations with the perspective of having hundreds of vehicles airborne simultaneously in a metropolitan area [20]. Similar to the FAA ConOps, vertiports are defined as nodes at the end of airspace corridors: "identifiable ground or elevated area used for the takeoff and landing of VTOL aircraft". In the NUAIR ConOps the NASA UAM maturity level 4 as defined by [62] is treated. Vertiport operations are conceptualized as (1) a wider vertiport operations area, (2) a smaller vertiport volume and (3) surface operations. A comprehensive list of vertiport stakeholders is provided. The ConOps claims that "no vertiport exists and operates today", that "heliports are the most analogous current-state model for vertiports of the future" and that early vertiports might be retro-fitted heliports [20]. Together, the FAA and NUAIR ConOps show maturing thoughts towards creating future vertiport design guidelines.

2.2.2. Historic and Future Regulatory Considerations for Vertiports

In the past, there have been attempts to formulate distinct vertiport design guidelines. While they were discontinued they still form the historic root for current vertiport design guidelines. Some things have changed dramatically, in particular aircraft technology, automation and the electrification of aviation. Selected vertiport considerations will be presented in this section.

In 1970 a vertiport study was published by [63] looking at intra-city air travel with tilt-wing configurations using conventional fuels. The study already considered similar aspects as today's efforts, among others passenger processing, air traffic management and design of vertiport airfields. One remarkable point is that noise and community acceptance had already been identified as a key constraint. In 1991, the FAA launched efforts to investigate vertiport design using larger tilt-propeller configurations for inter-city air travel [17]. The design of approach and departure slopes and other regulations resemble today's heliport regulations, except for the sizes of take-off and landing pads, which are larger due to the different vehicle sizes and configurations. Various studies followed, such as [64] designing a single-FATO, eight-gate vertiport layout to be built at the Hudson river. In order to operate the vertiport sufficient demand would be necessary and small access and egress times were identified as essential to meet this goal. In a follow-up study, 13 vertiport locations nationwide were investigated for passenger transport from the suburb to the city center [65]. It was concluded that only about half of the 14 cities have the demand structure to build a profitable vertiport. Only one vertiport was built, namely in Dallas. The FAA *AC 150/5390-3*, responsible for those efforts, was cancelled in 2010 [17].

Most recently the FAA released a pre-print of a new edition of vertiport design guidelines to be published in June 2022, which were already mentioned in Section 1.1.1. Many aspects are identical to the current FAA heliport design guidelines and the authors acknowledge that the guidelines will be subject to continuous change in the near future. Yet, one of the novelties is the explicit treatment of charging for electric vehicles and the question of vertiport placement in the proximity of airport runways. The report uses the term "controlling dimension" *CD* to describe the maximum dimension of the vehicle. The dimensions of a pad are defined as TLOF (1 *CD*), FATO (2 *CD*) and safety area (3 *CD*) depending on the maximum dimension of the vehicle, as can be seen in Figure 8 (left).

2.2.3. Air Traffic Management

Regulations for ATM are not exclusive to vertiports, but they overlap and, in particular, NASA has espoused ATM for UAS as part of their focus. First thoughts on how to integrate high numbers of UAS into the national airspace were presented by [66]. Here, it was already clear that "UAS operations today challenge the ATM system in several ways", seeing that human air traffic controller would quickly experience overwhelming workload. In 2014, NASA then coined the term UTM, which will "support safe and efficient UAS operations for the delivery of goods and services" [67]. A range of new concepts are introduced, such as dynamic geo-fencing, new flight rules and tactical de-confliction with improved CNS capabilities. In 2017, NASA published their ConOps for the UTM system [68,69], while the FAA released in parallel the ConOps for a Low Altitude Authorization and Notification Capability [70]. Another noticeable effort is the *ATM-X* project done by NASA, who started asking the question of how to integrate in particular UAM passenger services into the national airspace [71].

Finally, in the year 2018, the ConOps for UTM was published by the FAA in cooperation with the Department of Transportation under the umbrella of "NextGen" [72]; also under this umbrella the above-mentioned ConOps for UAM has been published in 2020 [19]. In the UTM ConOps the airspace class G below 400 ft (122 m) AGL is proposed for operations. Various principles are introduced, e.g., a hybrid of private/public partnership and guarantee of equal access to the airspace by all participants. Further, the UAS service suppliers or providers of services for UAM (PSU) are introduced and take on a central role in the envisioned architecture. In contrast to the initial European U-space ConOps (see Section 2.1.5), where vertiports are not specifically addressed yet, the U.S. UTM system explicitly includes vertiports in its concept.

2.3. International

Next to the U.S. and Europe, there are considerations around vertiport design worldwide, which also play a role in the current effort to draft first vertiport design guidelines. ICAO released its *Heliport Manual Doc 9261-AN/903* in the fifth edition in 2021 [73]. Yet, this document is not open to public and follows generally speaking the guidelines set by the FAA [57]. Airbus released a blueprint [74] sketching out principles for UTM and stakeholders involved in UTM. In this report, next to UTM efforts in Europe and the U.S., China [75,76] and Japan [77,78] are mentioned to have started investigating UTM. It is not clear if these investigations yielded mentionable results or were further pursued beyond 2018. Further, there where efforts in Australia in 2020 to define a ConOps for UTM involving the Airservices Australia and Embraer [79]. In this report the relevance of vertiport capacities was highlighted and an example for a vertiport network in Melbourne was presented.

Lastly, a most recent report by the *Organisation for Economic Co-operation and Development* (OECD) should be mentioned on the question of integrating drones into the transport system [80]. The report considers both cargo and passenger drones. Noise and the environmental impact are identified as key challenges, which will be important aspects to be considered while drafting future vertiport design guidelines.

2.4. Summary: Selective Comparison

Different approaches to formulating vertiport design guidelines in Europe, the U.S. and internationally have been described in the previous sections. Across these approaches there are many similarities which reflect the desire to integrate UAM into existing airspace regulations and structures. At the same time there are variations. A comparative summary of various design guidelines is contrasted in Table 5. This is a selective list and only reflects a momentary snapshot since the elaboration of vertiport design guidelines is still an ongoing worldwide development.

Table 5. Selection of diverging characteristics between various design guidelines.

Description	FAA	EASA	International
UTM airspace	below 400 ft (AGL) [72]	up to 500 ft (AGL) [51]	-
Main focus of reviewed reports	UAS/UAM [19,72]	(s)UAS/(UAM) [48]	UAS/(UAM) (see Section 2.3)
First mention of vertiports in the context of UTM	2020 [19]	2019 [48]	(2018/20) [74,79]
VTOL aircraft dimensions	Control dimension CD [18] (historically tip-to-tip span TTS [57])	Enclosing circle D [22]	maximum dimension MD [73]
Pad dimensions (references same as aircraft)	TLOF $= 1CD$ FATO $= 2CD$ Safety Area $= 3CD$	FATO $= 2D$	TLOF = 2 under-carriage FATO $= 1.5 - 2MD$ Safety Area $= +6\,m$
Pad symbol	cross [18]	letter "V" [22]	-
Approach/departure slope	7.1° (8:1) [18]	12.5° [22]	-
Vertical segment as part of approach/departure path	no [18]	yes [22]	-

3. Vertiport Location and Networks

> *"Ground infrastructure and planning decisions at this stage of the project development carry significant project risk, and hence, decision makers and stakeholders need to be able to make well-considered business and operations decisions."* [81]

According to [82], the following factors make a location favorable for placing UAM ground infrastructure: less densely built-up cities with substantial amount of free and undeveloped land; access to water like lakes and rivers; no existing strong and efficient public transportation network; large commercial airport located nearby. Furthermore, a city's climate degrades initial UAM operations if reduced visibility, wind and icy conditions are faced frequently. Therefore, an initial setup is recommended in consistent weather patterns and mild climate until more operational experience is gained. In addition, the wealth of the city and its population has to be considered since early implementation of UAM and on-demand mobility services require high investments and will create high initial operating costs.

How scientific publications are addressing the question of vertiport location and how they propose to solve the optimization problem of finding the best place for a vertiport and the right size of a corresponding network, is discussed in the following chapter.

For additional orientation, the reader is pointed to Figure 9 which shows the operating areas of those vertiport networks discussed throughout the sections addressing the use-cases: commuting, airport shuttle, holistic UAM system, other covering delivery and STOL operations, and mixed.

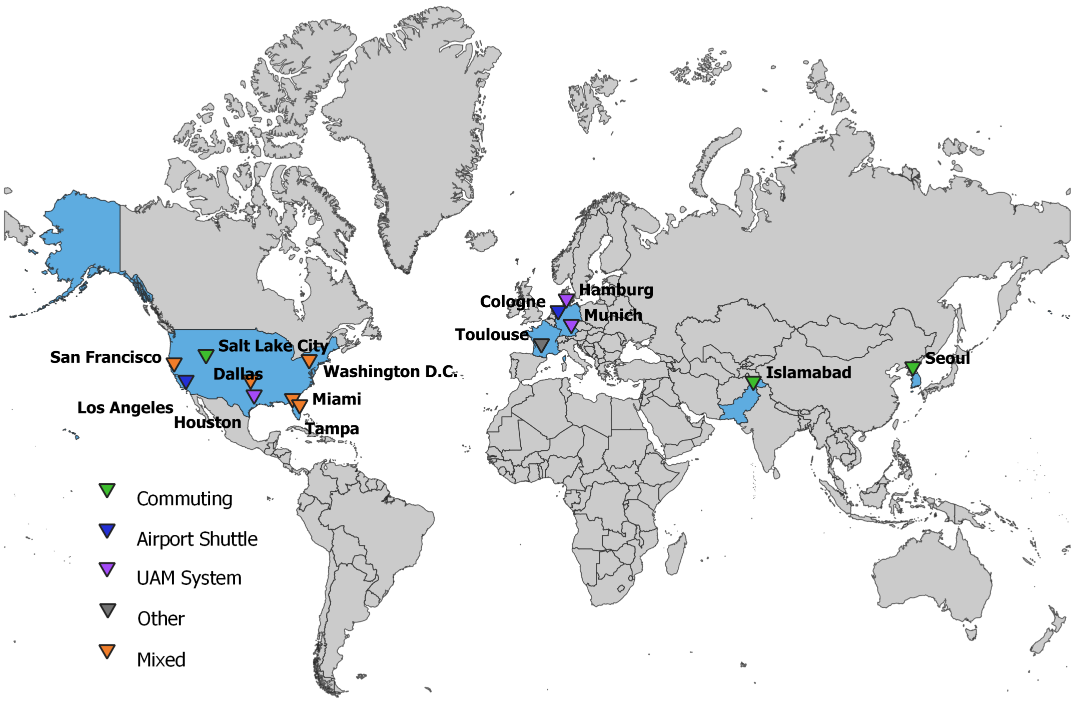


Figure 9. Vertiport network locations covered by selected scientific publications. Use-case is expressed through color-code.

3.1. Vertiport Networks Based on Commuting Trends

Air mobility operations may be differentiated between urban air mobility inside city limits, sub-urban air mobility connecting city and surrounding metropolitan areas (trip exceeds 20 miles (32 km)), and regional air mobility providing city to city transport [81]. Depending on the operation type, different repercussions on vertiport location, size, resource provision and operating concept may be expected. Historic commuting behavior can be used as a starting reference to evaluate where and to what extend air mobility may serve mobility needs. Once the need and potential demand is evaluated, a suitable location has to be defined for each vertiport of the network; on the one hand a vertiport needs to be conveniently reachable, on the other hand the amount of vertiports should be reduced to the most needed.

Developing theoretically a vertiport network may consider "uncapacitated" and "capacitated" facilities. The use of "uncapacitated" facilities makes sure that individual vertiports are not causing any operational bottlenecks during analysis and, therefore, are able to serve unlimited demand (see e.g., [81]). Instead, "capacitated" vertiports only serve limited demand (see e.g., [81,83]).

For the U.S areas *San Francisco Bay area*, and *Salt Lake City-Provo-Orem*, *Dallas-Fort Worth* and *Washington-Baltimore-Arlington*, the UAM market potential was investigated considering a multi-modal transportation network in which UAM provides single legs of a commuting trip [83,84], respectively. Further, ref. [81] analyzes a sub-urban air mobility vertiport network setup in *Miami (U.S.)* based on work-home trip data-sets. A data driven optimization framework for defining and solving the Mixed-Integer-Programming based network problem was used while targeting to minimize the vertiport network setup costs. Lastly, ref. [85] established a six-piece vertiport network in *Islamabad (Pakistan)* focusing on vertiport site selections next to frequently used commute routes and places where traffic congestion is faced.

In order to reflect different time saving requirements and to develop resulting vertiport performance constraints, ref. [83] proposes to cluster commuting travellers into long distance commuters and short distance commuters. For long distance commuters a time saving of 25%, and at least 50% for short distance commuters is required due to their different value of time in order to switch to the UAM mode. The demand and vertiport distribution problem is formulated as an uncapacitated facility location problem which uses k-means algorithm for clustering.

This k-means approach was also used by [86], who investigated a vertiport network of 10, 40 and 100 vertiports in the metropolitan area of *Seoul (Korea)*. Areas like Han River Park, highway intersections, rooftops of parking lots and existing helipads on skyscraper rooftops have been utilized for vertiports. In order to evaluate how well the data is clustered, the silhouette technique is performed. Final vertiport locations are selected by re-positioning them to the appropriate sites near the centroid of the cluster to comply with geographical conditions. This caused frequent challenges due to most of the clusters are being residential areas.

Another "clustering approach" was defined by [81] who introduces the concept of a "catchment area" (3 miles (4.8 km) radius) where vertiport locations are paired up. The resulting time saving based on different numbers of work-home blocks and vertiport pairs is analyzed for the operating area of *Miami (U.S.)*. The larger the catchment area the bigger is the number of potential vertiport locations and routing options which then requires less vertiport pairs to satisfy the demand. On the contrary, larger catchment areas impose longer egress and access legs for the customer.

Since a change of transport modes is inevitable when considering a multi-modal transportation network, increasing overall time savings always asks for optimized transfer times between subsequent modes of transport.

Transfer times of 5, 10 and 15 min and varying numbers of vertiports (1 to 30) are considered for the *San Francisco Bay area (U.S.)* by [83]. The direct haversine between the origin and destination of each trip is computed and compared to the travel time on ground based on different ground traffic congestion levels extracted from the *Mobiliti* simulation by [87] and *Google Maps'* API. Focusing on short distance commuters, even if high transfer times of 15 min and high ground congestion are assumed, 45% of the short distance commuters in the *San Francisco Bay Area (U.S.)* will benefit from switching to UAM. However, it requires a rather large network of 30 vertiports in the east and 24 in the west. This benefited commuting share drops significantly to 3% if uncongested traffic and 10 min transfer time is assumed. A smaller network of 29 vertiports in the east and seven in the west is required instead. By contrast, no benefit is created if transfer times of 15 min and uncongested traffic are assumed. Additional time-saving and efficiency analyses about choosing UAM instead of ground taxis were conducted e.g., for New York City (U.S.) and Hamburg (Germany), and parameters affecting UAM mode choice were analyzed for the city of Munich (Germany) by [88–90], respectively.

Potential vertiports in the U.S. cities *Salt Lake City-Provo-Orem*, *Dallas-Fort Worth* and *Washington-Baltimore-Arlington* were examined by [84] and resulted into potential vertiport network sizes of 38, 407 and 207 vertiports, respectively. Census data and tracts are used to approximate the vertiport location in the centroid of census block groups. Those networks generated by different heuristic methods such as elimination heuristic, maximal edge-weighted subgraph heuristic, greedy heuristic, greedy heuristic with updates are compared. 1200 different cases are explored differing in input variables such as location, network type, battery range, number of vertiports and vehicle speed. Overall, the two greedy algorithms with update steps concluded as best-performing algorithms and produced solution networks with 91% of the optimal value. When selecting optimal vertiports the interdependence of vehicle attributes, potential locations, and desired network structure was considered.

Rather uniquely in this set of vertiport-network-publications, a noise analysis around the UAM route is performed on the basis of the day-evening average sound levels for the vertiport network in *Seoul (Korea)* [86]. To measure the percentage of the population affected by noise, a curve fitting function of the Shultz curve is used. By dividing the area of Gangseo-gu into hexagonal tiles, according to [86], noise will affect roughly 400,000 people in the 41.6 km^2 area. Due to the lack of eVTOL noise data, noise maps are created by using an aviation environmental design tool and by assuming noise characteristics of a five-seat helicopter. A noise priority scenario defined as a flight along the least populated area was compared to a business scenario describing a flight following the shortest distance; the number of affected people decreased by 76.9% for the noise priority scenario.

3.2. Vertiport Network in Support of Airports

Establishing a vertiport network in the vicinity of airports and operating as first or last leg of a multi-modal trip to or from an airport may be convenient for the passenger and lucrative in terms of time-saving.

Placing a single vertiport of the network directly next to an airport requires the identification of constraints which might be locally different but since a lot of aerodromes are following (inter)national standards, they may be transferred and adjusted quickly. Based on the exemplary operating environment of *Cologne Bonn (Germany)* airport, ref. [91] developed a rating system considering passenger accessibility, obstacle clearance, noise impact on adjacent buildings, expandability, applicability and strategic availability in order to evaluate the potential of each identified vacant area adjacent to the airport. This included parking garages, parking fields and rooftops of an existing bus terminal and of a future hotel. Based on that rating system, ref. [91] prioritized the rooftop level of an adjacent parking garage which provided the best passenger accessibility and may enable an almost unhindered UAM operation. During this process, several requirements deemed crucial for successful integration including vertiport connection to existing transportation modes and the proximity to terminal buildings.

Similar but a more detailed analysis was conducted by [92] who used a 2019 LAX passenger survey as primary data set to determine the optimal vertiport location and network size based on the passengers' selected top ten origin destinations in the area of *Los Angeles (U.S.)*. Restricted airspace boundaries prohibiting overflying or restricting the placement of vertiports are taken into account. A mode choice model with varying assumptions for the in-vehicle travel time, additional shuttle time and the out-of-vehicle time was created to capture a traveler's mode-choice to and from the airport. The demand-driven vertiport placement methodology by [93] was used. As a result, a mixed logic model with different parameters such as travel time, travel cost and the value of time is created. Together with the Fuzzy C-means clustering method which places a certain number of clusters in a specific area, ref. [92] concluded with an optimally placed vertiport set of three network sizes: 50, 75 and 100 vertiports. Those vertiports located adjacent to LAX attract zero demand due to the short travel distance or airspace restriction, whereas the vertiport in LA downtown expected the highest demand.

Of contrast, for the 25 vertiport network in *Dallas Fort-Worth*, the vertiport adjacent to Dallas Fort-Worth airport shares 28% of the total UAM operation and resulted into the most demanded node [94]. Taken into account peak and off-peak demand distribution, an average vehicle load factor of 67 and by using a M/M/1 queuing model together with a target waiting time of four minutes, a 76% utilization factor for a FATO is proposed in order to be able to absorb operational deviations. A FATO count per peak, off-peak and average hours was calculated and concluded with a required number of 27.5 FATOs for the vertiport located at the airport in order to serve peak hours. Operating multiple pads will require sufficient separation on the ground (over 200 ft (61 m)) based on helicopter operations) and separate arrival and departure paths with individual obstacle-free protection surfaces.

The vertiport network in *Dallas Fort-Worth* assumed a 5% shift of long distance transportation, but still intra-city, into the air while considering early operations of UAM [94]. Ref. [92] derived a potential 3.6% market share of UAM operating mainly as an airport shuttle and providing trips from and to LAX. To achieve this, a vertiport network size of 75 vertiports is required. For comparison, ref. [95] predicted a 0.5% mode share for airport shuttle and air taxi operations in the whole U.S.

Since operating in airport environment often leads to operating in controlled airspace with multiple other airspace users, a safe separation has to be maintained throughout the entire operation. Ref. [96] investigates different route designs for VTOL aircraft operating as an airport shuttle in a non-segregated airspace inside the terminal radar approach control (TRACON) airspace of *Tampa (U.S.)*. By using a Rapidly Exploring Random Tree optimization algorithm, those trajectories with minimum design costs and sufficient distance to manned operations, obstacles and ground are being selected. A user-specified distance was set to 25 ft (7.6 m) which increased incrementally by 25 ft (7.6 m). Based on those selected routes, possible vertiport locations are determined. For the airport and TRACON airspace of Tampa (U.S.), three vertiport locations, two inside airport area and one outside, were found. The algorithm identified 100 ft (30.5 m) being the largest available distance for those two vertiports located inside which does not provide sufficient distance of terrain and manned aircraft. Therefore, "[. . .] no acceptable airspace volumes could be found that would be permanently available for VTOL trajectories under current operating conditions" [96] for the selected airport (layout) in *Tampa (U.S.)*.

Adding environmental constraints, uncertainties and passenger interaction to the operation of individual vertiports located inside a UAM vertiport network, different vertiport layout and performance capabilities might be required to serve "nominal" demand [97,98]. An airport shuttle network in the *Washington D.C. (U.S.)* area was analyzed by [98] in regard to changing performances of vehicle speed, boarding time, vertiport operations times and arrival demand. A full set of requirements including historic travel demand, location constraints, capacity of vertiports, number of vehicles and charging limitations are considered. Additionally, the vertiport network "shall emit Day Night Average Sound Level (DNL) less than or equal to 65 dB", "[. . .] shall limit vehicles arriving at vertiports from waiting more than 20 min for an available landing pad" and "[. . .] system shall provide passenger transportation with 95% flights being within 5 min of expected time" [98]. The deterministic simulation concluded with a five node vertiport network, two FATOs and two parking spaces each and 70 vehicles in total being able to serve the demand of high value travelers. Using normal distributions for vehicle speed, boarding time and vertiport operations time and a Poisson distribution depicting passenger arrivals, the required number of landing pads increased from two to three in order to achieve same orders of throughput. In contrast to [98], ref. [97] conducted a sensitivity analysis for several variables (e.g., arrival/departure service time at pad and stall) by applying a lognormal distribution in order to evaluate the impact on vertiport capacity and operational efficiency (for additional details see [99]).

3.3. Holistic UAM Network Approaches

Despite vertiport networks serving a specific purpose such as providing alternative means of transport for commuter traffic or specifically operating in airport environment as airport shuttles, several contributions focus on a holistic development of a vertiport network. The overall goal is to provide a structured and generic process on how a vertiport network can be developed based on e.g., socio-demographic, local travel/commuting and city planning characteristics. According to [100], many U.S. cities of UAM interest are following a "wheel-and-spoke" design with interstate highways radiating out from the city center and circumferential concentric beltways connecting the suburbs. Therefore, the generalized model of vertiport placement proposes a UAM traffic network aligned to existing highway traffic configurations which can be adjusted to *every American metropolitan area* by customizing the size of the hexagon. Following this approach of a generic city model consisting of a hexagonal vertiport placement pattern, a UAM system of system network was developed by [101] enabling the analysis of a UAM network of seven vertiports in *Houston (U.S.)* and five vertiports in *Dallas Fort-Worth (U.S.)*.

Based on socio-demographic characteristics and expected developments for the year 2030 (used tool: SILO for modelling a synthetic population), an existing agent-based traffic simulation model (used tool: MATSim for trip assignment, MITO for generating travel demand) is used and extended to determine UAM demand and potential modal share for the metropolitan area of *Munich (Germany)* [102]. Within this study, the vertiport was inserted as a black box being able to accept and release UAM traffic. Serving four different business cases (business, commuting, tourism, leisure), three level of vertiport archetypes are considered; a low density network (24 vertiports) covering large agglomerations, transportation hub and densely populated areas with large share of high income; a medium density network (74 vertiports) including main subway and suburban lines and employment centers; a high density network (130 vertiports) covering all relevant trips and target groups [103]. Moreover, number of vehicles, cruise speeds, processing times and ticket fairs are varied. Potential vertiport locations are determined in the course of several workshops with representatives of Munich Airport, city of Munich and Ingolstadt and the Upper Bavarian Chamber of Industry and Commerce. For the medium density network a total UAM mode share of 1% was predicted, whereas targeting for longer distances, the mode share prediction increased to 3 to 4% [102].

A collaborative simulation approach is proposed by [104], in order to analyze a UAM network inside the metropolitan area of *Hamburg (Germany)*. It follows the objective of defining low-fidelity analysis components such as demand, vertiport design, vertiport integration, routing, scheduling and setting them into relation in order to analyze interdependencies. The vertiport integration is based on published 3D building data, which is then used to select a vertiport location in the centroid of every quarter in Hamburg. This is being reconciled with the expected demand, airspace structure and resulting routes, and general restrictions like no-fly zones.

A 3D geographic information system map was derived from lidar data and used by [105] to determine the optimal vertiport location for the *Tampa Bay area (U.S.)*. Both, regulation constraints for eVTOL operations at vertiports and socio-demographic characteristics were additionally considered. The potential UAM demand is analyzed and the UAM mode share is evaluated based on allocation of user to vertiport, access- and egress-mode choices and the interaction between vertiports. Ref. [105] concludes, that UAM ride shares are small therefore congestion relief will be limited, but the passengers who choose UAM will experience substantial time savings. Inside the network design, trips fully conducted by UAM or ground transportation modes as well as multi-modal ride shares are feasible. The network optimization follows the objective to minimize generalized travel cost for all network users no matter what transport mode was chosen. It is seen, that with increasing number of vertiports the overall accessibility and UAM mode share increases. However, this is saturated choosing a vertiport network of 80 vertiports. The transfer time between ground based modes and UAM plays a decisive role, which leads into a drastic reduction in numbers of customers if the transfer time is increasing.

3.4. Other-Vertiport Networks Based on Parcel Delivery and STOL Operations

In the following section, other air mobility operations are described such as parcel delivery and passenger transport with STOL aircraft. Even if those use-cases differ from the core theme of this manuscript, resulting ground infrastructure requirements may be comparable. Ref. [106] investigated the use of eVTOL aircraft for same-day/fast parcel delivery in the *San Francisco Bay Area (U.S.)*. The placement of vertiports is optimized based on the maximum package demand served. Vertiports should be placed near to the customer subject to minimizing the number of vertiports. This objective is additionally challenged by high building costs and limited building locations. The foundation of the optimization is the estimation of same-day delivery demands which is assumed to be the highest in areas with larger population and higher income. For this use-case, the San Francisco Bay area is discretized. For each census tract a scaled income measure, a combination of population and average per capita income is defined representing the demand for eVTOL aircraft parcel delivery. The ground-travel time of a customer's origin to the pick-up location, based on *Google Maps* Directions API, was determined as crucial limiting factor impacting the amount of customers served by one vertiport. Additionally, airspace restriction are taken into account, prohibiting a vertiport placement in a census track with a centroid inside class B and C airspace. A vertiport network of one to eight vertiports with an additional ten minute last-mile driving threshold is assumed. As a near-term implementation result, a network of seven vertiports with a distribution center and six distributed vertiports was elaborated.

Another vertiport network serving a package delivery scenario was analyzed by [107] but for the area of *Toulouse (France)*. Four warehouses/vertiports and individual delivery points are considered in order to optimize traffic flow management based on the key performance areas fairness and equity. Two highly dynamic demand scenarios of 50 and 25 flights per hour per vertiport were assumed.

A variety of airpark designs for STOL operations are proposed in [82] in order to fit different locations: vacant land construction, barge construction, additive construction type and the re-use of pre-existing ground infrastructure. The size and location of ground infrastructure accommodating STOL operations depend on runway dimension, faced environment (e.g., obstacles), local atmospheric impact (e.g., on noise propagation) and weather conditions (ice, snow, wind) including magnitude and direction. An airpark fitting algorithm was used to provide a first estimate of the potential of vacant places (using a Quantum geographic information system software together with a Boolean filter) and to derive to a resulting airpark geo-density in the *Miami (U.S.)* metropolitan area.

3.5. Summary

It can be seen that competing approaches and solving algorithms are available to determine the optimal vertiport placement. During theoretical analysis, vertiports are either assumed to be constrained by capacity or not. Some are focused on specific business cases of UAM such as airport shuttle (cf. Section 3.2), commuter (cf. Section 3.1), delivery (cf. Section 3.4), STOL operations (cf. Section 3.4), others follow a generic and holistic approach (cf. Section 3.3). Network designs may also learn from use-cases outside of passenger-carrying UAM operations such as delivery and STOL operations. Vertiport locations are mainly derived from (commuting) demand heat maps, 3D geographic information, frequently used traffic routes or vacant areas based on e.g., lidar data. Most of the analyzed areas are cities or metropolitan areas located in the U.S. Other cities of interest are located in Germany, Korea, France and Pakistan. The vertiport network development starts with a determination of the overall demand clustered into areas of interest. It is then followed by a specific location analysis for each vertiport serving the selected area of interest. Therefore, the specific location and the environment in which the vertiport is implemented in is a crucial step for initially setting up a vertiport network. Throughout the sighted publications, the constraint of transfer times was determined as important factor, which contributes significantly to the decision if a future traveler is taking a UAM mode or not. Next to socio-economic and demography characteristics of a certain area like population centres, commute routes and income distribution, current airspace utilization, time savings, and considered ticket prices are important attributes influencing UAM market shares and therefore a vertiport network's shape and size. Unfortunately, no vertiport networks exist yet, however, future vertiport network plans have been announced recently: *Ferrovial Airport's* 20-piece vertiport network in Spain [108], 25-piece vertiport network in the United Kingdom [109] and its plus 10 vertiport network in Florida [110]. In addition, a four to six-piece *VoloPort* network in Singapore was announced by *Volocopter* [111].

4. Vertiport Design and Operations

> *"We have a unique opportunity in aviation history to develop technical standards from scratch which will ensure that vertiports are safe and can be adapted to a succession of new VTOL aircraft types that we expect to be developed in the future."* [22]

To conduct VTOL operations servicing UAM, not only infrastructure and procedures on the ground need to be elaborated, also procedures covering the airside operation in a strategic and tactical manner are required. Operational constraints affecting on-demand mobility may vary depending on where UAM should operate and topics such as ground infrastructure availability, scalability of air traffic control, emerging aircraft noise and community acceptance needs to be taken into account (see [112,113]).

Even though hundreds of VTOL aircraft designs are currently under development [45], only a handful flying prototypes are available and even fewer reached the process of certification. In terms of vertiports, the pool of available vertiport operators/manufacturers is even less. There are a few key players including *Skyports*, *Ferrovial* and *urban-Air Port*, contributing significantly to this development. But, the current development stage does not provide sufficient foundation to derive thorough conclusions regarding vertiport operations and designs especially under realistic environmental conditions. This will change rapidly once the first generation of VTOL aircraft and vertiports are available.

The following sections will provide a summary of vertiport design visions initially driven by architecture companies participating in *UBER* Elevate's UAM infrastructure challenge as well as by current infrastructure developers. Additionally, different approaches and concepts for vertiport airside air and airside ground operations will be discussed. This chapter will be concluded by first estimations of vertiport infrastructure costs.

4.1. Vertiport Design

After *UBER* Elevate's public UAM infrastructure challenge in 2016, many vertiport design proposals were developed and started circulating the web (e.g., [114–116]). One of the objective was to integrate all kinds of ride sharing in order to offer the customer a transfer to other individual and public transportation modes. Environmental integration as well as a neighbourhood's and customer's well-being, e.g., in terms of shopping, entertainment, relaxing areas, sound-barriers and sustainability, were also taken into account by the submitted design proposals. The vertiport was envisioned as a new public space for local residents rather than only providing UAM transportation services [117].

4.1.1. Visions

Following current vertiport design developments, proposals range from a ground-based single FATO (e.g., [118,119], left illustration of Figures 10 and 11), over one-story vertiports with multiple FATOs and stands (e.g., [117,120], middle illustration of Figure 10, and right illustration of Figure 11), to multiple/dozens of FATOs and stands distributed along multiple stories (e.g., [121,122] and right illustration of Figure 10). All serving different demand scales and operating environments.

Figure 10. Design visions ©MVRDV, Project "Airbus UAM" [118].

Figure 11. Design visions ©DLR, Project: "HorizonUAM" [123].

The "world's smallest airport" is provided by *urban-Air Port* [119] who partnered up with Hyundai Motor Group in order to provide an innovative, rapidly deployable, multi-functional and ultra-compact (fits in one container) infrastructure for manned and unmanned vehicles. The structure is cone shaped with a flat top part on which the FATO is located and which can be lowered to ground level. Additional access and egress is provided via staircases. The urban-air port provides charging, refuelling, as well as aircraft command and control suiting all kinds of UAM operations such as air taxi services, autonomous logistic services and disaster emergency management. Deployments on water (Marine One), on rooftops (Air One) and on ground (Terra One) are foreseen. The first fully operational Air One was unveiled in Conventry (UK) in April 2022 [124].

Multiple vertiport designs such as [117,120] consider the vertiport as extension of the public transportation network by re-using the roof of an already existing building or car park and turning it into an airside operating area with a passenger terminal. "Key to the designers' intent was creating a consistent, stress-free process that allows users to truly experience the joy of human flight. [...] Passengers' process of entering the building, rising to the waiting area, and boarding the aircraft is streamlined—and intentionally unlike a typical airport setup" [117]. By proposing the usage of a check-in app and biometric scanners integrated in the elevator, ref. [117] addresses the topic of safety and security. Ref. [117] vertiport design features an operating deck and a public area underneath which are connected by a terminal area in the centre. From there, the passenger follows a marked path towards the waiting VTOL aircraft. A designated sound barrier installed on the rim of the upper deck protecting the vicinity from noise and wind, caused by arriving and departing eVTOL aircraft, was incorporated into the design proposal.

If throughput needs to be increased drastically, modular and stackable vertiport concepts developed by [121,122] provide possible design options. [121]'s *The Hive 150*, a three-story high modular building including drop off, ride sharing, retail and public areas mainly on the ground level, provides two upper decks dedicated to air traffic operations. Each operating deck provides access to a terminal located in the center and offers several FATOs and the usage of aircraft parking stands connected by taxiways. On the top of the building, emergency FATOs are located offering an easy and quick access to the exit. A total of 168 take-offs and landings per hour (Deck 1: 108 landings/take-off, Deck 2: 60 landings/take-off) are envisioned. The *Hive* was developed in order to meet scalability constraints which enables different vertiport versions to accommodate different throughput levels. *UBER Hive 1000* may provide up to 1104 take-off and landings per hour while actively operating four operating decks.

Another stackable modular approach was designed by [122] consisting of 96 stands, six FATOs for landing and six FATOs for take-off, but here, all elements being connected to each other. A throughput of 1000 arrivals and departures each per hour is predicted. Instead of using lower levels for retail and entertainment purposes, they are used as vehicle parking stands. After landing, the vehicle will roll onto an elevator-pad which levels down and, similar to a car elevator, cycles through the parking position section until it finds its destination where the pad leaves the elevator and slides into the spot for disembarking and boarding. During the vehicle's turnaround time on the elevator-pad, it is charged automatically without any human in the loop. After boarding, the vehicle slides back on its designated elevator-pad into the elevator system and continues its way up to the area where it is leaving the vertiport. This way, different vertiport levels are servicing different destinations.

Next to architecture firms and infrastructure companies, eVTOL aircraft startups like *Lilium* and *Volocopter* are developing infrastructure requirements and design visions for vertiports. *Lilium*, a German eVTOL aircraft manufacturer, proposes a modular, adaptable and scalable vertiport concept tailored to their ducted electric vectored thrust aircraft design [125]. The vertiport needs to provide three key attributes: take-off and landing area, parking stands and a terminal. Ref. [125] proposes three vertiport configurations (courtyard, back-to-back, linear) based on the setup of stands at the terminal building. This setup can be scaled up to match the predicted/required throughput resulting into "micro", "small", "medium" and "standard" vertiport designs. All designs provide at least one FATO and two parking stands.

Different vertiport designs, based on size and location are also considered by *Volocopter*, another German eVTOL aircraft manufacturer naming them *VoloPort*. With the publication of the second whitepaper on the topic "Roadmap to scalable urban air mobility", ref. [28] highlights the first *VoloPort* demo case exhibited in Singapore in 2019 and introduces the development of a *VoloPort* in the area of Paris (France) for the 2024 Summer Olympic Games.

4.1.2. Sizing Approaches and Tools

Next to pure design visions, architecture firms, infrastructure companies, eVTOL aircraft startups and researchers are currently developing requirement catalogues and generic processes in order to provide a structured and automated way of designing a vertiport while still serving specific demand and implementation needs.

A very generic and systematic single vertiport design process was proposed by [33]. A six-step approach, including the systematic investigation of the topics *requirements*, *functions*, *architecture*, *validation/implementation*, *testing* and *usage/application*. Location criteria including building and infrastructure parameters, wind current, statics and building physics, space requirements, integration of charging infrastructure, noise protection, obstacles limitation surfaces, safety regulations, simultaneous VTOL operations and vertiport layout, have to be considered during the vertiport design process.

In order to support architecture groups in the trade-off between available vertiport surface area and attainable vehicle throughput, a vertiport design tool (behind paywall) was developed by [126]. The backbone of this analysis is defined by a stochastic Monte Carlo simulation calculating the vehicle throughput of three different vertiport design configurations: a multi-function single pad, a hybrid vertiport design consisting of a single landing pad and twin/trio staging areas, a solo/twin linear single function pads including a separate landing and take-off area and multiple parking spaces in single or double-row. Different design approaches result in varying noise contours depending on approach and departure flight paths and procedures. The more flight paths are available, the more distributed noise contours result into less impact to one specific residential area. For the multi-function single pad design, ref. [126] indicates an expected noise exposure at the center of the FATO of over 80 decibel (see [126]'s Figure 7). In addition, ref. [126] considers stakeholder interactions and tensions such as between community and property owners, between UAM transportation system and the user and three types of hazards eVTOL aircraft collision, charging and single pad operations. All constraints contribute to a certain vertiport operation followed by a specific design proposal. According to [126], the vertiport footprint has to increase by 420 m^2 in order to accommodate an additional vehicle per hour.

In a branch-and-bound fashion, the optimal gate to pad ratio for four topologies (single, satellite, linear, pier) is determined and the topology with the highest throughput capacity is selected by [127] based on mixed-integer programming. In this way, the optimal spatial layout of the vertiport airfield can be determined for any given area. In a follow-up work the vertiport "performance" indicator of "passenger throughput per hour and area" was defined in order to quantify the operational efficiency of any given vertiport airfield layout [128]. Through this indicator 10 prominent eVTOL aircraft (e.g., eHang, Lilium, Joby) are compared based on their operational "performance". Depending on the eVTOL aircraft design, one hourly passenger throughput needs 22–67 m^2 of airfield space, with the *CityAirbus* being the most favorable and *VoloCity* the least favorable performer [128]. In comparison, a small vertiport for 10 vehicles and a daily passenger throughput of 5400 was estimated to require an area of 4160 m^2, followed by a large vertiport for 50 vehicles and passenger throughput of 130,000 a day, resulting in over 20,000 m^2 footprint [102]. In contrast to VTOL operations, electric STOL operations might provide advantages in vehicle performance but are expected to require runway lengths between 100–300 ft (30–91 m) depending on the aircraft's technology level, desired cruise speed and battery performance [129].

Together with aviation industry-leading partners and architects, a *VoloPort* handbook was published to support vertiport design by guiding through design, constructions, material use, infrastructure adaptability and facility operations [130]. Operational needs are also discussed compliant with eVTOL designs, performance and ground handling needs like charging, maintenance and fire protection. This handbook is only available for Volocopter partners building UAM infrastructures.

4.2. Airside Ground Considerations and Operations

The vertiport airfield, or airside ground part of the vertiport, is a highly constrained element within the vertiport due to the limited inner-city space. High throughput demands are placed on this constrained space, which creates the need to optimize vertiport layouts under consideration of various boundary conditions towards maximum throughput capacity. Additionally, two processes are expected to be added to the airside ground operations, which are not or barely present on today's heliports: ground taxiing and charging of electric vehicles.

4.2.1. Airfield Layout and Capacity

The capacity of a vertiport is an important factor in the UAM system and depends on the type, number and dimensions of airfield elements (e.g., TLOFs, gates). Ref. [94] defines a vertiport as "taken to be one or more vertipads in close proximity that function as an integrated arrival/departure node within the UAM system". This statement reveals one of the major complexities, namely operating multiple take-off and landing pads simultaneously, who are in close spatial proximity. Ref. [131] did ground-breaking work in this area in 2019, suggesting three types of simultaneous pad operations: independent, dependent, partially dependent. Further airfield elements, next to pads, that are considered across the board are gates, parking stands, taxiways and the passenger terminal. Most sources derive their assumptions from the FAA heliport design guidelines [57] and some give a detailed treatment of airfield element dimensions [7,127,131,132].

Most publications determine the capacity of a vertiport analytically [91,132,133]. Ref. [131] on the other hand uses an integer-programming-based network flow approach. Ref. [127] developed an integer-programming-based branch-and-bound approach, which determines the number of pads and gates, the best suited topology and the anticipated throughput based on the shape and size of a given area. In the paper a range of generic scenarios is tabulated to determine the possible throughput on a given area or find the necessary area for a desired throughput.

Other publications use discrete-event-based [7,92] or agent-based [134] simulation approaches. In another work done by [135], the vertiport capacity is determined based on the different vertiport layouts, varying behavior of passengers and vehicles, imbalances in the vehicle fleet and magnitude and shape of the passenger demand profile with special focus on demand peaks.

The most common topologies proposed for vertiports are satellite, linear and pier topologies. Refs. [32,127,132] all give a detailed description of the different characteristics. Further topologies that are put forth are the remote apron topology [131], resembling today's commercial airports, the single topology [127], resembling today's helistops and a linear uni-directional flow topology (LIEDT [7], linear process configuration [20]) targeting for a high-throughput potential. Early contributions of [131] on the ratio between gates and pads have found the ratio to strongly depend on the turnaround time at the gates, which in turn depends on passenger boarding and vehicle charging. Ratios that are being put forth range from 2 to 8 gates per pad [104,132] and are therefore a novelty compared to today's heliports operations, which concerns itself almost exclusively with pad operations. Most publications place all elements on a two dimensional plane. Ref. [132] in turn suggests a level below the airfield, which is connected through staircases allowing the passengers to enter the airfield. Ref. [7] uses the same idea of a second level, but suggests elevators transporting the vehicle under deck for boarding and turnaround, freeing up space on the airfield.

There is a wide range of vertiport capacities being suggested from less than 10 to over 1000 operations per hour. A case study at Cologne airport determined an average of 9.6 movements per hour [91]. Another study focusing on business models in the Washington D.C. area considers 2–7 movements per half hour [98]. UAM network studies in San Francisco [97] and Los Angeles [92] found a maximum of 325 and 250 passengers, respectively, being serviced per day on the busiest vertiport. These studies showed that a vertiport network tends to have one vertiport with very high demand, a few semi-high-demand vertiports and a lot of low-demand vertiports. This was also depicted by [94] study for Dallas-Fort Worth. Ref. [84] also described this phenomenon differentiating between large vertiports and small vertistops while borrowing the hub-and-spoke concept from conventional aviation. Ref. [133] largest vertiport can handle up to 76 operations per 15 min and the use case study of [127] in northern Germany sees 60 to 780 passengers being processed per hour. The highest number found comes from [94] with 1400 passengers during the peak hour in Dallas-Fort Worth. Considering current operations, this number is in contrast to the Silverstone heliport, which becomes the "busiest heliport on earth" for a short moment each year during the Formula 1 British Grand Prix, with around 4200 helicopter operations in one day (average of around 260 helicopter operations per hour for a 16-h operational window) [136].

4.2.2. Ground Movement and Taxiing

A novel operational element on vertiports will be ground movement or taxiing of vehicles to free up landing and departure pads. The basic operation of a helicopter does not take ground movement into account to the extent we are familiar with fixed-wing commercial airliners. Following FAA's Helicopter Handbook [8], "taxiing" is conducted in three different ways: The first option is to "hover taxi", conducted above the surface and in ground effect at air speeds less than 20 knots. To reduce the ground effect, the height can vary up to 25 ft (7.6 m) AGL. The second option is to "air taxi", also above the surface but at greater heights (not above 100 ft (30.5 m) AGL) and at higher speeds (more than 20 knots). The third option is to "surface/ground taxi" describing taxiing on ground and a movement under the helicopter's own power.

When targeting high-density UAM operations, several vertiport designs consider a complex taxi-route system (e.g., [7,125,137]). It is assumed that the operating VTOL aircraft must somehow be able to taxi, which is an expected novelty compared to present helicopter operations. Different implementation approaches are already proposed including the use of e.g., conveyors [138] or autonomously towing platforms/carts [139]. Refs. [7,131,132] differentiate between vehicle taxiing under its own power (hover, ground taxiing) or being conveyed (ground taxiing). Yet, while different modes of taxiing are described, the speed is not differentiated: [132] gives an estimated 4 ft/s, ref. [131] assumes a median of 15 s taxiing time between pad and gate and [7] considers 2.6 m/s to meet the assumptions by [131]. Ref. [127] considers how taxiways and gates have different dimensions according to helicopter design guidelines depending in the mode of taxiing, which in turn affects to throughput capacity of a certain area. Ref. [7] further elaborates on the idea of towing vehicles on the ground and through elevators into levels below the airfield to safely process passenger handling and vehicle charging.

For the purpose of this review three types of taxiing will be differentiated: *hover*, *passive* and *active*. The authors are aware that these categories provide slightly different meaning in the context of helicopter operations. Yet, due to the expected novelty of vertiports operations and VTOL aircraft, new categories might be necessary. (1) "Hover taxiing" has been described above and combines all types of taxiing, where the *main engines* are in use. It might be possible to physically touch the ground while doing so, if the configuration has wheels/landing gears. In this exception, the used definition diverts from helicopter operations. In most cases though, hover taxiing is expected to be conducted without surface contact. The benefit of this way of taxiing is the low complexity and no need for external devices on the ground. The downsides are safety concerns and the energy intensity, in particular for tilt-wing or tilt-propeller configurations. (2) "Passive ground taxiing" sums up all the ways of moving an eVTOL aircraft on the ground with *all engines and motors shut down*. Conveyor belts or elevators have been mentioned before, but also towing bots and moving platforms are conceivable. This mode resembles the pushing of conventional aircrafts away from the gate onto the main taxiways, before they power up their main engines. (3) "Active ground taxiing" will be suggested as a third way, where the taxiing power comes from the vehicle, but from *motors other than the main engines*. One approach could be electric motors attached to the wheels of the eVTOL aircraft, which are powered by the on-board battery and let the vehicle taxi on the ground. Even though it is not common in conventional aviation, this approach has been investigated in the past and named alongside other modes of taxiing [140]. This novel taxiing approach might be of particular interest to vertiport operations.

A parameter value specification based on expert interviews has been conducted to determine the different taxiing speeds and related processes such as starting/stopping of engines or mounting/de-mounting devices for passive taxiing [141]. 17 Experts from the industry, research and active piloting were consulted with an average experience of over 10 years. Through statistical analysis the taxiing speeds were determined as follows: hover taxiing at 3.25 m/s, passive taxiing at 2.63 m/s and active taxiing at 2.15 m/s.

4.2.3. Turnaround at Gate: Boarding and Charging

Next to the operations on the pad, turnaround at the gate is the second most sensitive process on the vertiport airfield [141] and can encompass actions like passenger boarding and de-boarding, vehicle battery charging or swapping, pre- and post-flight checks and even minor MRO activities [126]. Ref. [131] found out that the turnaround time has a big impact on the ratio of gates to pads, which is one of the design drivers as discussed above. Several studies found the passenger processing time, which is directly linked to the vehicle turnaround time, to be one of the most relevant factors determining the market share UAM can achieve [102,105,142]. Parameter value specification for charging speed, swapping time, boarding, etc. are presented in a systematic fashion by [141].

The turnaround time assumed in scientific literature varies, but can be distinguished in short and long turnaround times. Short turnaround times take the perspective of a touch-and-go vertistop design, where only passenger boarding and de-boarding occurs at the gate as the minimal necessary operation. Turnaround times that are mentioned are 0.5–10 min [131], 2–10 min [105], 5 min [7] or 8 min [132]. Some of these studies leave the question open, whether charging/fueling might happen during this time, but full charging/fueling of vehicles is unlikely. Boarding of VTOL aircraft has not been studied in depth, but conventional aircraft boarding simulations could provide a starting point for initial assumptions [143,144]. Long turnaround times, in contrast, take the perspective of a well equipped vertiport or even vertihub design with 30 min [91] or more. Next to the charging of the vehicle, which will be discussed in the next paragraph, minor MRO activities might be conducted. Next to a few preliminary considerations [145,146] the question of eVTOL aircraft maintenance is not possible to be addressed in detail, yet, due to the missing experience of eVTOL aircraft operations.

One major question for turnaround length is the choice of primary energy source and its handling. While most current VTOL aircraft designs assume fully electric propulsion systems, a study conducted by [101] found LNG based designs to be more promising due to higher availability of LNG and lower occupancy times of vertiport infrastructure. Fully-electric designs, hybrid-electric fuel-cell based designs and direct combustion of LNG were considered. These variants are also conceivable with hydrogen instead of LNG. When choosing electric designs, the next question is direct charging of the vehicles or swapping of pre-charged battery packs. On the one hand, battery swapping might have potentials to mitigate peak loads on the electric grid and shorten turnaround times. On the other hand, charging is more easily implemented and the difficulties of defining battery pack standards in particular for mixed eVTOL aircraft fleets are unknown. Some studies considered the novel idea of battery swapping [98,147] and vehicle manufacturers such as *Volocopter* consider this approach for their vehicle design [148,149]. Further inspirations might be drawn from battery swapping in automotive applications [150,151]. Yet, during the time of writing, direct battery charging appears to be the preferred concept, possibly due to its lower complexity and wider application in related transportation modes.

4.3. Airspace Considerations and Airside Air Operations

Transitioning from vertiport airside ground considerations and operations to UAM airspace considerations and vertiport airside operations, it is important to define the structure of a UAM flight in order to decide on its operational framework. Following the classification of [79], a UAM flight is divided into six phases namely *pre-flight*, *departure*, *en route*, *approach*, *landing* and *post-flight*. A UAM flight starts with the pre-flight phase accommodating all actions related to flight planning and preparation including e.g., vehicle pre-flight checks, charging and boarding. It ends with the post-flight phase addressing all concluding actions after the particular flight is closed such as deboarding, vehicle servicing activities and log book updates.

Additional terms like *strategic* and *tactical* are used frequently between and inside different flight phases in order to address different time horizons and to refer to a certain scope of possible services available (e.g., in terms of U-space services) and actions choosable. For thorough description of both terms, please refer to [152,153]. Moreover, the term *pre-tactical* was defined to bridge the gap between strategic and tactical phases (e.g., used by [51,79]).

Providing on-demand UAM services require precise planning tasks on short time horizons under changing requirements. A quick and efficient exchange of relevant information between all involved stakeholders will be crucial. Since real UAM and vertiport operations are not existent yet, we do not have any planning approaches nor procedures in place. An impression on how it is currently conducted for commercial fixed-wing aviation is depicted in Figure 12. For commercial fixed wing operations, air traffic flow and capacity management tasks are conducted during four phases [154]. Passing each phase, uncertainties get more certain, adjustments can be made collaboratively by considering up-to-date information and the flight schedule created in the strategic phase gets more accurate. An optimized and automated conflict detection and resolution service will be of vital importance.

VTOL operations might follow a similar step-wise planning approach but addressing much shorter and highly-variable lead- and transition times.

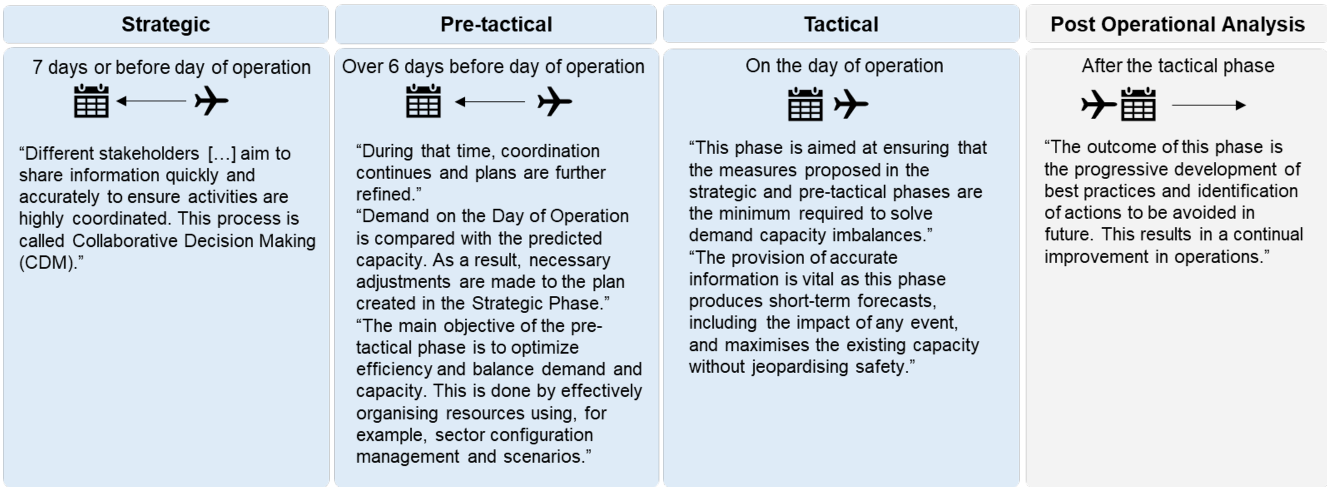


Figure 12. Air traffic flow and capacity management phases for commercial aviation according to [154]; all quotations by [154]; own depiction.

Especially during initial operations, UAM is facing very limited resources in terms of endurance capabilities and ground infrastructure availability. This will require a thorough analysis of demand and capacity balancing strategies on both strategic and tactical levels, deciding among others on the magnitude of possible UAM operations in the chosen operating environment (e.g., [88]). Furthermore, with rising UAM demand and increasing complexity of vertiport topologies (multiple FATOs, stands, taxiways, etc.), a highly automated flow and resource management will be necessary.

According to [155], flow management processes are seen as crucial operational services in order to provide future day-to-day UAM operations next to flight planning and authorization, dynamic airspace management and conformance monitoring. Vertiport capacity is declared to be initially the greatest limitation to the vertiport flow management service followed by airspace capacity when considering higher traffic densities.

A performance-based evaluation of a vertiport's airside traffic flow was conducted by [156]. For that purpose, a UAM tailored vertidrome airside level of service *VALoS* concept was developed in order to identify how well a specific vertiport setup can process a particular demand distribution based on a distinct vertiport layout, airside operational concept and emerging airside traffic flow. The multi-dimensional VALoS framework is build upon a set of stakeholder requirements, including but not limited to the VTOL aircraft operator, the vertidrome operator and the passenger. Based on those individual stakeholder constraints which are defining if an operation is acceptable or not, and a distinct definition of how a "flow" is measured, the processed airside traffic can be evaluated.

Furthermore, local airspace designs, current roles and responsibilities inside different airspace classes, as well as other airspace users need to be considered in order to establish a safe operation in- and outbound of vertiports. How current airspace classes will be modified or extended to fit UAM is not clear yet. In that regard, different airspace designs and management strategies such as density-based airspace management [157], full mix/layers/zones/four-dimensional tubes [158] (updates expected under [159]), ATM/U-space shared airspace *AUSA* [160] have been proposed and are currently under development. UAM airspace, whether it is going to be segregated or not, needs to be integrated safely and harmonized with already existing standards and airspace users. UAM airspace integration concepts and considerations for the U.S. airspace are currently developed addressing not only goals and objectives but also barriers and potential hazards [161].

Since eVTOL aircraft have significant short endurance characteristics, a detailed and highly precise scheduling and sequencing approach will be crucial. Scheduling and sequencing techniques can be conducted before departure but also during the flight. It may be assumed, the better an eVTOL aircraft flight is planned before take-off and strategic conflict detection and resolution strategies are applied, the less major tactical conflict resolution actions are required on a daily basis. Short UAM flight times of less than one hour could be favorable, nevertheless, all uncertainties can never be eliminated completely. Interaction with humans, appearing weather, CNS and technical degradation causing contingency or emergency situations are only predictable to a certain extent. Therefore, suitable strategic and tactical techniques and contingency measures like schedules and slots, buffers, aerial and ground delaying procedures, holding patterns and diversion to alternate vertiports need to be tested in order to investigate the potential of intercepting occurring deviations. Risk mitigation and maintaining the required safety standards are crucial.

Establishing a new ATM system coping with the peculiarities of on-demand, high density traffic in obstacle rich environment, CNS systems are technological key enablers. Ref. [85] identifies the need for fast and accurate communication between traffic controller and UAM vehicle, vehicle-to-vehicle, vertiport-to-vehicle and vertiport-to-vertiport. Additional needs are defined like self-position and situational awareness in the context of navigation and surveillance, vehicle tracking, position and identification updates. The overall CNS system must provide integrity, robustness, security and high geo-spatial accuracy.

Concluding, airspace and procedure design as well as information exchange are two substantial services in order to prepare the operating environment for upcoming UAM traffic [155].

In the following sub-sections, strategic and tactical measures as well as specialized approaches for operating UAM with respect to vertiports in airport environment are discussed.

4.3.1. Strategic Measures

In order to support strategic measures, several UAM mission and flight planning systems such as [162,163] and scheduling and sequencing approaches [107,133,164] have been developed .

A UAM mission planer algorithm considering capacity un-/limited origin and destination vertiports, flight trajectories, number of available vehicle, and constraints imposed by previously planned flights was developed by [162] and exercised for the Northern California region. After an available vehicle was matched to a request, a suitable take-off and landing time at the origin and destination vertiport will be determined. Subsequently, a conflict-free 4D trajectory connecting origin and destination vertiport will be calculated. The automated design and selection of the shortest strategically deconflicted 4D trajectory matching each UAM flight request is also provided by [163]'s low-altitude air traffic management system inside the developed automated flight planning system *AFPS*.

Strategic conflicts may occur, e.g., due to loss of separation or the crossing of no-fly zones. Several resolution actions may be applied such as departure delay, change of arrival/departure speed and direction, change in cruise speed and re-routing (for more resolution actions see [162]). Delay can be therefore generated on ground and in the air. Based on [162], a change in vertical speed during climb and descent appeared ineffective, whereas, using en route conflict resolution achieved 94% effectiveness. Departure delay was mainly used for resolving conflicts near the vertiport or in the first stages of take-off.

For a vertiport network in Dallas Fort-Worth (U.S.), ref. [164] concluded, when horizontal spatial separation values are reduced (0.3 nm to 0.1 nm) less conflicts and delay (−7.3%) were detected both on the ground and in the air. Instead, decreasing temporal separation (60 s to 45 s) resulted in even less conflicts and total delay (−28.4%) on the ground and in the air. Once the scheduling horizon was reduced (50 min to 8 min), total delay decreased and shifted its appearance from ground to mainly airborne delay since more conflicts have to be resolved post-departure. Considering a scheduling horizon greater than the actual flight time, most of the conflicts are resolved pre-departure generating ground delay.

Strategic conflicts may also occur due to multiple fleet operators utilizing same resources such as airspace and vertiport capacity. [163] introduces the *Unit Benefit Ratio* as a metric to measure the benefit of each operator instead of each flight due to possible market share differences. Under the aspects of system costs and operator equity, and based on formerly developed vertiport locations in Tampa Bay (U.S.) by [105], ref. [163] studied the applicability of a low-altitude traffic management system. Research on traffic flow management measures based on fairness and equity was also conducted by [107] for UAM delivery operations in *Toulouse (France)*.

The tension between multiple fleet operators may even increase if different business cases are operating simultaneously following different planning horizons such as expected for on-demand delivery, on-demand and scheduled air taxi services.

According to [107], on-demand delivery and UAM traffic may reduce efficiency and fairness of strategic UTM processes. Therefore, ref. [107] introduces three fairness metrics *reversals, overtaking, time-order deviation*. Furthermore a rolling horizon optimization framework is considered in order to include low (on-demand) and high lead time flights (scheduled) into the traffic flow. Therefore, a traffic flow management optimization problem is solved for each rolling horizon of the length of a certain time period allowing different ways of inserting or delaying demand pop-ups. The proposed approach is tested for the area of Toulouse (France) by exemplarily describing a drone package delivery scenario. If high number of pop-up demands are occurring on short horizons, inserting those pop-up demands should be preferred. Instead, if pop-ups are occurring less frequently under a short horizon, the option of inserting as well as delaying them are acceptable. It needs to be highlighted that the option of re-routing already airborne vehicles was not taken into account.

Following the most "natural" scheduling process and queuing approach, FCFS, [133] developed a theoretical model to evaluate the capacity of different vertiport configurations considering changing number of FATOs, parking spaces and occupancy times. A FCFS approach increases in inefficiency if numbers of resources increase. At least 80% throughput to capacity ratio can be captured by the FCFS model for most vertiport configurations in the 102 vertiport-network in Dallas Fort-Worth (U.S.).

4.3.2. Tactical Measures

Following the operational requirements made by EASA's *SC-VTOL-01*, VTOL aircraft certified in category enhanced and operating in European airspace, need to provide continuous safe flight and landing capabilities [21]. This means, once taken-off from the origin vertiport, a continuous flight to the destination vertiport or to an alternate vertiport must be possible after CFP. This will require additional extensive tactical contingency planning and information exchange.

Dividing flight path planning and trajectory computation into an online and offline phase, ref. [165] proposes a decision-based contingency approach calculating a tree of trajectories leading to the destination vertiport including branches leading to alternate vertiports. A Dubins path planner is used to ensure continuous transition between normal and contingency trajectories. Additional adjustments are made in order to enable diversion to other flight levels and local holding patterns for temporal de-confliction if velocity reduction is not sufficient anymore and would force the UAS into a hover state.

As soon as trajectory changes are executed during the active flight phase, separation violations and potentially occurring in-flight conflicts have to be evaluated and resolved prior. To do so, high situational awareness, precise and reliable tracking data and real-time traffic information is needed. This also means that airspace and safety conformance monitoring services need to be available ensuring safe conditions during all phases of the active flight. Since UAM operations are not yet conducted on a daily basis, the UAM and U-space/UTM community might consider emerging ideas proposed for traditional aviation such as [166–171].

Emerging in-flight separation conflicts of 40,000 simulated UAM flights in the area of Dallas Forth-Worth are being analyzed by [94]. During a three-hour time window, a departure scheduler ensured that emerging flights are not interfering with each other and causing immediate loss of separation due to their request time. A lateral separation bandwidth between 200 ft (61 m) to one nautical mile (1.85 km) and a cruise altitude ranging from 1000 ft (300 m) to 5000 ft (1500 m) was considered. The higher the separation value the higher the number and duration of conflicts. Flights with many occurring conflicts show, that many of those conflicts occur during the flight is approaching or leaving a vertiport and while interacting with flights towards and from vertiports located nearby.

Compared to [94] who focused on a departure scheduler and in-flight separation conflicts, the subsequent scientific contributions [172–177] are predominantly focusing on scheduling and sequencing the arrival stream towards a vertiport. Since in-flight changes may result into less-optimal flight paths (longer, additional maneuvers, varying wind conditions), critical delay can be accumulated. Assuming that UAM traffic is targeting a required time of arrival and is constraint by highly limited endurance capabilities, the arrival management may create a critical bottleneck [175]. For eVTOL aircraft, delay can be absorbed most energy efficiently if corrections procedures are conducted during the last leg of the cruise phase prior hovering directly above the vertiport [172]. Adding into operation various (e)VTOL aircraft designs such as tandem-tiltwing [172] and multicopter designs [173] may even increase the complexity of harmonizing the approach traffic flow.

Due to the fact, that winged aircraft have different cruise speeds than wingless eVTOL aircraft, ref. [174] proposes an airspace design in which both aircraft designs are operating but are separated into different traffic flows until they are merged at a metering fix. A sequencing and scheduling algorithm was developed in order to achieve the maximum on-demand arrival throughput of a mixed eVTOL aircraft fleet with different fleet mix ratios at a vertiport with only one FATO.

Building upon [173]'s energy-efficient trajectory optimization tool, a distinct vertiport terminal airspace structure and ConOps was developed in order to harmonize approaching UAM traffic [175]. The vertiport is assumed to be surrounded by a terminal airspace structured in concentric circles in which the innermost ring of the vertiport is controlled and designated for VTOL approach operations. The outmost ring defines the approach threshold at 3900 m (12,795 ft) distance from the vertiport at an altitude of 500 m (1640 ft) at which the arrival sequence is initiated. Each operation can adjust individually its descent angle to meet the requested time of arrival and to absorb delay (up to 3 min) if necessary without hovering or vectoring. Ref. [175]'s numerical experiment considered up to 40 arriving eVTOL aircraft per hour processed in a FCFS manner. It provides an optimal required time of arrival within a distinct planning horizon and selects arrival routes in order to minimize the total delay of all aircraft within a shared terminal airspace. This airspace concept was applied to a vertiport-hub with two FATOs located in the center of a hexagonal vertiport network [176]. A rolling-horizon scheduling algorithm was developed to support the tactical vertiport arrival management. It is highlighted that future work should be complemented by a departure scheduler and a conflict detection service in order to support planning and scheduling processes already in the strategic phase of a UAM flight and to ensure overall efficiency and safety.

Additional separation and collision avoidance services during the tactical arrival sequencing process were added by [177]. Each eVTOL aircraft is responsible for maintaining sufficient separation. Departing vehicles are assumed to operate either through distinct departure gates to separate both aircraft flows, or may operate below the altitude of the approach rings or may depart in hover mode through the center of the rings before transitioning into forward flight. Challenges are identified in the handover from the vertiport terminal area controller (responsible for flow through vertiport airspace structure) to the VTOL controller (responsible for sequencing the final approach). Proposals are made to change the first-in-first-out principle into a priority-based concept focusing on the remaining energy level and to dynamically add rings. It needs to be highlighted that the option of re-routing already airborne vehicles was not taken into account.

Ref. [178] identified "lacks" like the absence of an optimal airspace design for ATM and the neglect of a PAV capability of hovering while analyzing the approach of [175,177].

Additionally, ref. [178] highlights the concern "for safety in the surrounding urban areas due to unnecessary flights around the vertiport". Therefore [178] proposes not only dimensions of holding rings but also distinct holding points where PAV can hover in order to reduce unnecessary flights around the vertiport. Two different sequencing concepts for inward movement are developed: Sequence-Based Approach (SBA) and Branch Queuing Approach (BQA). For the SBA approach the PAV moves from the decision point into the inner circle based on the landing sequence and waits at the hover point. The SBA approach is more flexible and follows a clear landing sequence. In contrary, more conflicts are possible that require higher situational awareness and interventions by tactical de-confliction measures. For the BQA approach, only if a free holding point occurs which belongs to the starting point, the PAV is allowed to move to the inner circle which makes the landing sequence become inoperative. This will cause less conflicts and therefore less tactical de-confliction actions may be required. It creates a safer operating environment but neglects the landing sequence and therefore describes a more rigid and less flexible approach. For specific ring configuration and dimensions please refer to [178].

Furthermore, a third sequencing approach was analyzed by [179] by adding moving circles to the SBA approach (SBAM). After analyzing and comparing on-time performance and loss of separation, resulted into a non-favorable approach compared to SBAM and BQA of [178].

Following the prominent idea of a concentric airspace management structure, ref. [180] elaborated an adaptive control system to set up a multi-ring route ConOps including transition junctions inside the so called UAM multi-vertiport system terminal area and developed a corresponding scheduling model. The multi-ring concept includes approach, departure, emergency rings, junction points, approach and departure routes and waiting areas distributed at different heights and radius around a set of vertiports. Transition junctions are classified in different categories causing different levels of complexity and sets of transit conjunction control rules.

Expanding the focus from a departure and arrival scheduler at one vertiport towards a traffic management inside and between vertiport networks, ref. [181] proposes a decentralized, hierarchical approach to define ATM for UAM which allows the ATM concept to be scalable based on traffic densities and which can be used in a tactical and on-demand manner. Vertihubs, a conglomerate of individual vertiports and their corresponding local airspace "sector", are bundled into one control authority in which one vertihub is responsible for all operating vehicles in that local airspace as well as vehicle flows in and out of its sector. Thus, each vertiport is responsible itself for all vehicles taking-off and landing at their vertiport. Therefore, a UAM network can consist of multiple vertihub airspaces with differing capacity and changing responsibility which may result into several handovers between different vertihub controllers for specific UAM trips. A first application of the UAM ATM concept was conducted on the basis of large-volume UAM air traffic data addressing 1000 vertiports in the San Francisco area.

4.3.3. Measures in Airport Environment

Throughout the world, UAM is either envisioned to operate in a non-segregated airspace together with existing traffic (*U-space* in Europe) or is held separate by mandating UAM to operate within a corridor next to existing traffic (see *UTM* in the U.S.). The concepts of segregated and non-segregated may change over time when different maturity levels of UAM are approached. Specifically, the integration of UAM flights into controlled airspace and the consideration of vertiports located adjacent to airports may create additional challenges.

In this regard, ref. [182] "considers ATC as a critical barrier for the scaling of UAM operations (as opposed to terminal capacity or surface operations) [. . .]". Looking back in history, in 1960 both airports in Chicago (Midway International and O'Hare International) already processed an average of 135 helicopter flights per day [183].

In 1999, on one single day during the Formula 1 British Grand Prix, the temporary adjacent heliport recorded 4200 VFR aircraft movements [136]. It required the service of 24 air traffic controllers and the utilization of six ATC frequencies! In comparison, for general aviation airports, ref. [182] assumes that a single controller may be capable of managing 100 VFR helicopter operations per hour.

Official VFR routes and ATC protocols are used in order to manage theoretically UAM traffic to and from a vertiport adjacent to Koeln Bonn Airport (Germany) [91]. While the eVTOL aircraft is following the VFR route towards the destination vertiport, ATC needs to provide clearance to the aircraft to confirm final approach at a pre-defined way point. A similar clearance approach was proposed by [85] six-piece vertiport network in *Islamabad (Pakistan)*. For the vertiport adjacent to Koeln Bonn Airport, the UAM traffic should be able to operate in any cardinal direction which means, that no specific direction for approach and departure routes is defined prior. If the VFR approach is followed, the ATC would be able to create flexible flight routes, also distributed at a wider area where noise is able to expand within the controlled airspace. The separation between UAM to UAM and UAM to fixed-wing operations would be feasible, other than using special corridors designated only for UAM traffic. VFR routes and the corresponding compulsory reporting points forces the vehicle to comply with the safety minimum altitudes. Every UAM flight will be coordinated, managed and surveilled by an ATCO who is, in this case, now in charge of both the UAM and the conventional air traffic. This may increase fast in workload deteriorating a vertiport's airside to the predominant bottleneck.

What attributes are mainly contributing to the integration and scalability of UAM operations was investigated for the U.S. by [182]. The analysis addressed how existing arrival (SCIA, MAPt, PinS) and departure procedures can be used or adjusted to accommodate UAM traffic under either VFR or IFR. Next to separation minima and controller workload, ref. [182] also takes into account CNS capabilities (automatic dependent surveillance-broadcast (ADS-B), radio frequencies, traffic alert and collision avoidance system (TCAS) and performance based navigation) that may affect the density limit of concurrent operating UAM vehicles at airports. Five integration approaches are defined in which the UAM traffic is either mixed with conventional flights on a shared runway, closely or widely spaced from each other, operating independently or intersecting with conventional flights. After applying those operating schemes to Boston, San Francisco and Atlanta airport architectures, one departure (diverging departures) and four arrival procedures (converging arrivals, widely spaced VFR arrivals using an air taxiway, and widely spaced IFR arrivals following a PinS procedure) are concluded to be most suitable. From an ATC point of view, vertiports accommodating VFR or IFR UAM flight routes diverging by at least 15° from the conventional runway are not affected by wake vortices and therefore can be operated independently. Based on [182]'s insights, ref. [184] investigated different UAM implementation approaches at Hamburg Airport (Germany) and rated the achieved air taxi throughput while respecting the acceptable workload of an ATCO. A human in the loop study was conducted for the Dallas Fort-Worth Airport in order to elaborate the workload induced by integrating UAM flights in addition to existing commercial traffic [185].

Following standard procedures such as [182], ref. [20] adopts the point-in-space (PinS) approach, an existing standard for helicopter operation, to manage the inbound traffic inside the vertiport area. Here, "the PinS approach was taken as reference because it is used for existing helicopter operations, can be charted, and is rigid while allowing for some flexibility in arrival or departure procedure definition" [20]. The vertiport area is a dedicated airspace surrounding the vertiport and is located inside the vertiport operating area surrounding a single or multiple vertiports in which UAM traffic is assigned to UTM. Following the approach of a segregated airspace for UAM traffic, after the eVTOL exits the high-density UAM routes it starts descending into the vertiport operation area airspace at the initial approach fix. Afterwards, the vehicle proceeds its approach on a pre-defined pathway over the intermediate fix towards the final approach fix (FAF). The FAF is leading towards the decision point/PinS where it is decided if the aircraft proceeds the approach towards landing or if a missed approach will be conducted. Multiple FAF can converge towards a single PinS in order to develop a single stream towards the vertiport. Deciding to proceed with the final approach, the vehicle will enter the visual segment of the approach "where the vertiport has secured navigation and communication with the arriving aircraft" [20] which follows then a pre-defined landing procedure. Departure operations are not explicitly described.

4.4. Infrastructure Cost Estimation

Most of the building and operating costs of a vertiport are unclear as long as we do not know the demand and the VTOL aircraft's performance. Besides that, who is going to pay for it? A vertiport's cost heavily depends on what VTOL aircraft design and UAM "airline" needs to be accommodated, which VTOL aircraft fleet is being operated, what demand densities need to be served and where the vertiport is specifically located.

Considering all-electric and hybrid-electric propulsion systems, ref. [101] estimated energy operating costs as well as total cost per vertiport. Assuming a VTOL vehicle power level of 200 kW required in both propulsion systems, a vertiport network of five vertiports and 500 vehicles each, will require a total cost investment per vertiport of $72 million for operating only fully electric vehicles. This is assumed to decrease significantly to $2.25 million if purely refueling is needed. On the one hand, the amount of required chargers (160) will impose a significant burden on the city's electricity grid, but on the other hand, a fuel-based propulsion system will face non-revenue flights if refueling operations are centralized at a specific vertiport location. However, decoupling UAM transportation services from refueling operations would reduce a vertiport's footprint, creates faster turnarounds and therefore may increase potential throughput.

For a vertiport which offers only a multi-function single pad featuring the dimension of 39 by 69 m, the estimated costs are declared to be approx. $350,000 according to [126]. This increases to $750,000 and $950,000 if two or three additional parking areas are attached to the single FATO, respectively. The required footprint results into 72 by 99 m. Extending a vertiport to a linear design with one landing pad, one take-off pad and two disembarking, maintenance and embarking pads each, results into an expected vertiport cost of $1,600,000 and a footprint of 69 by 168. For the smallest configuration of *Lilium's* vertiports being ground-based with small terminal areas and a limited set of charging stands, an initial investment of €1–2 million is predicted [125]. Elevated vertiports with larger footprints and capabilities require investments between €7–15 millions depending on the resulting size and location [125].

4.5. Summary

Though many design proposals have been made and research papers have been published, there are no vertiports existing yet except of two single FATO designs such as the 2019's demo *VoloPort* in Singapore and Coventry's first *urban-Air Port*. However, the collection of vertiport designs displayed in Section 4.1 offer a wide range of ideas and approaches how to integrate UAM into urban and sub-urban environment and how to use already existent infrastructure. Keywords like *scalability*, *acceptance* and *sustainability* were raised frequently in this context. For those considered contributions, important topics influencing the vertiport design like energy grid capabilities, VTOL aircraft storage during non-operational hours, safety and security measures, contingency operations, check-in procedures, passenger flow and guidance from gate to the vehicle and operational weather dependencies are, if at all, described very briefly and not in detail. It is also unclear yet, on what basis a vertiport will be dimensioned; is it designed to accommodate peak hours, to fit the overall daily demand, or is the vertiport configuration dynamically adjustable to serve varying demand flows as proposed by [186]. Additional discrepancy is provided by the claimed footprint required for processing one vehicle per hour (cf. [102,126,128]). Vertiport throughput capacity has been studied both analytically as well es through simulation (cf. Section 4.2). There is a wide range of analyzed throughput addressing up to 1400 movements per hour. Various vertiport topologies, positioning pads, gates, and terminals, have been proposed such as satellite, linear and pier topologies. The ratio of gates to pads can vary from 2 to 8. It appears that vertiports will have strongly differing shapes and capacities depending on their location and demand profile they have to process. A novelty of vertiports compared to conventional heliports is the expected use of ground taxiing. Three types of taxiing are defined, namely hover taxiing, passive ground taxiing and active ground taxiing. Lastly, the turnaround at gates, which is driven by passenger de-/boarding and VTOL vehicle re-fueling will be of significant influence for the overall available capacity provided by the vertiport; the latter will depend on the primary energy source, which could be fully electric, hybrid-electric or LNG-powered. Transitioning from airside ground to airside air operations, high-density UAM operation itself is a challenging endeavor in terms of traffic management. But taking into account other airspace users such as commercial and general aviation, helicopter emergency and medical services will increase complexity immensely. This is even aggravated by first implementing piloted UAM operations and, over time, transitioning to automated and autonomous operations. The importance of harmonization between strategic and tactical measures of arrival and departure traffic is highlighted throughout Section 4.3. Different approaches how to structure a vertiport network airspace as well as a vertiport's local airspace and fair access to it was discussed. CNS and ATM capabilities are not only crucial for managing UAM traffic around vertiports, but also when merging UAM traffic with already existing airspace users and conventional traffic especially in airport environment. A need for a thorough strategic planning is discovered, but tactical measures cannot be neglected. The scientific publications discussed in Section 4.3 tend towards a FCFS scheduling and sequencing approach. However, it was clearly highlighted that certain parameters such as remaining endurance and agglomerated delay may impose critical constraints which may favor a priority-based sequencing concept. The transition from piloted to automated to autonomously operating UAM may impose additional implementation challenges especially in terms of traffic management, the distribution of roles and responsibilities, the way of communication and exchanging information while ensuring the highest standards for safety and cyber-/security. In Section 4.4, the prediction of vertiport costs was addressed, which seems to be not really part of scientific papers nor discussed frequently in the public. Neither are UAM and vertiport operations existent yet, nor does Europe has a mature high-volume urban air commuting market from which historic experience may provide reliable cost estimations. Current European research as well as UAM industry does not know what the real operation and traffic densities will look like. Existing aviation infrastructure like airports and heliports may be used initially. But, retrofitting and upgrading them to meet UAM needs and future standards, and integrating UAM traffic at those already existing traffic junctions may be limited and may result into even more additional investments.

5. Weather Impact on Vertiports

> *"Moreover, the weather enterprise needs champions in the aviation industry to embrace and promote weather as an integral component in the design, certification, and operation of aerial vehicles like eVTOLs or unmanned aerial systems (UAS)" [187]*

Airborne operations performing in urban environment do not only face challenges due to a complex obstacle environment, but also due to so far unknown weather conditions arising in highly and densely built-up areas. Every operating environment in which UAM services should be offered, needs to be evaluated locally and regionally depending on the vertiport network size.

Other than for vertiports, STOL contributions are "more conscious" about weather influencing the placement and orientation of the take-off and landing strip. Based on an initial airpark placement which focused on identifying the largest vacant area [82], subsequent contributions like [188,189] use historical weather observation data together with a detailed obstacle analysis to determine the location and orientation of the runway within those areas of interest. For a single runway, its orientation needs to be defined so that the emerging crosswind vector does not exceed 10.5 kts (5.4 m/s) more than 95% of the time [188].

From a European regulatory perspective, EASA's *SC-VTOL-01* provides the requirement "[...] the applicant must demonstrate controllability in wind from zero to a wind limit appropriate for the aircraft type" [21]. In the subsequent *MOC-2 SC-VTOL*, performance data was considered under wind conditions defining "take-off until reaching VTOSS (see *MOC VTOL.2115*) and from below VREF (see *MOC VTOL.2130*) to landing (i.e., the ground referenced phase), at least 17 kts of relative steady wind should be considered" [38]. Additional high-level requirements regarding visibility during falling and blowing snow are displayed in [38]. Other than that, no further requirements are yet provided.

5.1. Meteorological Conditions in Different Operating Environment

Targeting a vertiport network operation 99% of the operating hours per year in the metropolitan area of Munich, future UAM vehicles have to withstand headwind of 20 m/s (39 kts) after the average hourly windspeed, measured at 66 weather stations in the area of interest between 2016–2018, was evaluated [102]. In order to compensate local bad weather conditions an blackouts in the charging infrastructure, a diversion reserve of 10 km (32,808 ft) is demanded.

Moving UAM operations to the U.S. and considering METAR data of 28 metropolitan areas, ref. [100] derived a headwind requirement of 10 kts (5.14 m/s) if at least 50% of the operational window should be covered. This requirement is followed due to the assumption that not all flights are fully facing headwind conditions and necessary reserves will account for uncertainties and additional deviation. Furthermore, if the eVTOL aircraft can withstand wind of 20 kts (10.3 m/s) and 35 kts (18 m/s) of gusts, the operation can be conducted in any of the 28 metropolitan areas a minimum of 95% of the time meeting wind constraints and 95% of the time in all but two cities meeting gust constraints.

The meteorological repercussion on UAM operations in various U.S. cities was further analyzed by [190], who determined the average number of weather-impacted hours for each area of interest. Considering an annual operation with a daily operational window of 7 a.m. to 6 p.m., seven years of METAR surface data (2010–2017) were examined together with supplemental data of pilot reports. In order to elaborate potentially impacted hours, a set of "impact scores" is elaborated rating the captured METAR observation from 1 (minimum impact) to 10 (significantly impactful). This includes among others temperature, rain, ceiling, visibility, wind, hazel and snow grains, but also appearances of dust storms, tornadoes and volcanic ash. An hourly average impact score of three was defined as a threshold between minimal and significant potential impact. Throughout the areas of interest, ref. [190] concluded that an average of 6.1 h per day during the winter, 7.3 h per day in the spring, 2.9 h per day in summer and 2.2 h per day in fall could be potentially affected by considerable impactful weather conditions.

All three examples show that different operating environments call for changing operating hours and vehicle requirements. [191] highlights regional and local variation of weather amongst others caused by geographic influences like latitude defining solar radiation and temperature, major water bodies being the source of moisture, mountains affecting range of altitude and air density and landcover gradients providing differential heating. Other influences are described as diurnal and seasonal cycles, weather systems (wind, clouds, precipitation) and the cityscape causing local scale wind and turbulence. Additional weather challenges need to be considered such as winds at and above ground level (turbulent eddies, extreme and rapid changes in wind speed and direction, microburst translation), ceilings and visibility (sub-grid micro climates) and temperature (heat island effect, effects on density altitudes) [192].

5.2. Meteorological Characteristics in Urban Environment

According to [193], the local climate in cities often differs from surrounding areas. The "urban heat island" effect is a feature of the urban climate which is amongst others characterized by differences in temperature of up to 10 Kelvins in large cities. Additional changes can also be seen in air humidity, radiation, wind, air quality and noise.

Prevailing weather characteristics may also change on very small scales inside city boundaries creating the phenomena of micro-weather. For this purpose, the investigation of wind channeling, turbulence from buildings and urban canyoning, and the development of smart city sensing, micro-grid networks/weather models as well as high computational resources and machine learning approaches are required [187,192]. One of the biggest challenges is that "it is recognised that the weather information for UAS operations may be different from the one provided by today's meteorological service providers [...]. UAS can fly near buildings and in areas where current aeronautical meteorological information is not always provided" [51].

According to [192], additional smart urban sensing can be achieved by optimally placed sensors. A contribution is expected in the development of urban climatology, the improvement of forecasts and the reduction of uncertainties, while targeting optimal UAM flight routes. Expected hurdles are communication bandwidth associated with high costs of expanding the network and possible congestion of current wireless networks due to the amount of data collectors required to achieve sufficient coverage. Processing and computational resources to sight and analyze collected data are needed. The "optimal placement" of weather sensors needs to be investigated thoroughly.

Equipping every VTOL aircraft with weather sensors and thereby increasing enormously the amount of real-time weather data could be a supplemental approach. This data could be then shared inside the UAM network e.g., through a U-space weather information service provider and can be used for weather analysis and forecasts. However, this also requires equipment investments and may probably lead to reduction of payload.

5.3. Weather Impact on Vertiport Elements and Procedures

Based on interviews with experienced helicopter pilots, ref. [132] concluded that eVTOL aircaft should not attempt departure nor arrival operations with a tailwind possibly causing the eVTOL aircraft to enter vortex ring state conditions and facing crosswind greater than 15 kts (7.7 m/s). In the context of UAM, "Vertiport operations are sensitive to wind conditions which may inhibit the use of one or more TLOFs for approach, departure or both" [132]. Thus, weather influences the maneuverability of the eVTOL aircraft and therefore may degrade the performance of the flight or specific flight phases.

How the performance of a vehicle is degraded during the final approach phase and what landing pad size is required to safely accommodate deviations from the nominal flight path was researched by [194]. The Drydon wind turbulence model is used to depict upcoming light, moderate and severe turbulence. Ref. [194] elaborates operational requirements for eVTOL aircraft and analyzes changes in approach angles and speeds leading towards a set of approach surfaces with minimum energy and time considerations. Landing accuracy under different weather constraints resulting into varying FATO sizes was analyzed statistically. An approach surface of a 5 degree approach angle and 40 ft/s (12.2 m/s) approach speed and "for general light turbulence conditions, 95% of the trajectories end up within a radius of 20–30 ft (6–9 m)" for a FATO [194].

Increasing automation will, most likely, increase accuracy, throughput and may lead to affordable UAM ticket prizes. In aviation, camera-based and visual recognition have been researched for decades especially to support and, at some point, to initiate and conduct fully automatic approach and landing operations.

For UAM operations, ref. [195] analyzes requirements and approaches how an enhanced vision system (EVS) can be used for landing procedures at vertiports. EVS is currently used for enhanced visual operations ensuring a safe flight under visual flight rules during night and adverse meteorological condition. According to [190], those conditions affect UAM operation in the U.S. for almost 16% of the operational time. Next to requirements of minimum converted meteorological visibility and the field of view, ref. [195] proposes to consider urban wind fields and wind gusts for EVS sensor requirements. A visual contact with the FATO has to be maintained continuously in order to operate safely but affecting possible take-off and landing directions. As a result, future UAM ground infrastructure and their FATOs need to make sure to be clearly distinguishable in the EVS imagery from surrounding buildings and infrastructure elements on the ground. Additional challenges can be imposed by the surrounding urban lightning and the limited amount and small size of the installed lightning systems at vertiports. With the implementation of fiducial markers and ad-hoc light patterns, a high pose estimation accuracy could be provided in the last 300 m of the nominal approach path.

5.4. Summary

All sighted sources addressing the impact of environmental constraints on UAM operations claim the need for real-time weather data collection and monitoring due to probably very sensitive UAM aircraft. Weather will not only constrain vertiport locations but may also affect directly operational procedures and flight directions towards and from vertiports. On a macro level, historic weather characteristics decide the selection of the operating environment and therefor which vertiport network and what VTOL aircraft performance is required. The specific vertiport design, its allocation of FATOs, approach and departure path orientation and operating concepts are influenced by the prevailing weather conditions and shape UAM on a micro level. Feasible operating hours of certain areas are derived from historic weather data which are then compared to assumed vehicle capabilities. Another approach is to examine historic weather data. Based on appearance and frequency of certain weather phenomena, VTOL aircraft requirements may be formulated in order to cover a certain proportion of the operational window. In both cases, weather considerations including wind, gusts, temperature etc. are not sufficiently addressed and researched yet in the context of UAM flights and vertiport operations. Micro-weather research and the development of fine scale urban weather models need to be pushed forward by current UAM development because *weather* will play a crucial role during the development of future UAM operational procedures and *U-space*/UTM services.

6. Conclusions

"Say goodbye to congested streets, traffic diversions, and frustrating journeys" [196]

vs.

"Ground infrastructure experts wrestle with vertiport challenges" [197]

Urban Air Mobility needs vertiports to operate! This fact is unanimously acknowledged in the scientific community and industry, but at the same time, vertiports are not well understood and the research is scattered. This is the reason why we conducted a thorough literature review following the objective to summarize systematically the current state of the art and outline key areas where future research is needed. Due to the comprehensive collection of noteworthy UAM vertiport contributions, this manuscript provides the reader a structured setup, with each chapter concluded by a brief summary, which allows for selective reading.

Initial uncertainties in naming UAM ground infrastructure seem to be overcome since *vertiport* is now being predominantly used as the term of choice. After showing that vertiport is the most popular term for UAM ground infrastructure in Section 1.2, we continue to classify the field into eleven topics and analyze their prominence (see Section 1.3). In this manuscript, the scientific literature as well as industry and regulatory contributions such as existing vertiport and heliport design guidelines were reviewed extensively; All three bodies of publication are needed to frame the state of the art of UAM VTOL vertiports.

While searching for scientific publications in the database *Scopus* until the year 2021 (including), 49 scientific publications shared the overlap of "urban air mobility" on the one hand and "ground infrastructure" on the other hand which were used as a basis for this vertiport review manuscript. After analyzing all 49 scientific publications, it became apparent that airspace operations has been the strongest focus so far, followed by the general design of vertiports and its related considerations around throughput and capacity (see Section 4). Also the interaction between a UAM network and the choice of vertiport locations finds mention in the research as elaborated in Section 3. It was found that the majority of the vertiport network research considers U.S. UAM applications. Even German VTOL aircraft manufactures consider initial full-scale UAM applications outside Europe.

Vertiports are recognized as one of the critical elements of UAM by operating on limited spatial resources. Initial bottlenecks of a UAM network will be described by a vertiport's capacity and performance in the air and on ground. This will require thorough knowledge about the vertiport layout, dynamic behavior of airside air and ground operations and inter-dependencies of arrival, departure and passenger streams: who is responsible for coordinating arriving and departing VTOL aircraft traffic? How is a mixed VTOL aircraft fleet and multiple "UAM airlines" accommodated and managed fairly at a vertiport? What traffic densities can be processed and can UAM really reduce traffic congestion on ground?

Current vertiport designs, except of some early prototypes, are currently more describing a vision than providing a realistic and implementable proposal. And, although vertiport design and operations have been the predominant research focus, only few publications take into account non-nominal constraints and contingency incidences.

Continuing the review of current regulatory framework and design guidelines in Section 2, thorough content was virtually not existent until March 2022, when both FAA and EASA independently published a first engineering brief/prototype (respectively) covering only VFR vertiports. Discrepancies also arise when vertiport sequencing and scheduling procedures are discussed. On the one hand complex holding patterns and hover points are proposed for arriving VTOL aircraft traffic, but on the other hand UAM operations are considered using eVTOL aircraft currently providing very limited endurance characteristics. Therefore, further research is necessary to identify and quantify operating uncertainties and to evaluate the role and the limitation of strategic and tactical measures. The various UAM/vertiport design approaches are highlighted by contrasting similarities and differences of U.S., European and international standards (see Section 2.4). One crucial provider of uncertainty is described by the chosen operating environment and the prevailing weather conditions. Weather will be *the* factor constraining UAM and vertiport operational hours, consequently affecting throughput, ticket price and costumer segment. High efforts will be needed to understand urban weather behavior and phenomena in order to provide a safe but also efficient UAM operation. This review wants to highlight the importance of environmental constraints such as *weather* for future UAM and vertiport operations, since current vertiport research, except for a few publications described in Section 5, do not yet specifically focus on it.

The most underrepresented topic in the body of scientific research, but also in regulatory guidelines and vertiport design proposals is *noise* as well as *security*. None of the sighted contributions provide a distinct analysis of how noise is distributed at a vertiport considering e.g., different vertiport layouts, locations, arrival and departure paths/surfaces and VTOL aircraft designs. The same applies for the topic *security* which is mentioned rarely, and if so, only when passenger security checks are addressed. But, *security* means so much more especially when aviation eventually transitions towards a multi-connected, digitized and automated operating system. Implementing vertiports in densely populated environment will require thorough analyses in terms of noise propagation, safety and cyber-/security in order to create a business case finally being accepted by society.

Vertiport approaches and contributions considering different time horizons, maturity levels and traffic densities are currently available which need to be harmonized in order to allow for a structured development of UAM and to finally transition from vision to reality. A European UAM road-map is necessary in order to understand the (regulatory) complexity of UAM, the role of a vertiport and to derive realistic assumptions on societal implications. This literature review gathered a considerable amount of publications to depict the state of the art of UAM VTOL vertiports. The majority of them are of theoretical nature. At some point in the future of research, realistic operational constraints and requirements have to be considered which are going to require a lot of more research, testing, failing and lessons learned until we really reach the implementation of on-demand UAM.

This review manuscript will aid the harmonization process as it summarizes all major ongoing efforts and highlights both similarities and differences. We further hope that fellow researchers will find our work helpful to position their own work well into the context of vertiport and UAM research.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	advisory circular
AGL	above ground level
API	application programming interface
ATC	air traffic control
ATM	air traffic management
CNS	communication, navigation and surveillance
ConOps	concept of operations
CFP	critical failure for performance
DOI	digital object identifier
EASA	European Union Aviation Safety Agency
eVTOL	electric vertical take-off and landing
EUROCAE	European Organization for Civil Aviation Equipment
FAA	U.S. Federal Aviation Administration
FATO	final approach and take-off area
FCFS	first come-first served
ICAO	International Civil Aviation Organization
IFR	instrument flight rules
LNG	liquefied natural gas
METAR	Meteorological Aerodrome Report
MRO	maintenance, repair and overhaul
NASA	National Aeronautical and Space Administration
PAV	personal aerial vehicle
PinS	point-in-space
SC	special condition
STOL	short take-off and landing

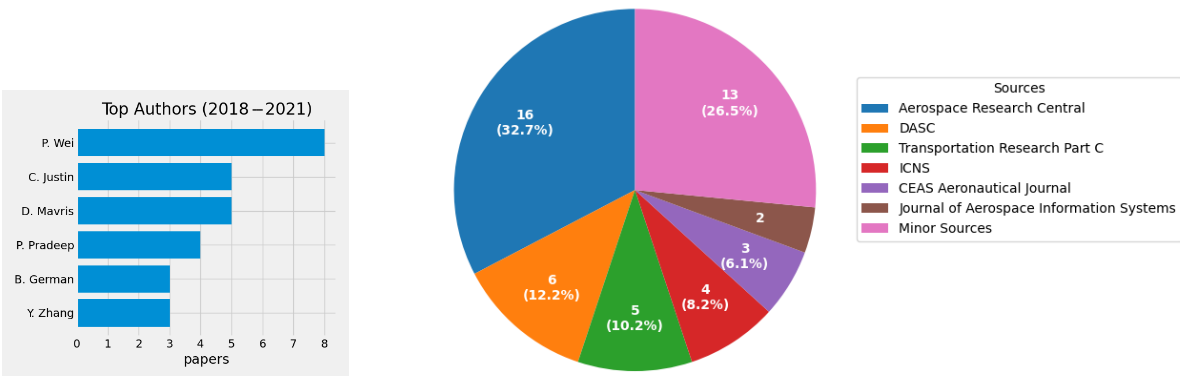
TLOF	touchdown and lift-off area
UAM	urban air mobility
UAS	unmanned aerial system
UTM	unmanned aircraft system traffic management
VFR	visual flight rules
VTOL	vertical take-off and landing

Appendix A

In Figure A1a, the top authors by number of publications in the field of vertiports are listed. Peng Wei, the number one, is an associate professor at the George Washington University in Washington, D.C. He published many papers with is co-author Priyank Pradeep. Another prominent institute is the Georgia Institute of Technology in Atlanta, Georgia: Cedric Justin, Dimitry Mavris and Brian German are associated with it. So far, it appears that the field is dominated by few strong players. In Figure A1b the top sources of publication are shown, which are both conference proceedings and journal issues. *Transportation Research Part C*, *CEAS Aeronautical* and *Aerospace Information Systems* are journals; the remaining major sources are conference proceedings. Minor sources are journals or proceedings with only one paper on vertiports. The 12 minor sources are the following with one source unknown:

- IEEE Transactions on Intelligent Transportation Systems
- International Journal of Aeronautical and Space Sciences
- MDPI Sustainability
- IEEE Metrology for Aerospace
- MDPI Applied Sciences
- Elsevier Engineering
- International Conference on Engineering Design
- Aerospace Science and Technology
- Transportation Research Record
- IEEE Transactions on Control of Network Systems
- MDPI Aerospace
- IEEE Chinese Guidance, Navigation and Control Conference

The top ten individual publications in the field of vertiports according to number of citations in *Scopus* are listed in Table A1. The reference day for the number of citations was 31 December 2021.



(**a**) Top publishing authors. (**b**) Top publishing conferences and journals.

Figure A1. Data analytics in the field of vertiports.

Table A1. Top 10 papers according to citations in *Scopus* (as of 31 December 2021) addressing vertiports in the context of UAM.

DOI	Year	Authors	Title	Citations in Scopus
10.1109/DASC.2018.8569645	2018	I. C. Kleinbekman, M. A. Mitici, P. Wei	Evtol Arrival Sequencing And Scheduling For On-Demand Urban Air Mobility	30
10.2514/6.2018-3677	2018	L. W. Kohlman, M. D. Patterson	System-Level Urban Air Mobility Transportation Modeling And Determination Of Energy-Related Constraints	27
10.2514/6.2019-0526	2019	P. D. Vascik, R. J. Hansman	Development Of Vertiport Capacity Envelopes And Analysis Of Their Sensitivity To Topological And Operational Factors	25
10.2514/6.2018-2008	2018	P. Pradeep, P. Wei	Energy Efficient Arrival With Rta Constraint For Urban Evtol Operations	20
10.2514/6.2018-2006	2018	B. J. German, M. J. Daskilewicz, T. K. Hamilton, M. M. Warren	Cargo Delivery By Passenger Evtol Aircraft: A Case Study In The San Francisco Bay Area	19
10.1007/s13272-020-00468-5	2020	K. O. Ploetner, C. Al, C. Antoniou, F. Frank, M. Fu, S. Kabel, C. Llorca, R. Moeckel, A. T. Moreno, A. Pukhova, R. Rothfeld, M. Shamiyeh, A. Straubinger, H. Wagner, Q. Zhang	Long-Term Application Potential Of Urban Air Mobility Complementing Public Transport: An Upper Bavaria Example	15
10.2514/6.2018-3054	2018	J. N. Robinson, M. D. Sokollek, C. Y. Justin, D. N. Mavris	Development Of A Methodology For Parametric Analysis Of Stol Airpark Geo-Density	12
10.1109/GNCC42960.2018.9018748	2018	P. Pradeep, P. Wei	Energy Optimal Speed Profile For Arrival Of Tandem Tilt-Wing Evtol Aircraft With Rta Constraint	12
10.2514/1.I010710	2019	P. Pradeep, P. Wei	Energy-Efficient Arrival With Rta Constraint For Multirotor Evtol In Urban Air Mobility	12
10.2514/6.2021-1189	2021	R. C. Busan, P. C. Murphy, D. B. Hatke, B. M. Simmons	Wind Tunnel Testing Techniques For A Tandem Tilt-Wing, Distributed Electric Propulsion Vtol Aircraft	9

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