Institute of Aircraft Design
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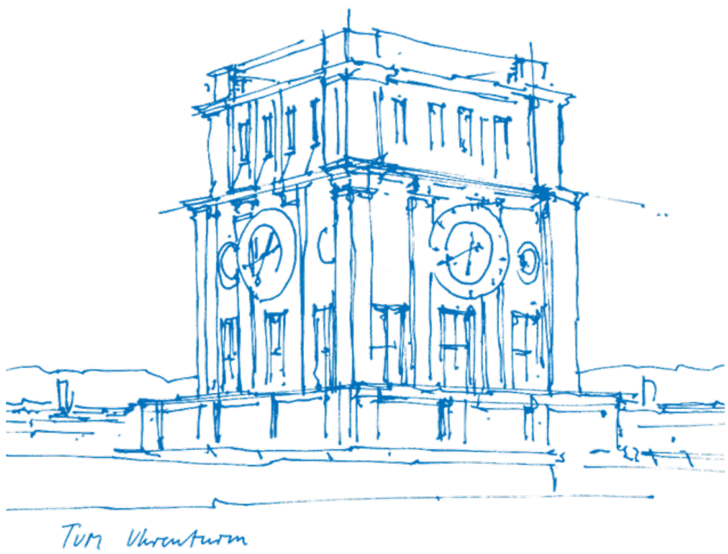
Vertiport Design and Operations –

Agent-Based Simulation of Urban Air Mobility Infrastructure

Lukas Preis



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Dedicated to Athena,
God's gift to me.

Abstract

Urban air mobility (UAM) is a new transportation concept made possible by electrification and automation. It has the potential to become an established mode of transport and enrich the existing transportation system. This could be similar to past revolutions caused by the automobile in the 1910s or the airplane in the 1950s. UAM's validity hinges on fast travel with time advantages over ground-bound modes of transport. Along the chain of travel, processing passengers and vehicles at vertiports is the strongest driver of travel time savings — more than access and egress or cruise speed. Also, vertiports have been identified as a key factor in introduction and scaling of UAM. Therefore, this thesis studies the design and operations of vertiports, a central contribution towards realizing UAM services in the coming decade. The contribution of this thesis is two-fold with the focus on the latter: vertiport layout design and vertiport airfield operations.

Vertiport design is studied through mixed-integer programming implemented in *MATLAB*. The central object of research is the relationship between available area for the vertiport airfield and the possible throughput. For this purpose, four geometric topologies are considered: single-pad, satellite, linear and pier. Various prominent vehicle designs (e.g. Joby S4, VoloCity, Lilium Jet) are studied under varying circumstances (e.g. turnaround time at the gate). The studies indicate that vertiport airfields need somewhere between $25 - 350\,m^2$ per passenger throughput per hour. Study results are tabulated in detail as well as presented in aggregated form as a rule-of-thumb to allow for first-order vertiport design without having access to the simulation.

Vertiport operations are studied through agent-based modeling and simulation implemented as object-oriented programming in *Python*. The model consists of pads, gates and stands, which are all connected by taxi-lanes and an interface to the airspace and the passenger terminal. The parameter values of the model were specified through an expert interview series and after iterative refinement the current model contains 20 parameters. With over 1,000 scenario simulations, it was possible to identify and quantify six drivers of operations: (1) peak-hour demand, (2) maximum imbalance between arrivals and departures, (3) number of pads, (4) number of gates, (5) approach and departure time and (6) boarding and de-boarding time. For example, the baseline scenario consists of 4 pads and 12 gates, has a $45\,s$ approach/departure time and a $95\,s$ boarding time. With a requirement of no more than 4 minutes average delay it can cater a maximum of 264 passenger per hour and buffer an accumulated imbalance of 33. It was shown that these six characteristics are sufficient to allow for a reasonably accurate prediction of operational efficiency (i.e. average delay). The final step in this thesis is a synthesis of operational insights into a vertiport design heuristic, which displays the interchangeability of the mentioned drivers of operations.

Further contributions of this work are a systematic literature review of vertiport design and operations in scientific literature and regulatory reports and a top-level study of vertiport networks, promising locations and suitable sites.

The results of this thesis are applicable both in academia and industry. First and foremost, the identified drivers of vertiport operations can inform future detailed research and help address inefficiencies in the envisioned UAM system. Second, the vertiport design heuristic is a simple but powerful tool to be used in preliminary airfield design. Third, rules-of-thumb for vertiport throughput present a metric to compare vehicle designs according to their ground performance. Lastly, this thesis and the attached literature review on vertiports gives a comprehensive overview of the current state of research.

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Now, this section is titled 'acknowledgements' and as a researcher I have learned to give due credit to all contributors and authors. With that said, there is one more person who must be acknowledged, for He is not only a contributor but the Creator, not only an author but the Author of Life. I want to thank Jesus Christ, my Lord and Savior, who has not only given me the gifts and intellect needed to write this dissertation, but He has given me life and sustains me everyday. For all things were created through him and for him and, therefore, to God be the glory forever and ever, Amen!

Soli Deo Gloria

Contents

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Abbreviations

AAM	advanced air mobility
ABMS	agent-based modeling and simulation
ATC	air traffic controller
ATM	air traffic management
ConOps	concept of operations
CTOL	conventional takeoff and landing
DLR	German Aerospace Center
EASA	European Aviation Safety Agency
eVTOLs	electric vertical takeoff and landing vehicles
FAA	Federal Aviation Administration
GDP	gross domestic product
GIS	geographic information system
GUI	graphical user interface
ICAO	International Civil Aviation Organization
MIP	mixed-integer programming
MRO	maintenance, repair and overhaul
NASA	National Aeronautics and Space Administration
NUAIR	Northeast UAS Airspace Integration Research Alliance
STOL	short takeoff and landing
UAM	urban air mobility
UML	UAM maturity level
UTM	UAS traffic management
VTOL	vertical takeoff and landing

1 Introduction

The world is changing at an increasingly rapid pace. For instance, two of the recent mega-trends[1] are urbanization and mobility [14].

Urbanization is the process that causes an area to take on characteristics of a city[2]. This is in large part due to an increase in population density in the respective area caused by people moving to cities. In 40 years (between 1975 and 2015) the global share of people living in urban centers increased from 37 % to 48 % and the share living in the urban domain increased from 69 % to 76 %. This happened while the world population grew from 4.06 billion to 7.35 billion people. Correspondingly, there is a relative trend of urbanization which is amplified by the absolute trend of population growth. Summing up both trends the average city hosts around twice as many people today compared to half a century ago [15].

Mobility is the ability to move spatially[2]. This ability increased strongly in recent decades as more people had sufficient expendable income that was not allocated to fulfilling their basic needs. In the U.S. 17 % of the average household's expenditures go to transportation; this is the second largest portion after housing (33 %) and before food (13 %) [16]. It is apparent that mobility plays a vital role in the world. At the same time mobility's efficiency is reduced by traffic: in 2019, the average commuter lost 149 hours to traffic in London and 140 hours in New York [17].

Urban Mobility is at the intersection of the two mentioned mega-trends and therefore vital to socio-economics, but suffers from the backlog of infrastructure construction, which can often not keep up with the growing demand. This is especially true for fast growing and poorly planned cities. The surface space available to mobility infrastructure is quickly used up and competes with real estate and recreational areas. This leaves city planners with two spaces to provide the needed infrastructure for growing urban mobility: going underground, which is costly and disrupts existing traffic for years during major construction; or going to the air. The latter option, often referred to as urban air mobility (UAM), is the aspiring mode of transport this thesis wants to explore with a special focus on ground infrastructure. *Volocopter*, a prominent electric vertical takeoff and landing vehicles (eVTOLs) developer, makes the case that "eVTOL aircraft will alleviate land-use pressure by tapping into underutilized air space above existing roads" using Singapore as example where UAM can reduce the need for roads [18].

UAM promises fast city-related transport and thereby could reduce travel time. The key factors determining whether travelers will use UAM as a new mode of transport are the travel time savings and the cost of the new service [19]. Other factors might come into play such as safety concerns, affinity to technology and service reliability, but these play a subordinate role [20]. UAM will become the transport mode of choice if the service will be cheap enough and the time-advantage compared to conventional modes of transport will be high enough. Cost and travel time are so central to UAM that *Lilium*, an emerging aircraft manufacturer, makes it their two main points of advertisement [21].

This thesis investigates UAM[3] infrastructure — the centerpiece of which are vertiports[4]. In Chapter 2 (Literature Review) the novelty and potential of UAM will be described and contrasted with commercial

[1] The *Zukunftsinstitut GmbH* defines a „mega-trend" as lasting at least 50 years, impacting all areas of life, having global reach and being complex in nature. Next to *urbanization* and *mobility* the institute names ten other trends: gender shift, health, individualization, globalization, connectivity, neo-ecology, new work, security, solver society and knowledge culture.

[2] Definition taken from *Merriam-Webster* dictionary online: `https://www.merriam-webster.com/` (accessed on 10.12.2022)

[3] According to NASA UAM is one concept within the larger field of advanced air mobility (AAM) [6]. Other concepts, such as regional or rural air mobility, are included in AAM as well. The methods and analysis of this thesis are largely agnostic to which concept within AAM is favored as long as VTOL aircraft are considered.

[4] The term „vertiport" refers to an airport with the particular characteristic that the aircraft have the ability to take-off and land vertically: verti-port. In publication #1 it is established that "vertiport" is the most common term used to describe UAM infrastructure, which is distinctly different from the otherwise more common name "aerodrome".

helicopter services. Further, the key hurdles of introducing and scaling UAM services will be discussed. In Chapter 3 (Methods) the design and throughput of vertiports is studied using a mixed-integer programming approach. It will also cover operations and demand of vertiports using agent-based simulation. In Chapter 4 three journal articles are summarized and the full-length articles are attached. The first article (publication #1) reviews the entire field of vertiport research and regulations in detail. The second article (publication #2) introduces a vertiport modeling method and the connected agent-based modeling and simulation (ABMS) framework. The third article (publication #3) shows results of various simulation studies, identifies the main drivers of design and operations and provides the synthesized results in the form of a vertiport design heuristic. In Chapter 5 (Conclusion) the main findings are discussed and the vertiport design heuristic, the key contribution of this thesis, is shown. The technical documentation of the ABMS software can be found in Appendix A.

2 Literature Review

The central advantage of UAM compared to ground-bound modes of city-related transport is savings in travel time. It is in question whether this advantage is large enough – and whether UAM services could become inexpensive enough – to create an attractive market potential. The potential of UAM and its novelty compared to other aircraft, particularly helicopters, is presented in this chapter. At the end, the key hurdles of introduction and scaling this new mode of transport are discussed. It will be shown that infrastructure is among the key hurdles which gives reason for the topic of this thesis: the in depth analysis of vertiport design and operations.

Throughout this thesis the term UAM will be used without intending to exclude other concepts of advanced air mobility (AAM). While AAM describes a wider scope of possible applications, UAM has become the prominent term used in academia; this was shown by various review articles [22, 23]. As long as the aircraft have vertical takeoff and landing (VTOL) capability and at least one end of the trip is located in an inner-city environment, the methods and results of this thesis are equally applicable. In this sense, vertiport design and operations are agnostic to the particular application of AAM. It should further be remarked that this thesis only treats the passenger transport aspect of UAM and does not include cargo or other applications of unmanned drones.

2.1 Novelty of UAM

The novelty of UAM is best understood by contrasting eVTOLs with past and current commercial helicopter services. As [23] points out the main technological upgrades from helicopters to eVTOLs are electrification and autonomy, which have the potential to substantially reduce vehicle and operating costs. The definition of UAM by the *National Air Transportation Association* gives an overview of similarities and differences between eVTOLs and helicopters: "[UAM is] on-demand air transportation within core urban areas [...] using new, electric-powered, vertical takeoff and landing aircraft [...] [and provide] connectivity in a more efficient and cost effective way" [24].

2.1.1 Commercial Helicopter Services

eVTOLs aim to compecte in the existing helicopter market and hope to expand it. [25] analyses various operational issues that hindered or terminated helicopter operations and finds that high operating costs (mostly fuel cost), maintenance, repair and overhaul (MRO) and aircraft crew could be reduced by operating novel electric, autonomous VTOL aircraft. Further, safety might increase with eVTOLs over helicopters. For instance, three fatal accidents caused a prominent helicopter operation, *New York Airways*, to terminate their business after 25 years in 1979 [26]. *Los Angeles Airways* suffered a similar fate in 1968, after operating since the late 1940s [27]. Figure 2.1 shows both historical examples of helicopter services. [28] says that eVTOLs will be fifteen times more reliable and two times safer than helicopters. Factors potentially increasing safety are among others lower complexity of electric motors, redundancy through distributed propulsion and improved (automated) avionics.

Next to safety, noise could be substantially reduced by four to five times from helicopters to eVTOLs [28, 29]; down to the degree where eVTOLs, even during takeoff and landing, are slightly quieter than heavy road traffic [18]. While noise remains a key hurdle [25] large improvements are feasible and thereby could increase community acceptance.

(a) New York Airways [26].

(b) Los Angeles Airways [27].

Figure 2.1 Historical examples of helicopter operations.

2.1.2 Electrification

It can be argued that electrification is the key technology that enables UAM. Electric motors are less complex and thereby cheaper and better scalable than turbine engines. This leads to the sister-advantage of electric propulsion: distributed propulsion [30]. With many small, distributed, electrically-powered fans the design space for aircraft is expanded giving rise to theoretical potentials of increasing aerodynamic efficiency among other positive effects [30]. Yet two factors limit the expansion of electrification of aircraft: battery capacity and charging speed [31].

Battery capacity is determined by the specific energy density which is less dense than conventional fuels. Multiple studies suggest that eVTOLs need a specific energy density of $400\,{}^{Wh}/_{kg}$ on a pack level to have a comparative advantage over helicopters and indicate that this number as a threshold for profitable large-scale UAM operations [30, 32]. This portrays a state in the future; most studies of the near- to mid-term consider battery capacities of $250 - 350\,{}^{Wh}/_{kg}$ [33, 34, 35]. The German Aerospace Center (DLR) defined two scenarios in the *Horizon UAM* project assuming $300\,{}^{Wh}/_{kg}$ for 2025, and $500\,{}^{Wh}/_{kg}$ for 2050 [36]. This shows that battery research is an essential enabler of UAM, especially when considering that batteries have been identified as one of the main cost drivers [32], and that the lifetime of a battery could be as short as one month[1].

Charging eVTOLs at high speed will become crucial to reduce downtime of vehicles and not waste precious inner-city space for long aircraft turnaround. Charging powers that have been proposed range from $125\,kW$ in the near-term to $1000\,kW$ in the long-term [32, 33, 36, 38]. These assumptions are in stark contrast to a comparable application today: electric cars. In Germany a typical charging power for AC is $11\,kW$ with charging points having a limit of $30\,kW$ which they can draw from the electric grid [39].

One way to address this gap is a large increase in charging powers, which might create the need for expansion of the electric grid and active battery cooling during the charging process. Another way to cope with the gap in current state of charging technology, and shorten turnaround times simultaneously, is battery swapping. *VoloCopter* proposed this concept early on for eVTOLs [37] and various publications have studied the benefits of swapping over charging on operations with swapping times around 5 minutes [38, 40]. Justin et al. present a detailed review of swapping concepts for eVTOLs, electric cars and public transport vehicles [38]. At the same time, direct charging appears to remain the "fueling type" of choice, possibly due to unknown complexities of defining battery pack standards and the penalties on aircraft weight when designing (quickly) removable batteries.

2.1.3 Autonomy

Creating autonomous aircraft for UAM operations has two lines of reasoning. First, if the aircraft does not need a pilot, one more seat is available which can be sold to a passenger; and the cost for pilot (and crew) is no longer present. This is particularly important as the pilot has been identified as the element

[1] *Volocopter* estimates their battery lifetime at 600-800 cycles and sees 20-30 flights per day per vehicle [37]. These assumptions result in 20-40 operating days before the battery has to be disposed.

with the highest individual cost on UAM operations [41, 32]. Both helps the operator to increase profit and thereby create a more competitive business case. Second, if the number of flights further increases in an environment where human air traffic controller (ATC)s already come to their limits, autonomy will be necessary to enable the new density of operations. The effect further increases in severity when considering complex inner-city environments compared to today's commercial airports where ATCs usually operate.

BOSCH claims "self-piloting will be key to mass adoption of eVTOL aircraft" [42] and companies like *Amazon*[2] and *XWing*[3] are pioneering the way in this area. While autonomy is beneficial (and might be necessary in the long run), it is not clear how well autonomous systems will be accepted by the users. Hurdles in acceptance and legislation are likely to force eVTOLs to operate with an on-board pilot in the near-term. As in other areas, like autonomous driving, the degree of autonomy will probably increase gradually over time and will include remote-piloting along the path to full autonomy.

2.1.4 Lower Cost

Operating a helicopter today costs per passenger $3.73\,\$/km$ (6 USD/mile) [41] to $5.59\,\$/km$ (9 USD/mile) [43]. This results in trip costs of more than $200: *Voom* offered airport shuttle services in San Francisco for around $220-275[4], *Blade* offered flights to airports in the New York City area for $295[5] and *Uber* looked at starting service in Manhattan for $200-225[6]. In contrast, operating costs of eVTOLs are expected to be 50 % lower [43] and the capital expenses for the vehicle up to 90 % lower [28]. One study claims that even in the "near-term electric vertical takeoff and landing aircraft may be able to significantly increase the expected user base when compared with present-day helicopters flying the same mission." Here the assumed baseline operating cost is $662\,\$/h$ for eVTOLs and $1253\,\$/h$ for helicopters [44]. Along the same lines, *McKinsey* projects that while the total cost of helicopters (including initial capital expenses) is $3.73 - 4.97\,\$/km$ (6 to 8 USD/mile) it could be as low as $0.31 - 1.55\,\$/km$ (0.5 to 2.5 USD/mile) for eVTOLs with the vehicle cost being one major difference next to lower infrastructure cost and eliminating the crew cost [41]. These estimates would indicate close to 80 % lower total costs and are in line with the above-cited sources[7]. Whether the vehicle costs of eVTOLs will truly be lower than helicopters is yet to be seen, but the lower complexity of an electric propulsion systems compared to a conventional turbo-shaft engine gives reason to expect at least some cost reduction.

2.2 UAM Market Potential

There are a number of indicators measuring the potential of UAM: market share, business revenue, ticket price and number of daily trips. Other indicators, such as service level or vehicle cost and fleet sizes, could be considered, but do not seem to be as prominent in scientific literature. All estimates are made depending on an explicit or implicit time frame, which might be the strongest factor of all: how far into the future do the forecasts look?

[2] Amazon showed its first autonomous package delivery in 2016: `https://www.amazon.com/b?node=8037720011` (accessed on 1.1.2020).

[3] XWing retrofits small aircraft and showed its first fully autonomous gate-to-gate flight in 2021: `https://www.zdnet.com/article/first-gate-to-gate-autonomous-airplane-flight/` (accessed on 20.4.2021).

[4] `https://www.voom.flights/` (accessed on 5.12.2019)

[5] `www.forbes.com/sites/michaelgoldstein/2018/08/21/blade-puts-helicopter-or-fixed-wing-flight-just-an-app-away/?sh=41065af94efc` (accessed on 11.7.2022)

[6] `https://www.nytimes.com/2019/06/05/travel/uber-helicopter-nyc-jfk.html` (accessed on 11.7.022)

[7] Comparing the median value of eVTOL costs (1.5 USD/mile) to the median value of helicopter costs (7 USD/mile) results in 21.4 % of the original total costs, which is close to an 80 % reduction in total costs.

2.2.1 Market Share

Market share in the transport market was investigated in two comprehensive studies by *Bauhaus Luftfahrt* in Germany and *GeorgiaTech* in the U.S. The former considers five scenarios (from conservative to progressive) for the year 2030 in the Munich metropolitan area. The mode shares calculated by means of agent-based transport simulation range from $0.03 - 1.29\,\%$ [45]. The latter presents a sensitivity study of global UAM demand for the year 2035 and finds mode shares between $0.014 - 8.5\,\%$ [46]. Both studies agree on the main factors determining their market share: ticket price and vertiport density. Further, Rothfeld did extensive work on the achievable UAM market shares when looking only at travel time advantage and neglecting prices [47]. For the use cases of Munich, Paris and San Francisco, and under variation of UAM cruise speed, passenger processing time and vertiport density, the market shares range between $0.4 - 26\,\%$ [48]. As UAM can be expected to be (substantially) more expensive than established modes of transport, this range needs to be interpreted as an upper limit to the potential market share.

One use case with currently garnering a lot of attention is the airport shuttle. [49] find potential to substitute $0.5\,\%$ of ground taxis and other airport access transport modes in the U.S. Similarly, [50] look at LAX airport in Los Angeles, but make a more optimistic claim based on discrete events simulation: $3.6\,\%$ of current trips to the airport could be replaced by UAM.

Business revenue could be anywhere from $2.5 billion in the near-term [49, 51] to $32 billion annually and globally by 2035 [28]. [23] reviews various market studies and the middle ground seems to be single-digit billion USD revenues in the 2020s and double-digit billion USD revenues in the 2030s. *VoloCopter* claims to see a UAM market of $141 billion by 2035 [29]. While not explicitly stated, the number has to be accumulated and not annually to make sense of related statistics (the passenger transport market according to *VoloCopter* is $10.2 trillion, which would correspond to estimated market developments [52] if taken as accumulated market volume). This would imply an average annual market between the publication of the report in 2021 and the projected year 2035 of $9.4 billion and $1.4\,\%$ market share – a median estimate compared to other market studies. In a follow-up study for Singapore, *VoloCopter* estimated an accumulated market of $4 billion (Singapore dollars, exchange rate ca. 0.7 USD) until the year 2030 [18].

2.2.2 Ticket Prices

Ticket prices will be a composite of fixed costs (e.g. vehicle purchase) and operating costs (driven by energy costs) plus operator profit. Most considerations base their trip cost on a distance-related ticket price, while some also include a base fare per trip. Conservative estimates land at $3.88\,\$/km$ (6.25 USD/mile)[8] [51] or $4.20\,\$/km$ (4 CHF/km) [53]. As time progresses, prices could drop by $60\,\%$ to $1.55\,\$/km$ (2.5 USD/mile) [51] and to $2.10\,\$/km$ (2 CHF/km) [53]. The above-cited studies from *Bauhaus Luftfahrt* (year 2030) starts at $5.75\,\$/km$ (5 EUR/km) and goes to $1.15\,\$/km$ (1 EUR/km) for the progressive scenarios [45]; estimates from *GeorgiaTech* (year 2035) range from $0.3 - 3.6\,\$/km$ [46]. *Uber* optimistically predicted initial $1.85\,\$/km$ (2.97 USD/mile), $0.61\,\$/km$ (0.98 USD/mile) in the near-term and $0.29\,\$/km$ (0.47 USD/mile) in the long-term [54]. Other publications base their studies on vehicle costs of $1.80\,\$/km$ [28], general trip ticket price of $0.5\,\$/km$ [55] or $1.24\,\$/km$ (2 USD/mile) [56] and an airport shuttle ticket price of $1.24\,\$/km$ (2 USD/mile) [57]. Studied base fares range from $4.2\,\$$ (4 CHF) [53], over $5.75 - 11.50\,\$$ (5 to 10 EUR) [45] and $15\,\$$ [57], all the way to $30\,\$$ [56].

The previous paragraph showed that assumed ticket prices vary drastically. High prices are just below today's helicopter costs, this would kill all potential of UAM. Low prices are projected even lower than car costs[9] and potentially lower than public transport — not a view that seems very realistic. The difficulty in this regard is that UAM demand and its market share will be strongly driven by the ticket prices. This

[8] All values in this paragraph are given in USD per km. If units deviate in the source, the original values and units are given in brackets. For conversions from EUR to USD a 10-year average of 1.15 is assumed. For conversions from CHF to USD a 10-year average of 1.05 is assumed.

[9] According to the *General German Automobile Association (ADAC)* the total cost for a VW Golf GTI, the most popular car in Germany, is $0.69\,\$/km$ (60.6 ct/km) [58].

variation of ticket-price-assumption explains the vast spectrum of opinions about UAM which exist in the public and scientific community.

2.2.3 Summary of Potential

Number of expected trips are studied for different points in the future (short-term to 2050), different time frames (daily vs. annual) and different regions (globally, nation-wide and individual metropolitan areas). As the levels of analysis vary and the expected trips are a function of the above-described factors, it is difficult to compare the studies. Instead of a direct comparison a review of studies is listed in Table 2.1.

Table 2.1 Review of studies on UAM market potential including expected number of trips.

Source	# trips	# vehicles	Time frame	Ticket price	Year	Area
[53]	18k	-	Daily	2 CHF/km	-	Zurich
[57]	7109	-	Daily	2 USD/mile	-	LAX airport
[49]	82k	4k	Daily	-	Near-term	USA
[59]	-	28k / 98k	-	-	2035 / 2050	Global
[60]	750M	-	Annual	-	2030	USA
[61]	10M	-	Annual	-	2040	Australia
[28]	-	23k	-	1.8 USD/km	2035	Global
[62]	15M / 3B (flight hours)	-	Annual	-	2035 / 2050	Global
[55]	90B / 162B	-	Annual	0.5 USD/km	2035 / 2050	Global
[45]	105k	-	Daily	2 EUR/km + 5 EUR	2030	Munich
[56]	532	-	Daily	2 USD/mile + 30 USD	Near-term	Tampa Bay, FL

In summary, it appears while the market potential of UAM is hard to predict, it will remain a niche market (likely below $1\,\%$ market share). Thereby, UAM will not revolutionize the transport sector. At the same time this market share corresponds to an annual multi-billion dollar market, which presents plenty of profitable business opportunities. [22] summarizes it well: “UAM is not expected to be a mass transport service. Thus, an efficient integration with existing modes of transport especially public transport is essential. The aim should be to complete and not compete with public transport”.

2.3 Hurdles to UAM Introduction and Scaling

UAM has the potential to lower cost compared to commercial helicopter operations. This cost reduction enabled by electrification and autonomy is expected to open up an annual multi-billion dollar market. In the next step the hurdles to introduction and scaling of UAM services will be investigated and it will be shown that infrastructure is a key hurdle. Three reputable sources have described challenges of UAM systematically, which will serve as a starting point in this discussion. First, *MIT* started in 2017 to systematically identify “scaling constraints for UAM” [5]. Second, National Aeronautics and Space Administration (NASA) published the “NASA UAM Framework Barriers” in 2020 [6]. Third, and on the European side, DLR proposes a framework of studying UAM and its challenges in the *Horizon UAM* project [36].

2.3.1 Identification of Key Hurdles

Scaling Constraints for UAM (MIT)

Parker Vascik at *MIT* identified 19 potential operational challenges [63] and through expert interviews, which were accompanied by a survey with over 500 participants [64], compares them to eight potential

UAM constraints [25]. This process (illustrated in Figure 2.2) yielded a list of 5 prospective operational constraints: aircraft noise and community acceptance, availability of takeoff and landing areas, scalability of operations under ATC, community access to takeoff and landing areas and scalability of operations outside ATC [65]. He further analyzed these constraints and identified ground infrastructure, ATC and noise as the most challenging elements [66, 67].

In follow-up publications Vascik briefly touched on noise [67] and dedicated one conference contribution to ground infrastructure [68]; otherwise his focus shifted to ATC. While he was the first to analyze scaling constraints in a systematic fashion — and with that laid important ground work — the scope of his analysis is limited compared to the work of NASA and DLR.

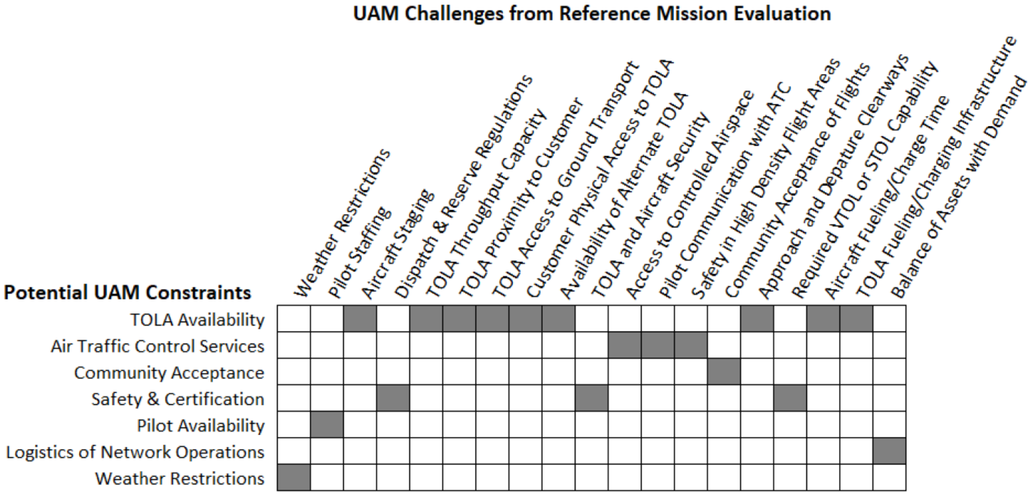


Figure 2.2 Process guided through expert interviews at *MIT* to identify scaling constraints for UAM [5].

UAM Framework Barriers (NASA)

NASA presents a multi-layered framework of barriers with three categories at the top: *Aircraft & aircrew*, *airspace* and *community integration*. At the second layer the first category ("aircraft & aircrew") is split into the groups *aircraft design* and *aircraft operations*, and the second category ("airspace") into *airspace design* and *fleet operations* [69]; the third category ("community integration") remains a single unit. In short, these five groups are named "Airspace," "Infrastructure," "Airmen," "Vehicle" and "Community" [70], and their full description is as listed below and shown in Figure 2.3 [6]:

1. Aircraft Development and Production
2. Individual Aircraft Management and Operations
3. Airspace System Design and Implementation
4. Airspace and Fleet Operations Management
5. Community Integration

Under each of these groups, or "pillars" [69] as NASA calls them, four to six barriers are listed [6]. The barriers that are most relevant in the context of this thesis are "UAM Aerodrome Design" under the pillar of "Airspace System Design and Implementation" and "Efficient/Scalable Airspace Operations" under the pillar of "Airspace and Fleet Operations Management". NASA further mentions a list of aspects that play a role in each pillar: safety, security, affordability, noise, automation, UAM aerodromes and regulations/certification [6].

Upon their own admission, the NASA UAM framework is work-in-progress and meant to guide research instead of describing the full future UAM system. It can be seen that the vision is driven by aircraft and airspace, which might lead to a bias neglecting for example passenger and infrastructure-related questions. Nonetheless, the UAM aerodrome occupies a prominent role.

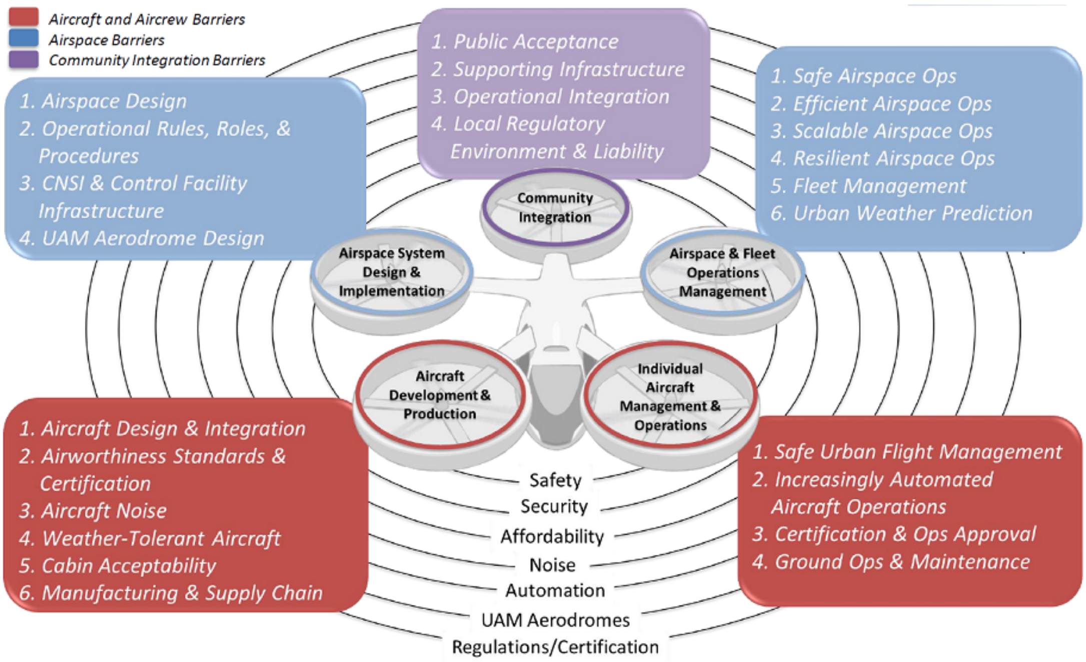


Figure 2.3 NASA's UAM framework barriers [6].

Horizon UAM Research Areas (DLR)

DLR identified four areas of research in the *Horizon UAM* project[10]: vehicles, infrastructure, operations and (public/community) acceptance [36] (see Figure 2.4). There are other factors mentioned such as services, market development, safety and security, but these only occur sporadically in the project description. As stated in the introduction of the project [36] the results of *Horizon UAM* will be published through the annual *Horizon UAM* symposiums. During the first symposium in 2021 the four areas were confirmed and "infrastructure" was equated with "vertidrome" [7].

Compared to the work at *MIT* and NASA, the description of the UAM system by DLR is rather rudimentary. This is due to the later start of the project and more detailed results can be expected in the next 1-2 years. Yet, it is interesting to observe the broadening of the focus towards inclusion of public acceptance and infrastructure.

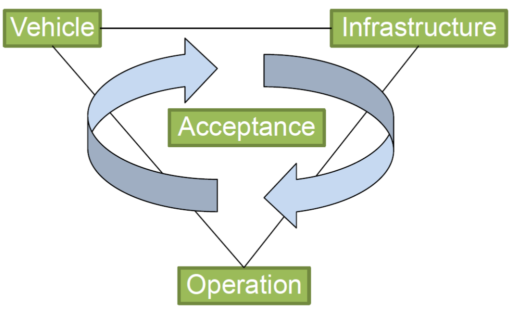


Figure 2.4 DLR's reserach focus in the *Horizon UAM* project [7].

Summary of Hurdles

It is evident that vertiport design and operations are key hurdles for introduction and scaling of UAM. This view is affirmed by all three reviewed source, who systematically studied UAM challenges; a summary

[10]The project has a duration of three years, ends in 2023, has a funding of 9 million EUR and includes ten DLR institutes [36].

of key research areas is shown in Table 2.2. Even as early as 1970 a *MIT* report on "Future Intracity Air Transportation Systems" identified ground operations and vertiports as central issues next to vehicle design and ATC. While the nuances and focus might differ, the overall picture is similar: vertiports are essential to UAM and therefore need to receive adequate attention. This thesis builds on the premise that infrastructure has received less attention than eVTOLs design and air traffic management (ATM) and a gap exists which will be addressed in Chapter 3 onwards. Before that the existing research on UAM infrastructure will be summarized in Section 2.3.2.

Table 2.2 Key hurdles for UAM introduction and scaling according to *MIT*, NASA and DLR.

Research area	*MIT*	NASA	DLR
Infrastructure	strong focus	secondary focus	strong focus
Vehicle design and operations	not considered	main focus	strong focus
ATM and airspace design	main focus	main focus	secondary focus
Community acceptance and noise	secondary focus	strong focus	strong focus

2.3.2 Infrastructure

Heliports

The common view is that heliports are the blueprint for future vertiports. *National Air Transportation Association* says about UAM that “the closest example of existing infrastructure is that which supports helicopter operations, i.e. heliports” [24] and Northeast UAS Airspace Integration Research Alliance (NUAIR) states that “heliports are the most analogous current-state model for vertiports of the future” [8]. NASA defined six UAM maturity level (UML) as a framework of analysis [6], which is taken as basis for NUAIRs concept of operations (ConOps) seen in Figure 2.5. According to NUAIR early vertiports are likely to be retrofitted heliports with extra sensing and communication technology [8], but to sustain the expected volume of 80-120 hourly operations for UML-4 future vertiports must evolve [71].

Heliport operations had their peak in the previous century, exemplified by 50,000 annual operations at Chicago Midway international airport and 47,000 operations at Chicago O’Hare international airport in the year of 1960 [72]. These were operated by *British United Airways* and made up 13 % and 19 %, respectively, of all airport operations. In contrast, the busiest heliports today are located in New York City with 12,000 to 27,000 annual operations [24]. Comparing this to expected UAM operations the volume of operations would increase by one order of magnitude. This increase could be illustrated by saying that future vertiports will have to cater the number of flights in one hour that past heliports catered in one day. An outlier in heliport operations is the well-known Silverstone heliport, which holds the world record for most operations within one day: 4,200 movements for the 1999 *Formula One Grand Prix* in Silverstone. This example is a fascinating study case, but is by no means a scalable model considering that 24 ATCs where active on 6 different radio frequencies [73].

Airports

Airport operations at large international hubs reach 175-300 hourly movements during peak hour and might, therefore, be comparable in volume to future vertiports [74], but there is a list of factors limiting the comparability. First, airport capacities are calculated based on runways (and their surrounding airspace) alone. Gates and taxiways are explicitly ignored in the throughput capacity analysis [74]. This approach would fall short in accounting for all driving aspects of vertiports: it was shown that gates (next to runways/pads) need to be considered in vertiport throughput analysis as they can become an operational bottleneck (this insight was uncovered in publication #2 [2] and confirmed in publication #3 [12]). Second, the different capabilities between VTOL for vertiports and conventional takeoff and landing (CTOL) for airports substantially changes the design space both on the ground and in the air[11]. Third, eVTOLs hold much smaller number of passengers compared to commercial or even thin-haul aviation, The range of seats for current vehicle developments is between one to seven [1]. Fourth, the space constraints of vertiports (in inner-city environments) are much tighter than airports. VTOL operations are often the only option inside a city, which is one central reason to even consider them while CTOL operations would be more energy efficient.

Vertiports

Vertiports are, in short, heliports that can serve the demand of airports on the footprints of inner-city buildings. This highly constrained design space will be explored in Chapter 3 and summarized briefly in the following. On one hand, the passenger terminal including ticket scanning, security screening and optional luggage drop-off needs to allow for quick passenger processing. As the overall UAM travel time is short compared to commercial aviation, all these processes will need to take place within a few minutes. On the other hand, the airfield including pads for approach and departure, gates for boarding and optional stands for parking idle eVTOLs needs to be operated safely and efficiently. In particular, the expected ground taxiing presents a new operational challenge [77]. The mentioned elements and processes are well captured by the NUAIR ConOps shown in Figure 2.5.

While these challenges are not trivial, the effort to study vertiports is needed and worthwhile. According to NASA the effort is needed because "studies that analyze anticipated performance of an array of projected aircraft and make associated recommendations on UAM aerodrome design requirements would be beneficial because of the long lead times and costs associated with obtaining and preparing urban real estate for UAM operations" [69]. According to Volocopter the effort is worthwhile, because "evtol aircraft will alleviate land-use pressure by tapping into underutilized air space above existing roads" and thereby addressing the potential for reduced need of roads (e.g. in Singapore) [18]. Simply put, there is a need to understand vertiports now in order to start planning and building them so UAM can actually take off in the next 5-10 years.

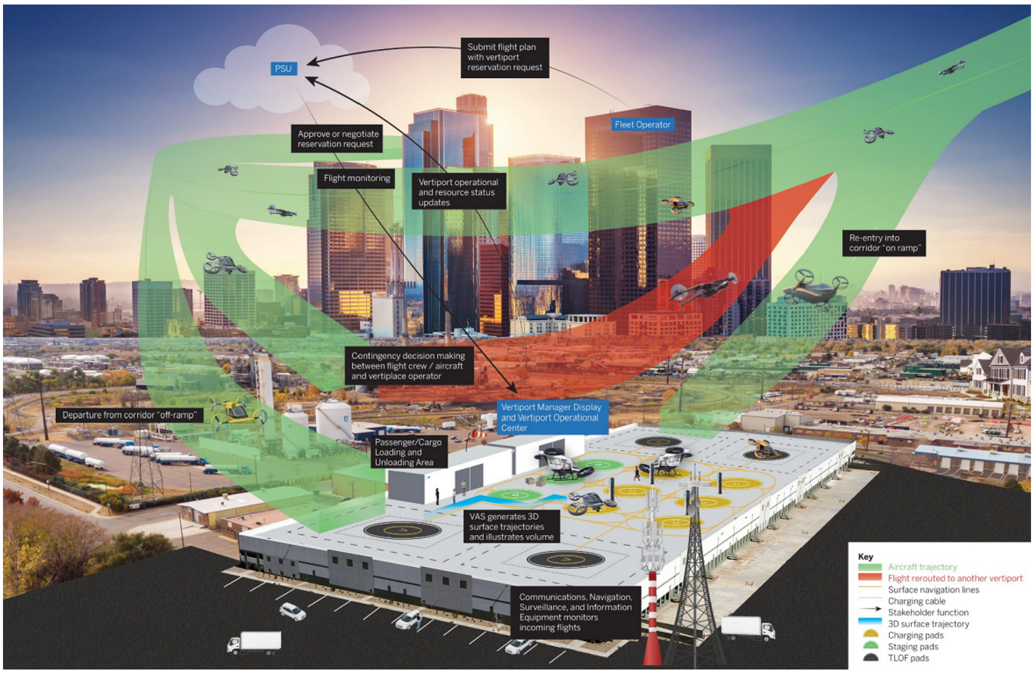


Figure 2.5 NUAIR ConOps for high-density automated vertiport operations [8].

[11] Ports for short takeoff and landing (STOL) are an application that combines characteristics of both vertiports and (conventional) airports [75, 76].

2.3.3 Other Hurdles

Vehicle Design

The design of eVTOLs has been studied in countless scientific publications. One aspect causing this high interest in the research community is the expanded aircraft design freedom through the introduction of distributed electric propulsion. Three configurations seem to be most prominent: multi-copter[12], lift-plus-cruise[13] and tilt-wing/prop[14] configurations (one example per configuration is shown in Figure 2.6). Between these there there does not seem to be a clear favorite and it is likely that different applications will need different configurations. This is in contrast to commercial aviation where most designs have converged to one optimal standard configuration. Further, there are various reviews in literature looking at designs, feasibility and high-level economics of eVTOLs [78, 79, 80, 81, 82, 1, 32]. The industry is also active with 754 eVTOLs design concepts[15] as recorded in "Electric VTOL News" published by the *Vertical Flight Society* [83].

(a) VoloCity[12] (multi-copter).

(b) Beta ALIA-250[13] (lift-plus-cruise).

(c) Joby S4[14] (tilt-prop).

Figure 2.6 Prominent examples of multi-copter, lift-plus-cruise and tilt-wing/prop configurations.

Air Traffic Management and Airspace Design

ATM is a large and complex field of study that has been espoused by the regulatory agencies in the U.S., Europe and around the globe. With the expected volume of UAM traffic, conventional (i.e. human) ATC will not be able to function as they have been and eventually automation must be introduced. This presents a disruptive change in an area that has evolved over many decades and by its evolutionary approach has reached unprecedented levels of safety. Next to novel (i.e. semi- or fully-automated) ATC, new structures of the airspace are considered with detailed sectioning and dynamically changing airspaces.

The regulatory aspects of future ATM for UAM are reviewed in detail in publication #1 [77] and will only be reiterated briefly here. The Federal Aviation Administration (FAA) published two ConOps for (non-passenger carrying) UAS traffic management (UTM) [84] and (passenger carrying) UAM ATM [85] in 2018 and 2020, respectively. Of particular interest for this thesis are the FAA heliport design guidelines from 2012 [86], which are in the process of being updated toward vertiport design guidelines [87]. On the European side a “Means of Compliance with Special Condition VTOL” was published by European Aviation Safety Agency (EASA) in 2021 [88] giving details on heliport and vertiport operations. In terms of (non-passenger carrying) UTM the *SESAR Joint Undertaking* has been actively discussing the *U-Space* framework [89], whose ConOps was published in 2019 [90]. So far a ConOps for ATM for (passenger carrying) UAM is not publicly available in Europe.

[12] „VoloCity“ by *VoloCopter* is an example of a multi-copter configuration: `https://www.volocopter.com/solutions/volocity/` (accessed on 1.8.2022).

[13] “ALIA-250” by *Beta Technologies* is an example of a lift-plus-cruise configuration: `https://www.beta.team/aircraft/` (accessed on 1.8.2022).

[14] „S4“ by *Joby Aviation* is an example of a tilt-prop configuration: `https://www.jobyaviation.com/about/` (accessed on 1.8.2022).

[15] The "eVTOL Aircraft Directory" of the *Vertical Flight Society* (`https://evtol.news/aircraft`) is continually updated and the listed numbers were taken on December 3, 2022. The list is split into five groups (number of concepts in brackets): Vectored Thrust (253), Lift+Cruise (133), Wingless/Multicopter (210), Hover Bikes (107) and Electric Rotorcraft (51).

Community Acceptance and Noise

Noise is expected to be the main hurdle for community acceptance; especially around vertiports where eVTOLs are close to the ground and thereby the noise impact is highest. For this reason noise and community acceptance are often treated simultaneously: "the dominant problem in implementing an urban air system is community acceptance of the [vertiport], and the prime factor would be the noise of the air vehicles" [91] and "in order to scale up demand, new ground infrastructure with larger operational capacity would need to be built, [...] [but] increased demand would risk posing greater noise concern for impacted communities" [51].

Studies have found that noise negatively affects revenue of UAM [92], constrains operations [93], demands selecting routes with detours [94] and lets STOL be favored over VTOL aircraft [76, 95]. In publication #1 [77] noise was found to be an underrepresent topic in vertiport research and NASA published a whitepaper on UAM noise highlighting various research gaps [96]. The issue is further complicated by insights stemming from a whitepaper on aviation noise from International Civil Aviation Organization (ICAO); not only the volume, but also the frequency spectrum plays a role in creating annoyance. ICAO further emphasizes that "although there is only a very limited amount of research on subjective reaction to noise from these new aircraft types [i.e. UAM aircraft], indications that the noise characteristics differ from traditional aircraft warrant further research to understand and predict human perception of these sounds" [97].

Fraunhofer considered the noise of eVTOLs to be lower than helicopters [98, 99]. This matches other sources as discussed in Section 2.1.1, they claim eVTOLs to be four times quieter than helicopters [28, 29]. Noise appears to be a large enough issues that *Joby Aviation* advertises only two features on their electric aerial ridesharing website[16]: travel time savings — the reason for the existence of UAM as shown in Chapter 1 — and a low noise profile. The general consensus appears to be that eVTOLs will acheive lower noise profiles compared to helicopters on a vehicle level. At the same time it is unknown to which degree the expected increase in operations and the proximity of vertiports to residential areas will negatively impact the public acceptance. The topic of noise, therefore, continues to be a central research gap within the field of UAM.

[16] https://www.jobyaviation.com/ (accessed on 23.7.2022)

3 Methods

Infrastructure is essential for the introduction and scaling of UAM and has unanimously been identified as one of few driving constraints (see Chapter 2.3). The vertiport[1] is at the heart of UAM infrastructure. In this chapter two methods will be summarized analyzing vertiports at different levels of fidelity. First, a low-fidelity mixed-integer programming (MIP) approach is described in Section 3.1. Its aim is to provide a quick estimation of vertiport throughput and an optimization of airfield layouts. Second, a high-fidelity ABMS approach is described in Section 3.2. The second approach constitutes the heart of this thesis and is subject in publication #2 [2] and publication #3 [12]. The central quest is identifying the drivers of vertiport operations. Both methods are connected through an interface described in Appendix B.3.

3.1 Vertiport Design and Throughput

High throughput at vertiports is crucially important for scaling the UAM system. At the same time, throughput is limited by the constraints of the inner-city environment (see Section 2.3.2 for further considerations related to infrastructure). Therefore, two aspects are vitally important: first, choosing a fitting vertiport location, and second, optimizing the vertiport layout for the chosen site.

3.1.1 Geographic Location

Vertiport location is a central and under-represented topic with need for future research [100]. For the purpose of this section two definitions are introduced: a "promising location" as a general area with potential for UAM services (with a maximum radius of a few hundred meters); and a "suitable site" as the physical surface for a vertiport (e.g. a rooftop or vacant land). Various studies use geographic information system (GIS)-based approaches to identify promising locations, but these typically fall short of identifying suitable sites [101, 102, 103, 104, 105, 106, 107]. Simultaneously, a range of suitable sites has been suggested in the research community, while not applying it to concrete locations [100, 108, 23, 54, 109].

There are three known efforts who consider both promising locations and suitable sites in a holistic way. First, [110, 111] identified promising vertiport locations across Germany by looking at current travel behavior. Once a location was identified a catalogue of criteria was applied to find a suitable site and vertiport throughput was calculated by means of MIP [9]. Second, [112] found promising vertiport locations as a mathematical optimum in Seoul by applying *k-means* clustering. Subsequently, a quantitative GIS-based approach combined with a qualitative repositioning process was facilitated to find suitable sites [94]. Third, [9, 113] undertook vertiport layout and throughput studies for real-life areas in Northern Germany and Berlin (see Figure B.2 in Appendix B.1). The focus of this thesis will now shift to the analysis of individual vertiports, but it should be emphasized that the holistic research of vertiport locations (and networks) is a research gap.

3.1.2 Airfield Layout

The optimal layout of a vertiport is determined primarily by the ratio between gates to pads and the spatial aggregation of these elements [68]. In [9] four vertiport topologies (i.e. generic ways of ordering vertiport elements) are described: single-pad, satellite, linear and pier. All layouts proposed in the literature can be assigned to one or multiple of these topologies, wherefore they represent an exhaustive list of relevant

[1] The name "vertiport" is strongly favored by the research community over the otherwise more common term "aerodrome" as was shown in publication #1 [77]. In this publication a systematic review of vertiport research can be found.

vertiport layout options[2]. How these generic topologies are applied for concrete layouts can be seen in Appendix B.4 where a number of vertiport design renderings are reviewed.

The following sections give a definition, a schematic representation and a list of relevant publications for each topology. [113] defines a detailed geometric model[3] of concretizing these four generic ways of ordering vertiport elements on different sizes and shapes of areas. The motivation for this detailed analysis of vertiport layouts comes from publication #2 [2], where it was shown that the number of pads and gates are one design driver for vertiport operations. All four topologies use pads for approach and departure and neglect stands for (long-term) parking of eVTOLs. The differences and commonalities of the topologies are listed in Table 3.1.

Table 3.1 Differences and commonalities of vertiport topologies.

Topology	Approach/ departure at...	Turnaround at...	Taxiing	Parking stands considered
Single-pad	Pad	Pad	None	No
Satellite	Pad	Gate	Beeline between elements	No
Linear	Pad	Gate	Beeline between elements	No
Pier	Pad	Gate	Designated taxiway	No

Single-Pad

The single-pad topology[4] consists of only one element type: pads. Vehicles do not taxi on the ground and all processes, including passenger boarding, happen on the pad. Single-pads are therefore compareble to today's helipads. Figure 3.1 shows the single-pad topology schematically and Table 3.2 lists relevant sources using this topology.

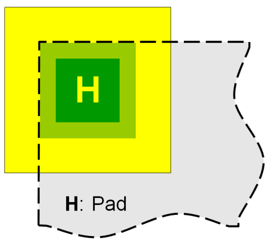


Figure 3.1 Depiction of single-pad topology.

Table 3.2 Literature review of single-pad topology.

Source	Name
Deloitte [114]	- (vertistation)
Taylor et al. [115]	Multi-function single pad
Volocopter [116]	-
NUAIR [8]	Single pad design

Satellite

The satellite topology consists of pads (typically in the corners of the area) and gates surrounding the pads in a circular shape. As the gates are in direct proximity to the pads there are no designated taxiways. Passenger boarding and vehicle charging happens at the gates. Figure 3.2 shows the satellite topology schematically and Table 3.3 lists relevant sources using this topology.

[2]Some of the layouts found in the literature are a hybrid of multiple topologies — or even change dynamically — but can still be described by a combination of the four proposed topologies.
[3]For all four topologies distinctions are drawn for 1, 2, 3, 4 and more than 4 pads, laying out individual spatial rules for all cases.
[4]To avoid confusion it needs to be clarified that the "single-pad" topology does not limit the number of pads to one; instead it refers to the absence of other types of elements. In other words, "single-pad" is synonymous with "pad-only".

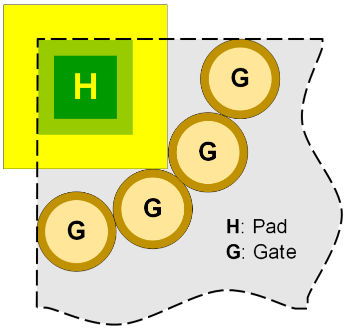


Figure 3.2 Depiction of satellite topology.

Table 3.3 Literature review of satellite topology.

Source	Name
RWTH/FKB [117, 118]	-
Deloitte [114]	- (vertihub)
Purdue [119]	Satellite
DLR [120]	Circular arrangement
Uber [54]	- (satellite/linear hybrid)
Taylor et al. [115]	Hybrid pad with staging
NASA [121]	Disconnected design
MIT [68]	Satellite
NUAIR [8]	Hybrid design
Wisk [122]	Minimum footprint vertiport

Linear

The linear topology consists of pads (typically lined up along the long side of the area) and gates positioned as a second row behind the pads. The gates are in sufficient proximity to the pads to neglect designated taxiways. The topology can have one or two rows of pads. In the latter case, one row could be for arrival only and the other row for departure only. Pads facing the same direction need a minimum distance of FATO/FATO ($200ft$ according to [86]) to allow for simultaneous operations. Passenger boarding and vehicle charging happens at the gates. Figure 3.3 shows the linear topology schematically and Table 3.4 lists relevant sources using this topology.

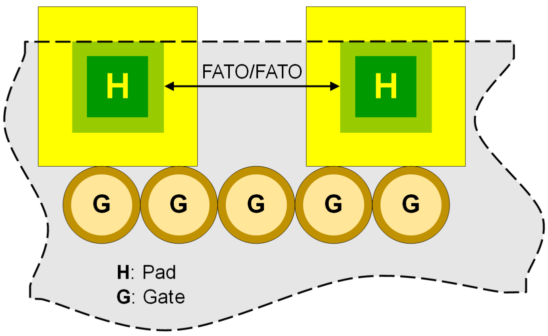


Figure 3.3 Depiction of linear topology.

Table 3.4 Literature review of linear topology.

Source	Name
FKB [117]	-
McKinsey [41]	-
Lilium [123]	Linear
Uber [54]	- (satellite/linear hybrid)
Taylor et al. [115]	Linear single function pads
MIT [68]	Linear
Volocopter [116]	-
NUAIR [8]	Linear process design
Wisk [122]	Linear/drive-through vertiport

Pier

The pier topology consists of pads and gates that are connected by designated taxiways. Pads can have their own taxiways, share it with a second pad or be connected with all pads via one central taxiway. Gates are lined up along the sides of all taxiways. Passenger boarding and vehicle charging happens at the gates. Figure 3.4 shows the pier topology schematically and Table 3.5 lists relevant sources using this topology.

The remote apron topology by [68] and perimeter design by [121] are more unique layouts, but can in the wider sense also be assigned to the definition of the pier topology. Further, [124] proposes dynamically changing layouts, which by definition cannot be assigned to one particular topology. However, all layouts shown in the patent fit into one of the four proposed topologies.

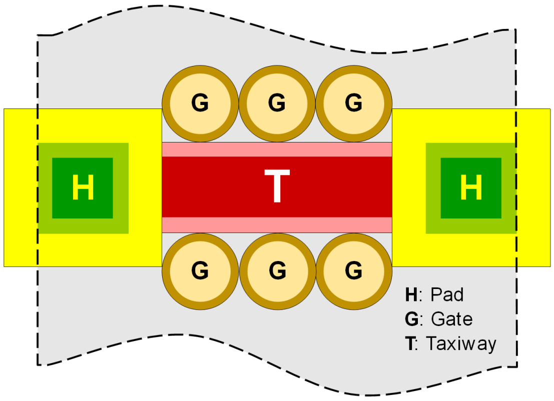


Figure 3.4 Depiction of pier topology.

Table 3.5 Literature review of pier topology.

Source	Name
RWTH/FKB [117, 118]	-
Lilium [123, 21]	Courtyard, Back-to-back
Deloitte [114]	- (vertiport)
DLR [120]	- (satellite/pier hybrid)
NASA [121]	Central design
MIT [68]	Pier
Volocopter [116]	-
Wisk [122]	Airport-like vertiport

3.1.3 Throughput

After choosing a vertiport location (see Section 3.1.1) and defining the airfield layout (see Section 3.1.2), now the throughput of a vertiport design can be estimated. In this section a MIP approach will be presented optimizing vertiport designs in an iterative process including the three aspects of vertiport location, layout and throughput estimation. The method was originally described in [9] and expanded and applied in [1, 113].

Throughput, capacity or size are used at different points to describe the same general idea: how many aircraft or passengers can be processed in a given amount of time (usually an hour) on an aerodrome. For a holistic view the entire chain of steps from a passenger stepping through the door of the facility all the way to the passenger sitting in an aircraft leaving the controlled airspace (or vice versa) needs to be considered; then the throughput or capacity is determined by the most constraining link in the chain — the bottleneck. While conventional airport's throughput equals the runway capacities as the dominating bottleneck [74], it was shown in publication #3 [12] that this approach is deficient for vertiports.

Mixed-Integer Programming Approach

The throughput method described in the following asks the questions of "how much throughput can be achieved on a given area". A MIP problem maximizing throughput (see Equation 3.1 [9]) is formulated as follows: the throughput T is the maximum possible throughput of the bottleneck (i.e. the throughput of the element i with the lowest throughput). The throughput of one element T_i (pad, gate or taxiway) is the number n of the elements of that type n_i multiplied by $1\,hour$ divided by a factor k_i and the time needed for one process t_i. k is the number of processes (e.g. boarding, approach, etc.) needed to fulfill one throughput. The definition of “1 throughput” as shown in Figure 3.5 encompasses the following chain of steps: approach, taxi to gate, turnaround at gate (including boarding), taxi to pad, departure.

$$\begin{aligned} &\text{maximize} && T \\ &\text{subject to} && T = \min_{\forall i} T_i, \quad i = pad, taxi, gate \\ &\text{with} && T_i = \frac{n_i * 1h}{k_i * t_i} \end{aligned} \tag{3.1}$$

The number of elements and geometric distribution is determined by an optimizing algorithm that was first published in [9]. Later the model was expanded and a detailed list of geometric rules is described by Hack Vazquez in [113]. The software code is implemented in *MATLAB R2019a*. In Appendix B.2 look-up tables can be found that will aid first-order estimation of vertiport throughput without needing access to the MIP software.

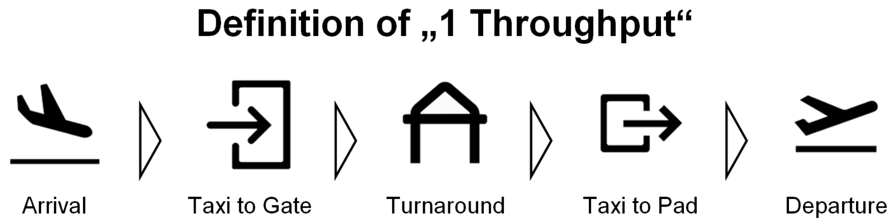


Figure 3.5 Definition of throughput including two air movements (approach and departure) [9].

Baseline Scenario

Main factors for the MIP-based model are on one hand the maximum dimension of the vehicles and its number of seats. A review of prominent eVTOLs was first published in [1] and an expanded list is shown in Table 3.6. On the other hand, the throughput of an optimized layout depends on the length of various processes, namely (1) approach and departure time, (2) taxiing time determined by taxiing speed and layout geometry, (3) boarding and de-boarding time and (4) fixed turnaround time at the gate driven by charging time. Further factors with smaller impact are intermediate processes such as starting and stopping motors, taxiing mode and minimum distance FATO/FATO. [1] defines a baseline case as shown in Table 3.7 derived from parameter value specifications in publication #2 [2].

Table 3.6 Scouting of prominent eVTOLs designs and their relevant data for ground operations (expanded from [1], all sources accessed on 14.8.2022).

Company and name	Configuration	PAX	Maximum dimension $[m]$
Airbus CityAirbus[5] (defunct)	MC	4	7.9
Airbus Vahana[6] (defunct)	Tilt	2	6.25
Archer Maker[7]	Tilt / L+C	5	12.2
Autoflight V1500[8]	L+C	4	12.8
Bell Nexus 4EX[9] (concept)	Tilt	5	12.2
Beta ALIA-250[10]	L+C	6	15.2
eHang 216[11]	MC	2	5.16
Joby S4[12]	Tilt	5	11.6
Lilium Jet[13]	Tilt	7	13.9
Pipistrel 801[14] (concept)	L+C	5	13.7
UBER[15] (concept)	Tilt	4	15.2
Volocopter VoloCity[16]	MC	2	11.3
Wisk Cora[17]	L+C	2	11.0

[5] https://transportup.com/airbus-cityairbus/
[6] https://www.airbus.com/en/innovation/zero-emission/urban-air-mobility/vahana
[7] https://evtol.news/archer-maker
[8] https://www.autoflight.com/en/products/
[9] https://evtol.news/bell-nexus-4ex/
[10] https://www.beta.team/aircraft/
[11] https://www.ehang.com/ehangaav
[12] https://www.futureflight.aero/aircraft-program/joby-evtol
[13] https://lilium.com/newsroom-detail/technology-behind-the-lilium-jet
[14] https://www.futureflight.aero/aircraft-program/801-evtol
[15] https://s3.amazonaws.com/uber-static/elevate/Summary+Mission+and+Requirements.pdf
[16] https://www.volocopter.com/solutions/volocity/
[17] https://wisk.aero/aircraft/

Table 3.7 Specification of parameter values for baseline scenario ([1] based on publication #2 [2]).

Parameter	Value
Approach and landing time	99.2 s
Taxi speed	3.25 m/s
Taxi mode	hover
Start/stop engines time	4.75 s
Passenger boarding time	92.7 s
Passenger de-boarding time	92.5 s
Take-off and departure time	72.2 s
Maximum dimension vehicle	11.3 m
Tip-to-tip span vehicle	11.3 m
Minimum distance FATO/FATO	200 ft (61 m)
Number of passengers	2
Turnaround time at gate	30 min

Simulation Study

In the following the MIP method will be put into practice using the baseline scenario as defined in Table 3.7. A simulation study was conducted taking *VoloCity* as reference vehicle for areas from $100 - 10,000\,m^2$. The step size between areas is $100\,m^2$ and each area was considered in three variations as rectangles with aspect ratios 1:1, 1:2 and 1:3, yielding a total of 300 scenarios.

The resulting throughputs for each area are shown in Figure 3.6 on the left. The throughput of each scenario divided by its area is shown in the center, which allows for comparing space efficiency of different sizes of vertiports. Lastly, all area-normalized values are aggregated into a box-plot on the right side of Figure 3.6 with a median value of $0.0053\,PAX/h/m^2$. [125] defines this value as a performance indicator called "hourly passenger throughput per area." The same process is applied for all eVTOLs from Table 3.6 and for different turnaround times; the rules-of-thumb are shown in Table 3.8.

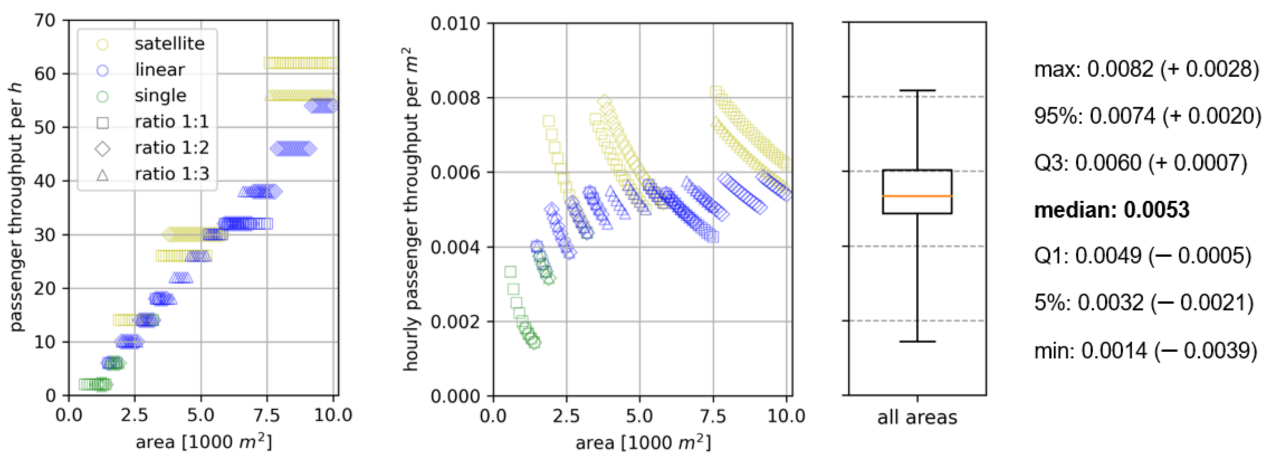


Figure 3.6 Throughput study based on *VoloCity* and baseline scenario: passenger throughput per hour (left), hourly passenger throughput per area (center), rule-of-thumb (right).

Table 3.8 Rules-of-thumb for vertiport throughput of prominent eVTOL designs (median value of "hourly passenger throughput per area" [$PAX/h/m^2$]; ranges correspond to 5th and 95th percentile).

Company and name	Boarding only	30 min charging	60 min charging
Airbus CityAirbus	$0.0379^{+0.0272}_{-0.0105}$	$0.0217^{+0.0071}_{-0.0064}$	$0.0111^{+0.0025}_{-0.0032}$
Airbus Vahana	$0.0271^{+0.0275}_{-0.0099}$	$0.0175^{+0.0049}_{-0.0055}$	$0.0091^{+0.0018}_{-0.0018}$
Archer Marker	$0.0209^{+0.0097}_{-0.0099}$	$0.0113^{+0.0047}_{-0.0061}$	$0.0056^{+0.0021}_{-0.0028}$
Autoflight V1500	$0.0168^{+0.0084}_{-0.0088}$	$0.0081^{+0.0032}_{-0.0041}$	$0.0039^{+0.0013}_{-0.0020}$
Bell Nexus 4EX	$0.0209^{+0.0097}_{-0.0099}$	$0.0113^{+0.0047}_{-0.0061}$	$0.0056^{+0.0021}_{-0.0028}$
Beta ALIA-250	$0.0134^{+0.0055}_{-0.0074}$	$0.0085^{+0.0035}_{-0.0055}$	$0.0039^{+0.0016}_{-0.0020}$
eHang 216	$0.0308^{+0.0435}_{-0.0136}$	$0.0225^{+0.0093}_{-0.0061}$	$0.0133^{+0.0043}_{-0.0038}$
Joby S4	$0.0231^{+0.0104}_{-0.0106}$	$0.0125^{+0.0050}_{-0.0052}$	$0.0063^{+0.0021}_{-0.0031}$
Lilium Jet	$0.0163^{+0.0062}_{-0.0075}$	$0.0120^{+0.0044}_{-0.0076}$	$0.0057^{+0.0019}_{-0.0029}$
Pipistrel 801	$0.0159^{+0.0064}_{-0.0071}$	$0.0088^{+0.0031}_{-0.0053}$	$0.0042^{+0.0013}_{-0.0021}$
UBER	$0.0121^{+0.0058}_{-0.0061}$	$0.0056^{+0.0024}_{-0.0036}$	$0.0026^{+0.0011}_{-0.0013}$
Volocopter VoloCity	$0.0123^{+0.0066}_{-0.0044}$	$0.0053^{+0.0020}_{-0.0021}$	$0.0026^{+0.0008}_{-0.0013}$
Wisk Cora	$0.0129^{+0.0071}_{-0.0048}$	$0.0056^{+0.0021}_{-0.0022}$	$0.0028^{+0.0009}_{-0.0014}$

The performance indicator "hourly passenger throughput per area" shown in Table 3.8 can be applied as a rule-of-thumb as follows. Assuming the vertiport airfield has an area of $2,000\,m^2$ and the *Joby S4* vehicle is operated which might need 30 minutes for charging, the expected passenger throughput would be $0.0125\,PAX/h/m^2 * 2,000\,m^2 = 25\,PAX/h$. The 95th percentile would be at $+10.0\,PAX/h$ and the 5th percentile at $-10.4\,PAX/h$. Therefore, on the given area a throughput of 9 to 35 passengers per hour can be expected with a confidence of 90 % .

3.2 Vertiport Demand and Operations

Vertiport airfield operations are the central focus of this thesis and in order to capture operational dynamics it was decided to use agent-based modeling and simulation. In this section, first, the vertiport model (Section 3.2.1) and software framework (Section 3.2.2) will be described; second, the nature of demand profiles is discussed (Section 3.2.3); third, the pre- and post-simulation analysis capabilites of the framework are shown 3.2.4); and fourth, the results of simulation studies are summarized (Section 3.2.5). At the end a vertiport design heuristic is presented in Chapter 5, which captures the accumulation of this thesis' work. For a more detailed description of each part, the reader is referred to the five publications that were published in the context of this method and topic: the titles and classifications of their functions within this thesis are listed in Table 3.9.

Other publications investigating vertiport airfield operations are discussed in publication #1 [77]. The distinct quality of this thesis is the combination of high-fidelity analysis of individual scenarios through simulation, while at the same time spanning a wide range of possible scenarios through simulation studies. All other research is either limited to low-fidelity analysis of vertiport operations; or a small number of scenarios.

Table 3.9 Overview of publications in the context of vertiport operations simulation.

Title	Function	DOI
Ground Operation on Vertiports – Introduction of an Agent-Based Simulation Framework	Explain software architecture of ABMS framework.	10.2514/ 6.2021- 1898
Identification of Driving Processes for Vertiport Operations Using Agent-Based Simulation	Show pre- and post-simulation analysis capabilities. Identify demand-related drivers of operations.	10.2514/ 6.2022- 0215
Vertiport Operations Modeling, Agent-Based Simulation and Parameter Value Specification	Describe vertiport model. Identify layout-related drivers of operations. Define and select parameters and specify their values.	10.3390/ electronics 11071071
Simulation of Individual Aircraft and Passenger Behavior and Study of Impact on Vertiport Operations	Describe stochastic model extension. Study impact of stochastics in demand profiles and agent characteristics.	10.2514/ 6.2022- 4074
A Vertiport Design Heuristic to Ensure Efficient Ground Operations for Urban Air Mobility	Synthesize and expand studies of operational drivers. Quantify study results and create design heuristic.	10.3390/ app 12147260

3.2.1 Model

The vertiport airfield model as depicted in Figure 3.7 consists of three types of elements: (1) pads for vertical take-off and landing, which are the interface towards the airspace surrounding the vertiport. (2) Gates for boarding and de-boarding of passengers, which are the interface towards the terminal where the pre-flight passenger processing happens. (3) Stands for parking vehicles during off-peak times. These three elements are connected through taxi lanes. In this virtual environment, two types of agents can move and interact: vehicles and passengers. To simulate a day of operations, the simulation needs four types of inputs: (A) a vertiport layout given by the coordinates of the centers of the three elements described above; (B) a list of plans, which consists of requests of passengers and arrivals of vehicles; (C) an initial population, which are the vehicles parked on the vertiport at the start of the simulation; (D) a list of parameter values defining the length of individual processes occuring on the airfield. Together, inputs A to D make up a scenario. The simulation is time-step based and uses a default time-step of 1 second. A full explanation of the model is given in publication #2 [2].

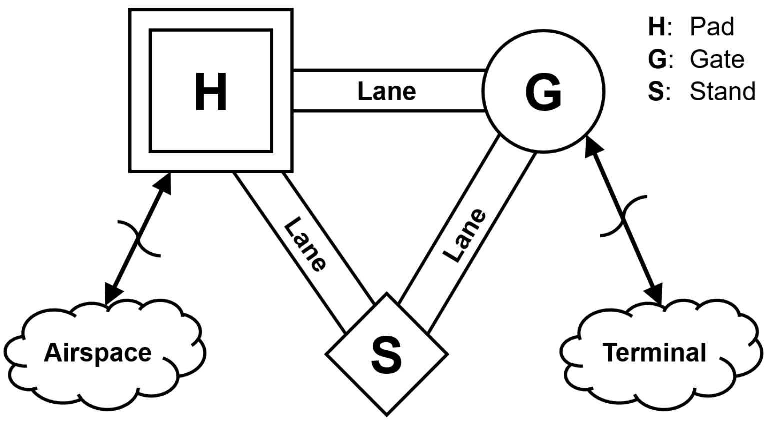


Figure 3.7 Depiction of vertiport airfield model (adapted from [10]).

Relevant parameters for the model were selected and their values were calibrated through a process involving literature review and expert interviews as described in publication #2 [2]. The resulting parameter value specification is given in Table 3.10 including an indication of statistical confidence. All parameters are further illustrated in Figure 3.8. At the point of writing not all parameters present in the model are implemented in the simulation framework (see Section 3.2.2); instead the simulation runs based on the aggregation of parameters as shown in Table 3.11.

Table 3.10 Parameter value specification of vertiport model (adapted from publication #2 [2]).

ID	Parameter	Value	Unit	Confidence
B1/B6	Terminal to/from gate	31.9	s	low
B2	Enter gate	19.7	s	low
B3	Boarding	73.0	s	medium
B4	De-boarding	65.8	s	medium
B5	Leave gate	26.7	s	low
T2	Passive taxiing	2.63	m/s	low
T1/T3	(De-)mounting passive taxiing device	27.0	s	low
T4	Active taxiing	2.15	m/s	low
T6	Hover taxiing	3.25	m/s	low
T5/D1	Start engine	4.50	s	low
T7/A3	Stop engine	5.00	s	low
A1	Enter airspace	46.3	s	medium
A2	Final hover	22.9	s	low
D2	Initial hover	13.5	s	medium
D3	Leave airspace	28.7	s	medium
A4/D4	“Cool-down” after landing/take-off	30.0	s	medium
E3	Charging speed	311	kW	low
E2	Battery capacity	133	kWh	high
E1	Energy loss	7.17	%	medium
E4	Swapping time	349	s	medium

Data from the expert interviews was later used to expand to vertiport airfield model towards stochastic modeling of agent characteristics. The model extension using skewed normal distributions was developed by Cheng and is described in [4]. As mentioned above, only the aggregation of parameters as shown in Table 3.11 is currently implemented in the simulation software. The implementation of non-aggregated values is among the suggested future work as described in Section 6.2.

Table 3.11 Aggregated vertiport operations parameters as currently implemented in the software [3].

Parameter	Unit	Expected value μ	Standard deviation σ
Vehicle approach	s	46.4	23.7
Vehicle departure	s	41.8	23.3
Vehicle taxiing speed	m/s	3.01	1.55
Passenger boarding	s	111	42.8
Passenger de-boarding	s	81.4	26.0
Passenger walking from terminal to gate	s	71.4	20.2
Passenger walking from gate to terminal	s	71.4	20.2

3.2.2 Software

The ABMS framework is a stand-alone piece of software, which was built from scratch in cooperation with Amirzada [10] and was continuously updated and expanded. The first functional version of the software framework is described in [13]. It is written in the programming language *Python 3.8* using both procedural programming (for data-formatting and post-simulation analysis) and object-oriented programming (for simulation). Its conceptualization of transport networks and software design patterns are inspired by *MATSim*

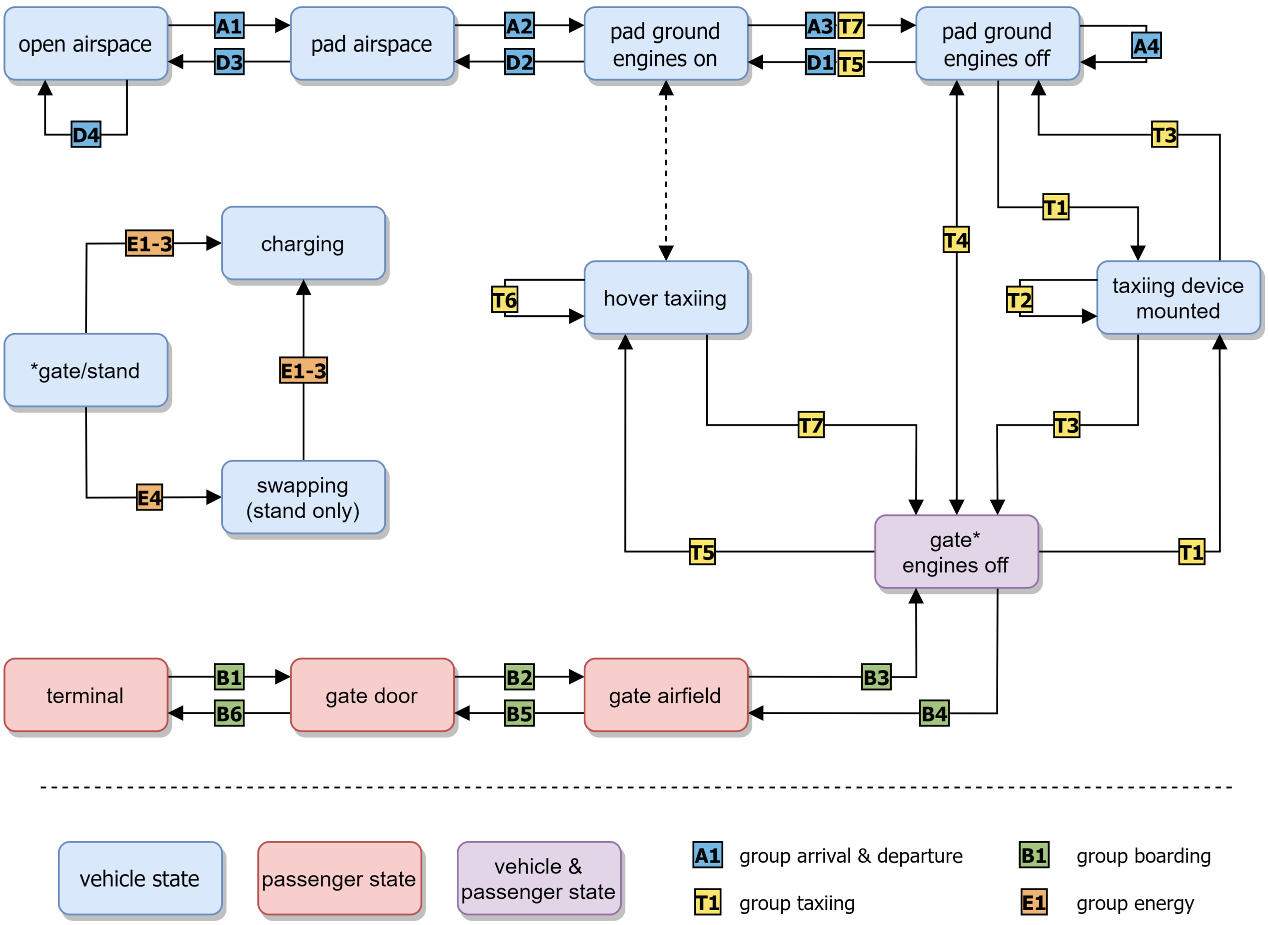


Figure 3.8 Visualization of vertiport model parameters and state changes as shown in publication #2 [2].

[126]. The runtime of a single scenario can be anywhere from a few seconds up to almost one hour. The runtime of the full package of post-simulation analysis (see Section 3.2.4) ranges from 5-10 minutes.

The ABMS framework will be described in detail in the appendix; the software architecture including an overview of the file structure and a "How-To" for running simulations is presented in Appendix A.2. Further, Appendix A.1 lists all updates since the first publication by Amirzada [13] and Appendix A.3 explains the included extensions and how to use them. Lastly, Appendix A.5 contains the full list of rules that determine the decision-making and actions of all agents in the simulation.

One downside of ABMS is the near-impossibility of retracing all cause-and-effect chains and the thereby quasi non-deterministic nature of the system. In order to find falsely implemented decisions or actions based on sample tracing, the framework provides two debugging scripts: first, a script to trace an agent or element through all or part of the operations highlighting all state and location-changes (name: "track_object.py"). Second, a script giving a detailed account of all states and locations of all agents and elements at a chosen moment of operations (name: "track_moment.py"). The traced samples can then be compared to expected behavior to help narrow down the search for falsely implemented decisions or actions.

3.2.3 Demand Profile Generation and Analysis

The ABMS framework described in this thesis has the capability to generate demand profiles based on six input parameters. A demand profile is a combination of uniform and normal distributions. The most common profile has a bi-modal shape, as is discussed in Appendix B.5.3, and will therefore be used for illustrating the parameters in Figure 3.9. Three other profiles were also considered in the following studies: uniform, single-peak and four peaks. All six parameters needed to generate a demand profile are described in the following, summarized in Table 3.12 and illustrated in Figure 3.9. The parameters are:

(A) the number of peaks; (B) the time of each peak; (C) the breadth if each peak, which equals $6\,\sigma$ of the normal distribution; (D) the ratio between base and peak demand (expressed as how many movements will be modeled through uniform and normal distributions, respectively); (E) demand magnitude, which is the total number of movements within the operational window; and (F) start and end time of the operational window.

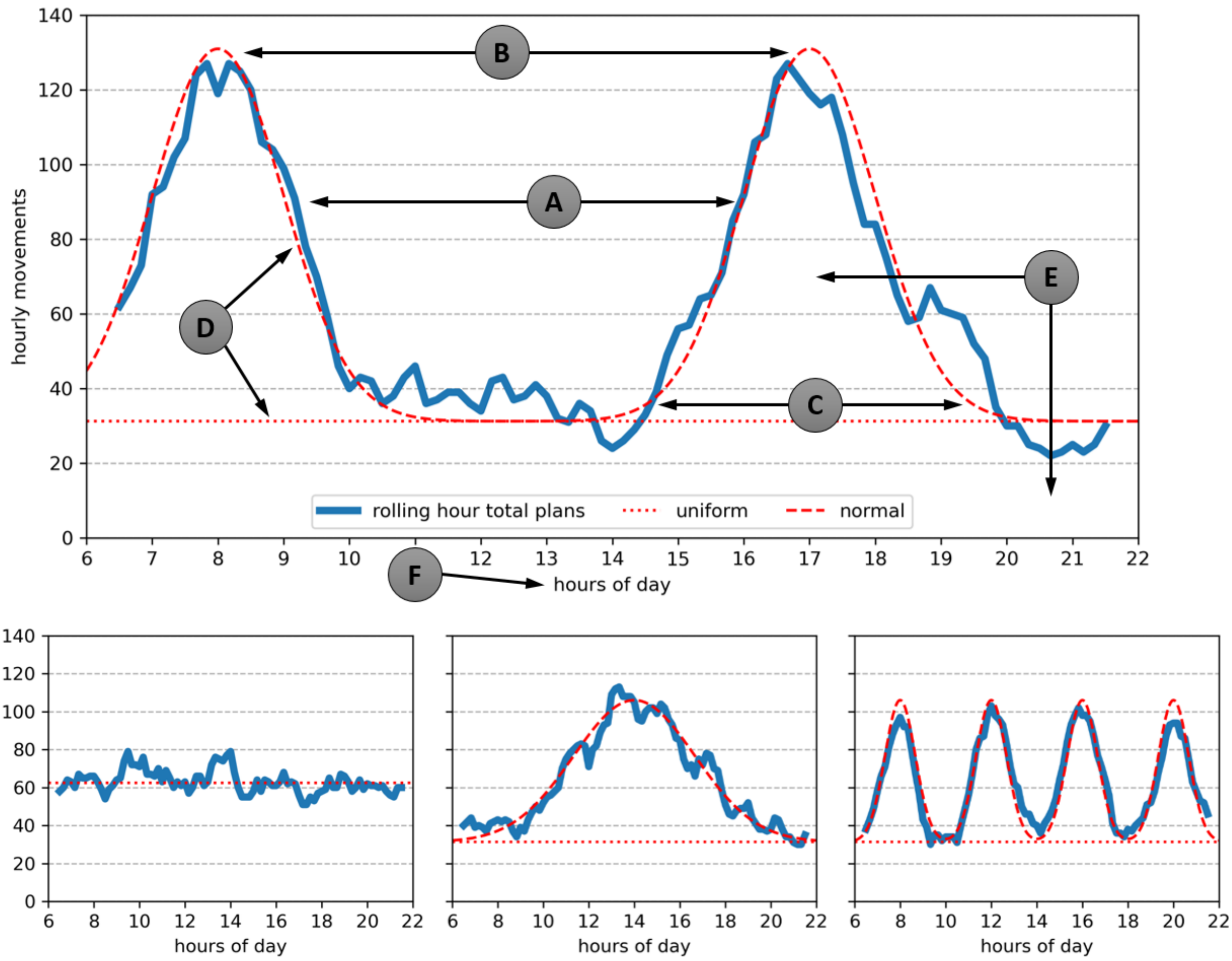


Figure 3.9 Illustration of parameters needed to generate four types of demand profiles: uniform (bottom left), single-peak (bottom center), bi-modal (top), four peaks (bottom right).

Table 3.12 Parameters needed to generate a demand profile.

ID	Description	Example value
A	Number of peaks	2
B	Time of peaks	8 am, 5 pm
C	Breadth of peaks	6 hours
D	Share of base demand	50 %
E	Demand magnitude	1000 per day
F	Operational window	6 am – 10 pm (16 hours)

After generating demand profiles the ABMS framework further provides the capability to analyze them. There are seven characteristics of demand profiles which can be visualized in a time-resolved manner (see Figure 3.10) and printed out as time-aggregates (see Table 3.13). The descriptions of the characteristics are given in Table 3.13 including the values of the example case (the IDs correspond to the visualization in Figure 3.10). These analyses are happening pre-simulation and are helpful ways of characterizing scenarios by reducing the dimensionality of results. A scenario can be expressed in just a handful of representative values, which then allows for hundreds of scenarios[18] to be compared in simulation studies.

Table 3.13 Pre-simulation analysis results of demand profile.

ID	Description	Maximum value from example
A	Hourly movements	165
B	Hourly arrivals	79
C	Hourly departures	92
D	Imbalance with excess hourly arrivals	22
E	Imbalance with excess hourly departures	20
F	Stock of vehicles	39
G	Stock of passengers	34

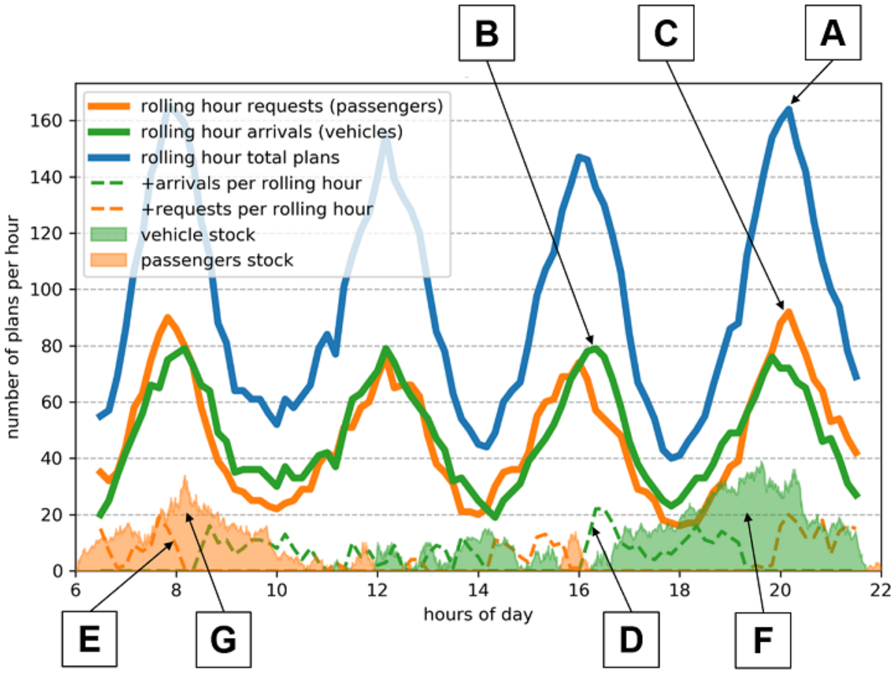


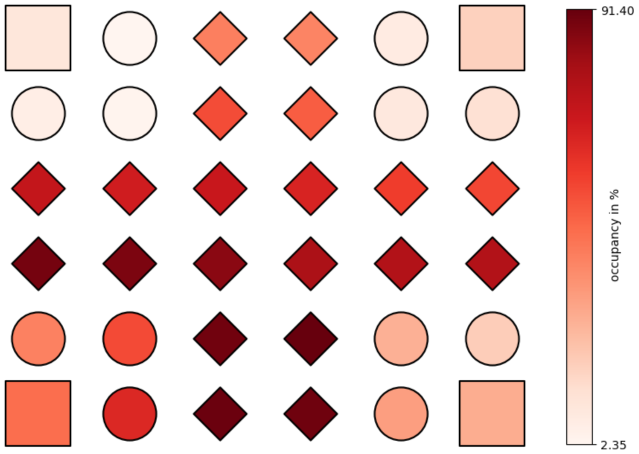
Figure 3.10 Visualization of demand profile and illustration of pre-simulation analysis results.

3.2.4 Simulation Analysis

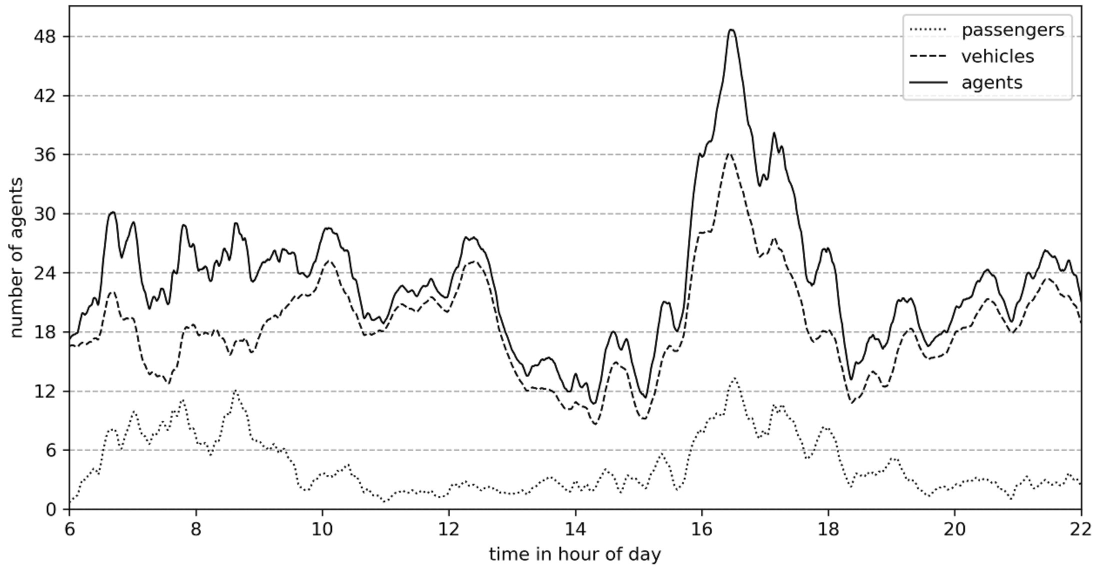
There are three types of post-simulation analysis in the ABMS framework, of which one representative example each will be shown in Figure 3.11. More visualizations are published in [11]. The three types are (1) layout-based visualizations who show the spatial layout with a color-code representing the time-aggregate of a chosen state (see Figure 3.11a). In contrast, (2) time-based visualizations show information in a space-aggregated time-resolved fashion and thereby the progression over the length of operations (see Figure 3.11b). Lastly, (3) bin-based visualizations, mostly applied to agents, indicate the distribution of ratios of states across all agents (see Figure 3.11c). For each type, the software allows to quickly choose between different elements, agents and states; and it provides a range of hybrid analysis options to

[18]While creating the vertiport design heuristic shown in publication #3 [12] over 750 scenarios were simulated and the results were condensed to six drivers of operations. This large-scale analysis is only possible through the mentioned characterization of scenarios and reducing the dimensionality of analysis.

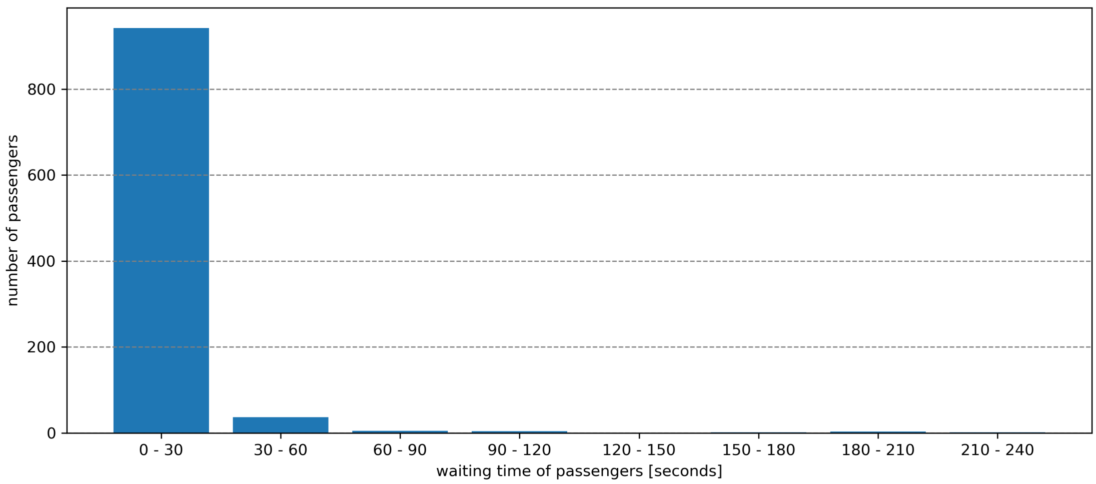
highlight customized pieces of data (see Figure 3.11d as an example). A full treatment of the framework's analysis capabilities can be found in Appendix A.4.



(a) Layout-based time-aggregated visualization: occupancy of airfield elements.

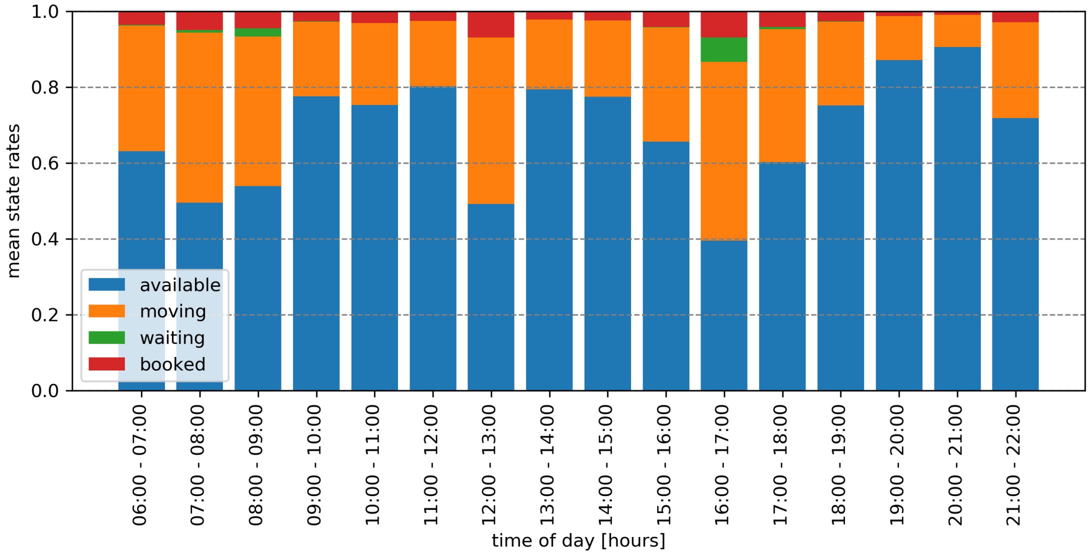


(b) Time-based space-aggregated visualization: agents on vertiport.



(c) Bin-based agent-aggregated visualization: waiting time of passengers.

Figure 3.11 Post-simulation scenario-related visualizations (examples from baseline scenario in [11]).



(d) hybrid visualization: vehicle states.

Figure 3.11 Post-simulation scenario-related visualizations (examples from baseline scenario in [11]) (cont.).

3.2.5 Study Results

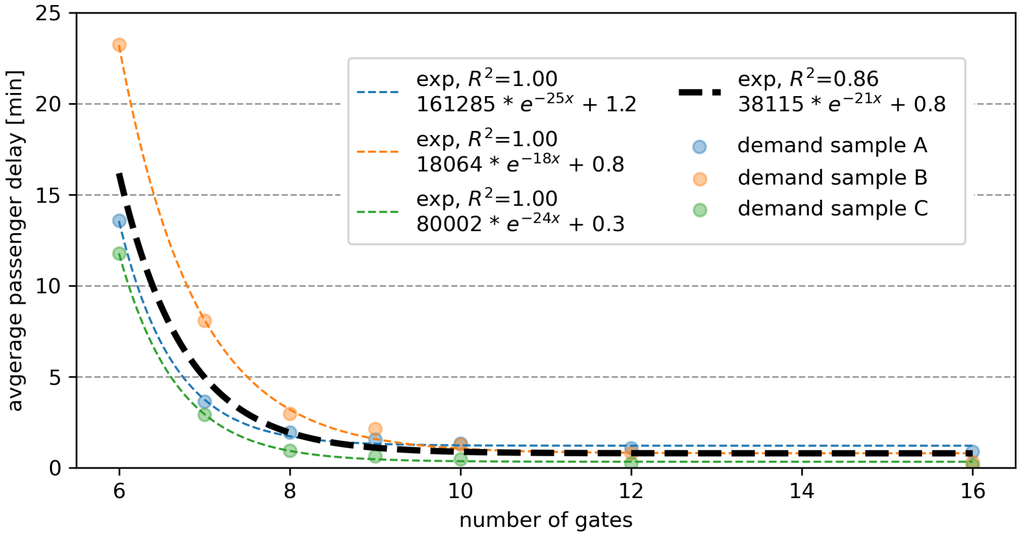
In the course of this thesis over 1,000 simulation scenarios were conducted; about half to identify drivers of vertiport operations and the other half to quantify the drivers and synthesize them into the design heuristic (see Figure 5.3). Drivers related to the following were studied: vertiport layout, demand profile and characteristics of passengers and vehicles. Starting with single-factor variation for identifying the drivers, the later scenarios included multi-factor variation while forming the design heuristic.

Layout-Related Drivers

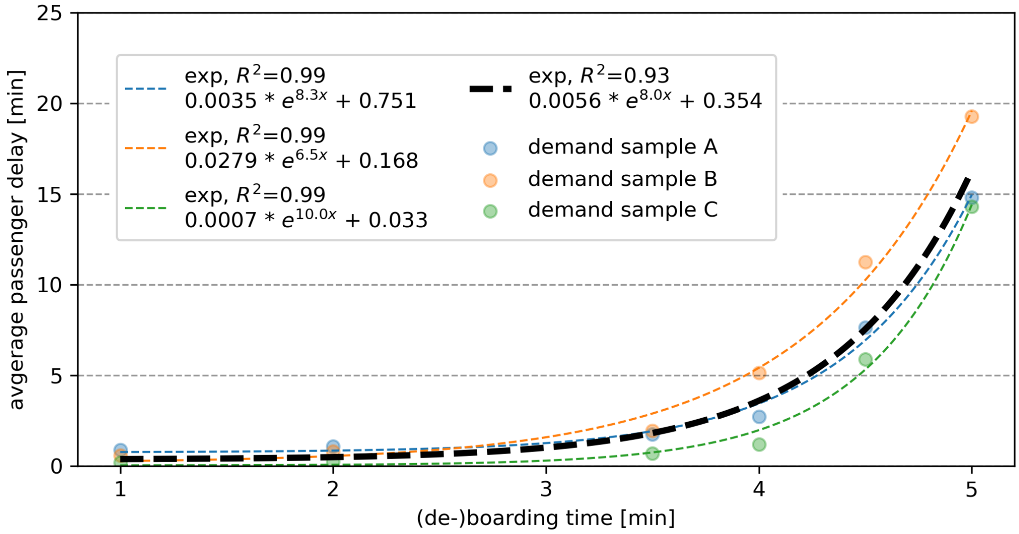
Studies on layout-related drivers were first shown in publication #2 [2]. It was found that when varying the number of pads and gates there is a region of stable operations. Then once a threshold is crossed, operations become unstable indicated through exponentially increasing delays. While the effect for pads is stronger, it is true for both pads and gates, which is one of the surprising insights: operations on gates can be bottlenecks to operations and, therefore, cannot be neglect (as is done for conventional airport capacity planning). The effect is illustrated in Figure 3.12a. The same effect was observed for varying the length of approach/departure times on pads and boarding/de-boarding time on gates. While the lengths of processes appear to have a smaller impact than the number of elements on the stability of operations, they too show exponential increases in delays (with a less prominent threshold). The average passenger delay with increasing boarding times on gates is visualized in Figure 3.12b. It can therefore be said that enlarging the time of a process has the same (qualitative) effect as reducing the number of elements. This correlation gave reason to categorize the length of processes as “layout-related” drivers, while it can be argued that they are “agent-characteristic-related” drivers.

Demand-Related Drivers

Demand-related drivers of operations were more complex to identify and quantify than layout-related drivers. The first study concerning demand was published in publication #2 [2] and showed that accumulated daily demand is generally speaking not a good indicator for the efficiency of operations. Next, time-resolved demand profiles were investigated in [11] finding more obvious correlations. The strongest correlation between demand and operational stability was for peaks in demand: if a peak was high enough (i.e. above an unknown threshold) passenger delay occurred with about half an hour time offset. The



(a) Variation of number of gates and effect on average passenger delay: prominent threshold between stable and instable operations.



(b) Variation of boarding time and effect on average passenger delay: observable threshold between stable and instable operations.

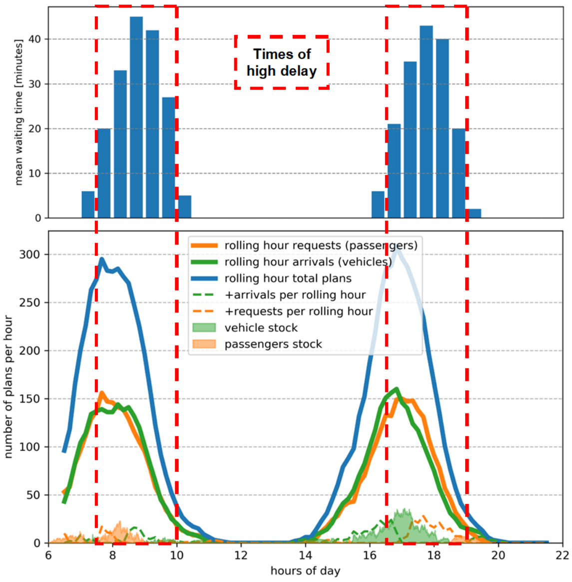
Figure 3.12 Layout-related drivers of operations (adapted from publication #2 [2]).

second strongest correlation was for imbalances between arrivals and departure causing "stock"[19]; if the stock was above a certain threshold, it caused delay immediately. In Figure 3.13 visualizations from [11] are shown to exemplify the effects of peaks in demand and stock caused by imbalances between arrivals and departures.

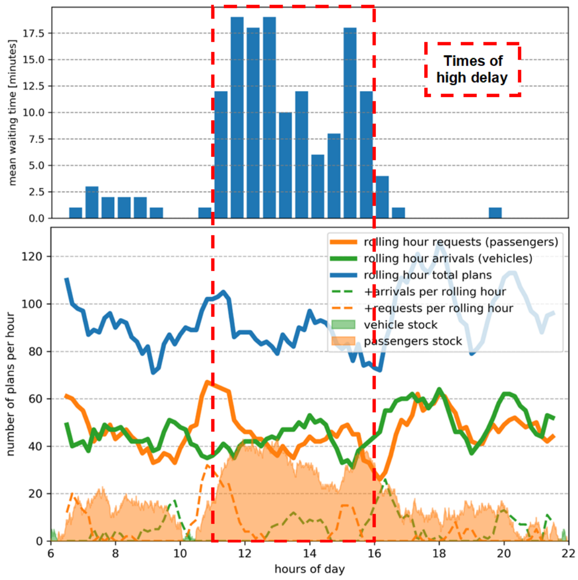
Other Drivers

Studies of passenger and vehicle characeristics were published in [3]. Here it was shown that individual variations of these characteristics have a negligible effect on operations. At the same time, it was confirmed that local variations in demand have a significant impact on operations; this observations reinforces the need to consider dynamics of operations when studying vertiports.

[19] "Stock" in the context of this thesis is defined as the increased or decreased amount of vehicles present at the vertiport caused by imbalances in arrivals and departures. These imbalances were identified as particularly strong research gaps as discussed in Appendix B.5.3.



(a) Peaks in demand have major impact on delay.



(b) Imbalances between arrivals and departures have minor impact on delay.

Figure 3.13 Demand-related drivers of operations [11].

Vertiport Design Heuristic

In publication #3 [12] the identified design drivers of vertiport airfield operations were quantified in a simulation study through multi-factor variation and finally synthesized into the vertiport design heuristic. The design heuristic is the single most valuable contribution of this thesis and is therefore prominently placed in the conclusion (Chapter 5) in Figure 5.3. In the course of the study it became apparent that while accumulated daily demand is generally not a good indicator for delay, a bi-modal distribution (with low stock) is an exception to the rule (see Figure 3.14). For reasons of discrete visualization the accumulated daily demand was therefore taken to form the design heuristic. However, when the shape of the distribution and the maximum stock is unknown it is preferable to use peak-hour demand (instead of accumulated daily demand) as the indicator of operational efficiency (see Figure 3.15).

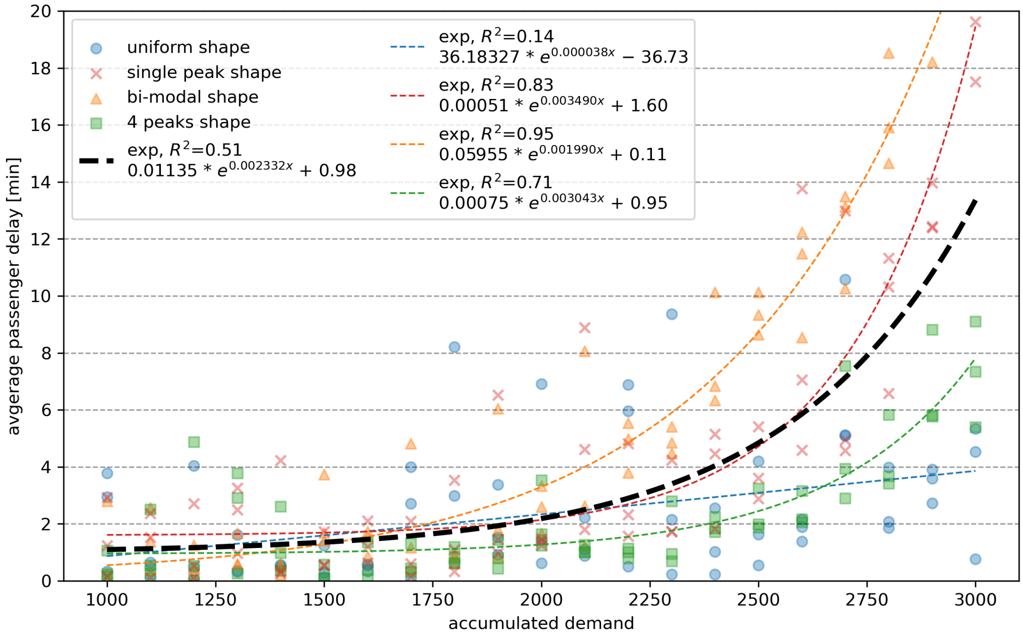


Figure 3.14 Variation of accumulated demand and mixed connection to average passenger delay as shown in publication #3 [12].

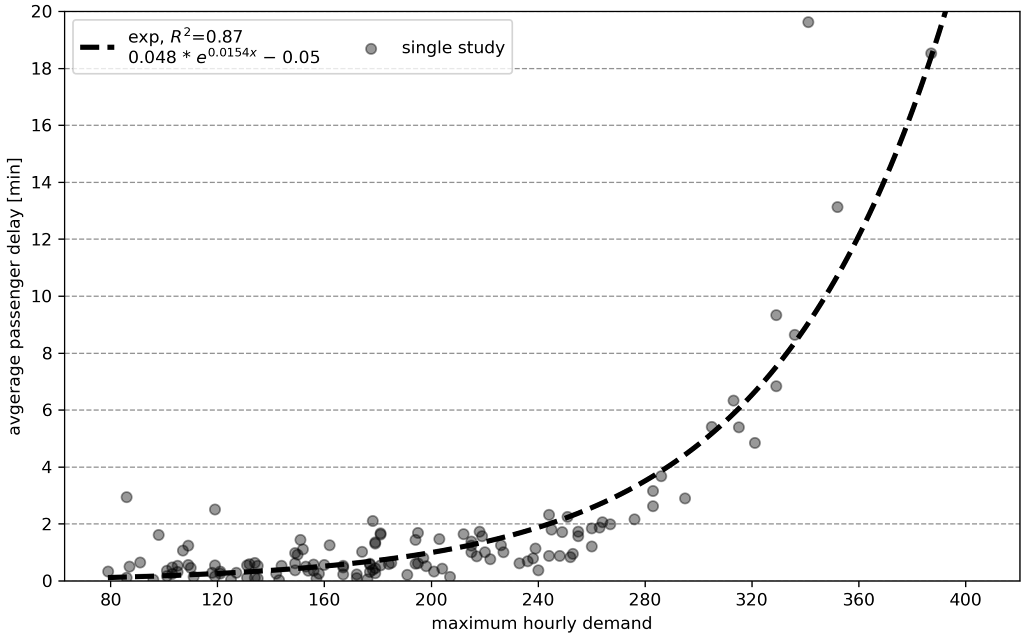


Figure 3.15 Variation of maximum hourly demand and clear connection to average passenger delay (update from publication #3 [12]).

4 Vertiport Airfield Simulation

The main body of research of this doctoral thesis is made by of three peer-reviewed articles published in international journals. The articles address the issues of literature review (Section 4.1), modeling (Section 4.2) and simulation results (Section 4.3) and are attached to this thesis. In the following sections the three articles are described including the title, a summary, authors contributions, suggested citation and a graphical abstract. The graphical abstract is meant to aid a quick understanding of the conent of each article. Further, an extended list of publications that emerged in the context of this thesis is included in Section 4.4.

4.1 Review of Vertiport Research and Regulations (Publication #1)

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

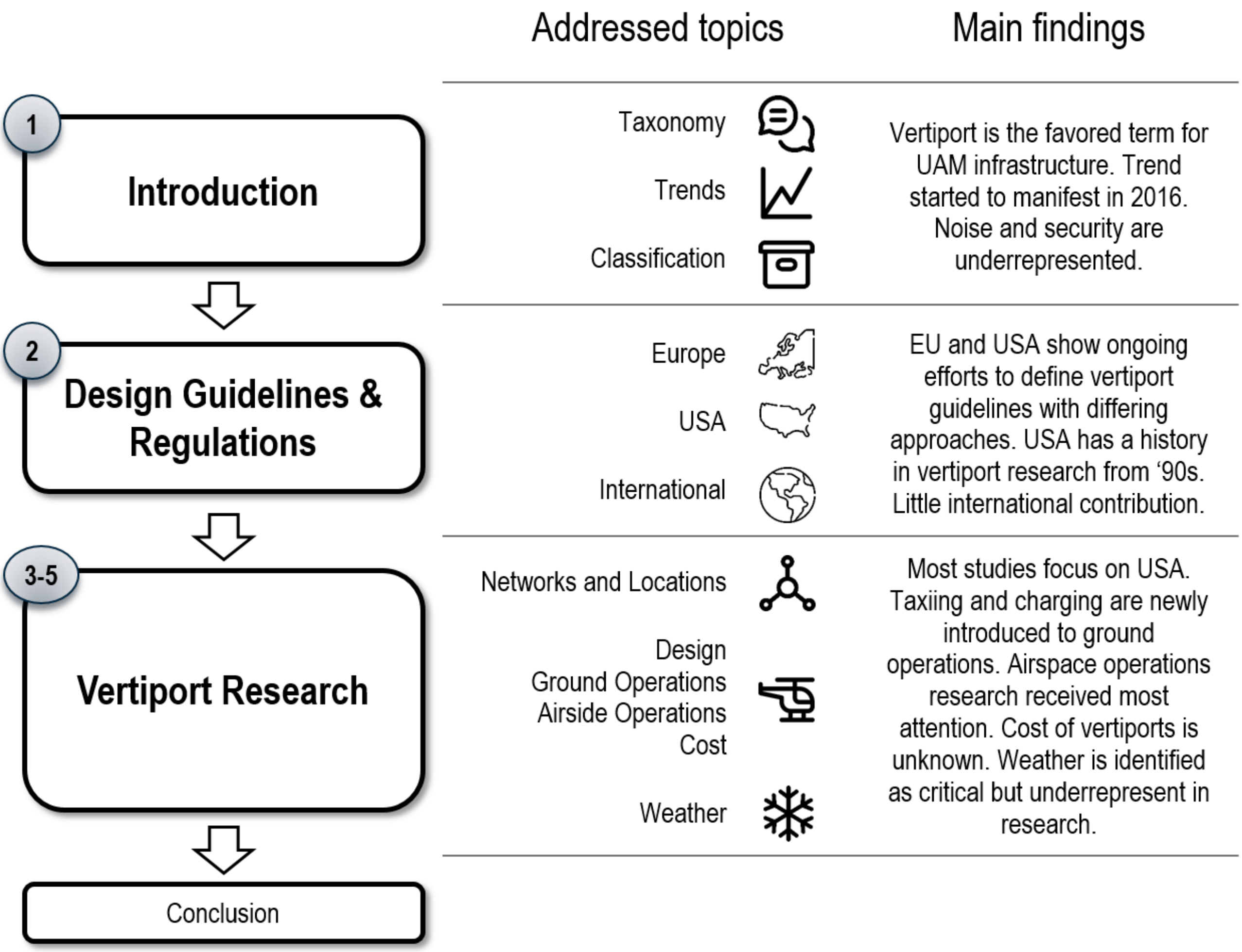


Figure 4.1 Graphical abstract of publication #1: "Urban Air Mobility: Systematic Review of Scientific Publications and Regulations for Vertiport Design and Operations".

4.1.1 Summary

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.

4.1.2 Contributions

Conceptualization, K.S., L.P.; methodology, K.S., L.P.; formal analysis, L.P.; investigation, K.S., L.P.; data curation, K.S., L.P.; writing—original draft preparation, K.S. (Sections 1.1, 2.1, 2.4, 3, 4.1.1, 4.1.2, 4.3, 4.4, 5 and 6), L.P. (Sections 1.2, 1.3, 2.2–2.4 and 4.2); writing—review and editing, K.S., L.P.; visualization, K.S., L.P.; funding acquisition, K.S.

K.S.: Karolin Schweiger (DLR)

L.P.: Lukas Preis (BHL)

4.1.3 Citation

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Article

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.

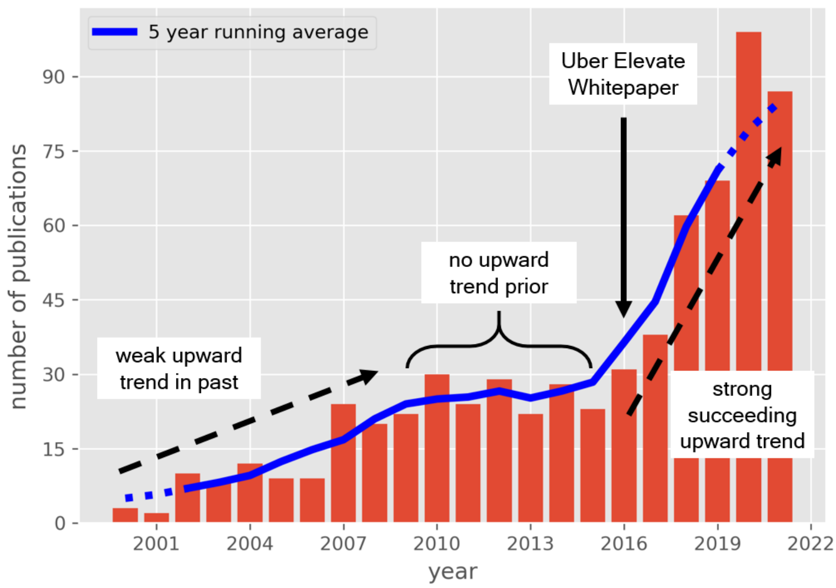


Figure 1. Publications related to UAM ground infrastructure as listed in *Scopus* after the year 2000 and in relation to the publication of *UBER*'s whitepaper in 2016 [27].

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 18 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 ine	1	1	1	1
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*.

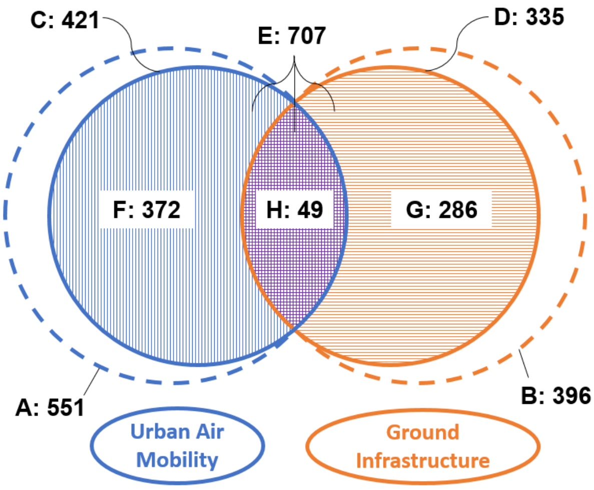


Figure 2. Overlap between databases derived from the keyword "urban air mobility" and 11 keywords related to "ground infrastructure".

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.

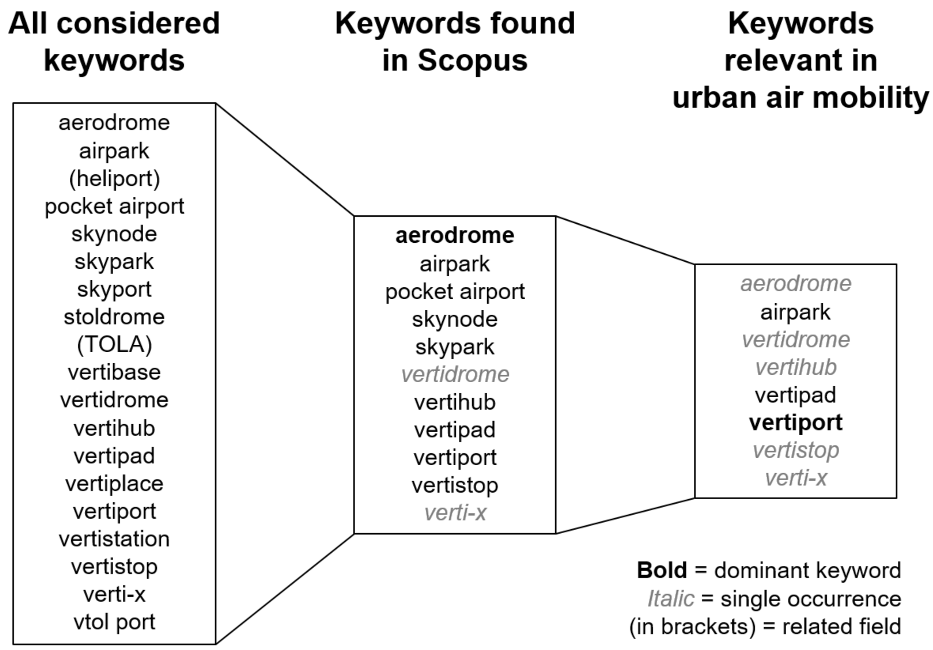


Figure 3. Selection process of keywords used to describe "ground infrastructure" in the context of "urban air mobility".

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 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.

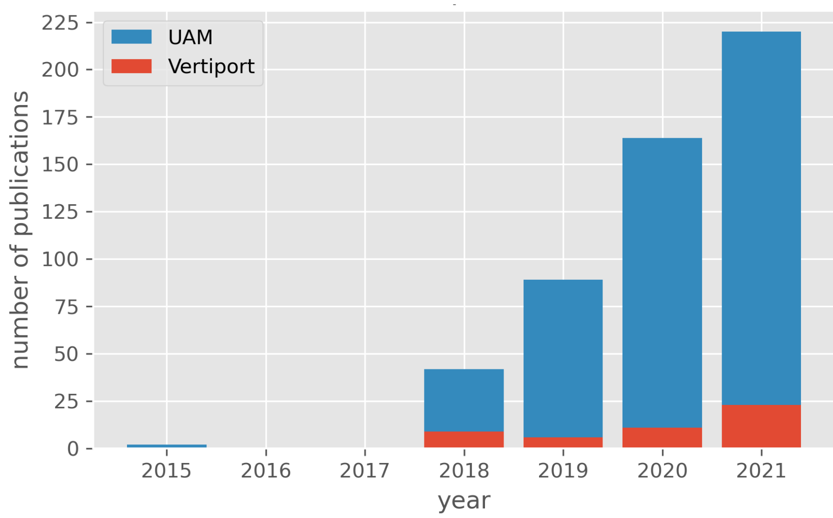


Figure 4. Trends of publication in the fields of UAM and vertiports.

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.

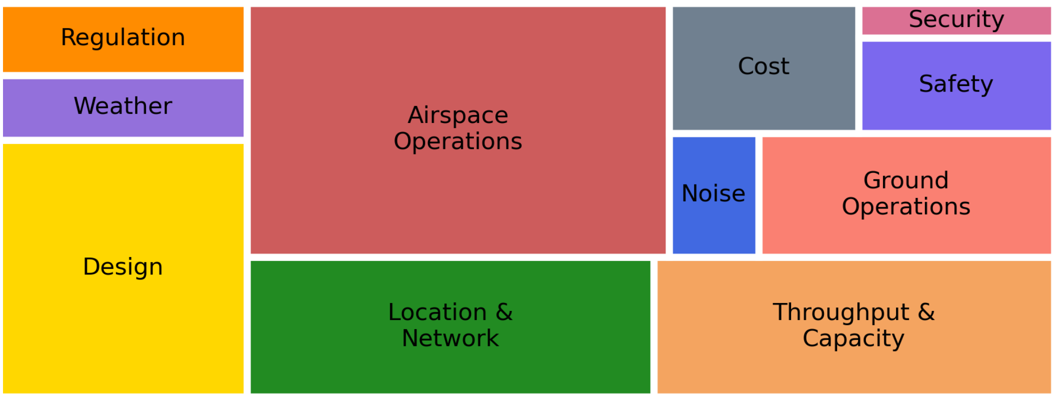


Figure 5. Classification of vertiport-related topics and their weight in the reviewed scientific literature (49 publications); size of rectangle corresponds to prominence of the topic.

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.

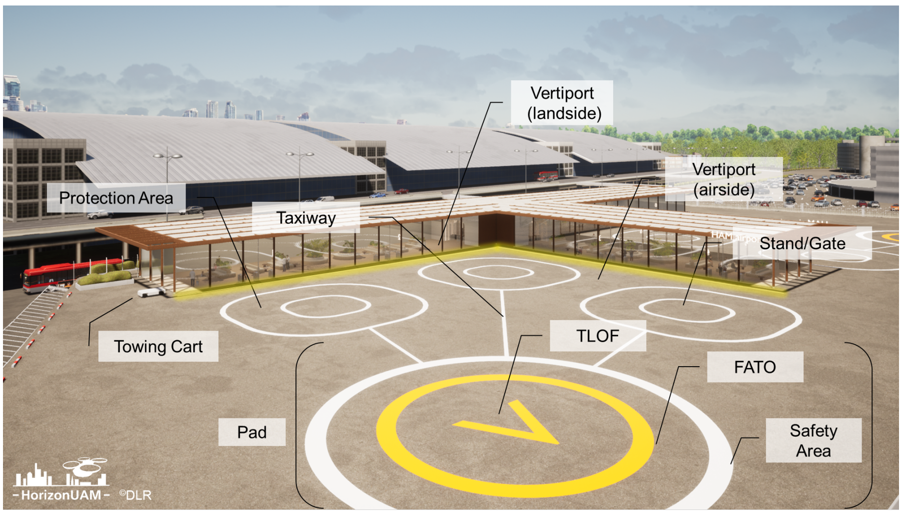


Figure 6. Vertiport topology terms used in the context of UAM.

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.

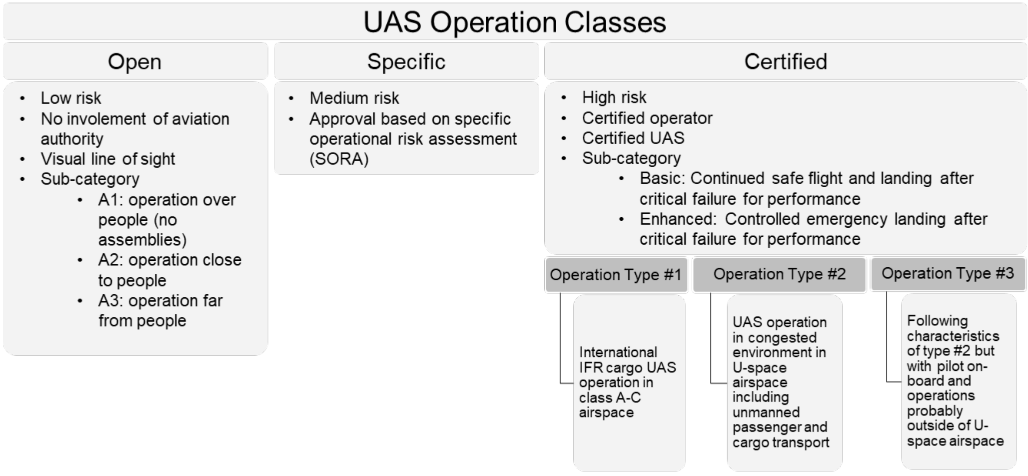


Figure 7. European UAS operation classes, subcategories and types based on [41,43,44].

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

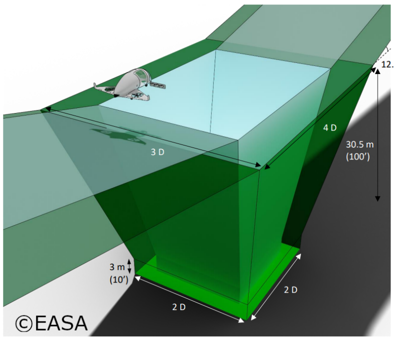
After examining the design requirements for a vertiport's airside ground topology, the airspace directly attached to the vertiport accommodating among others approach and departure paths (airside air) needs to be structured. Reviewing different regulatory proposals and guidelines, in the second publication 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.

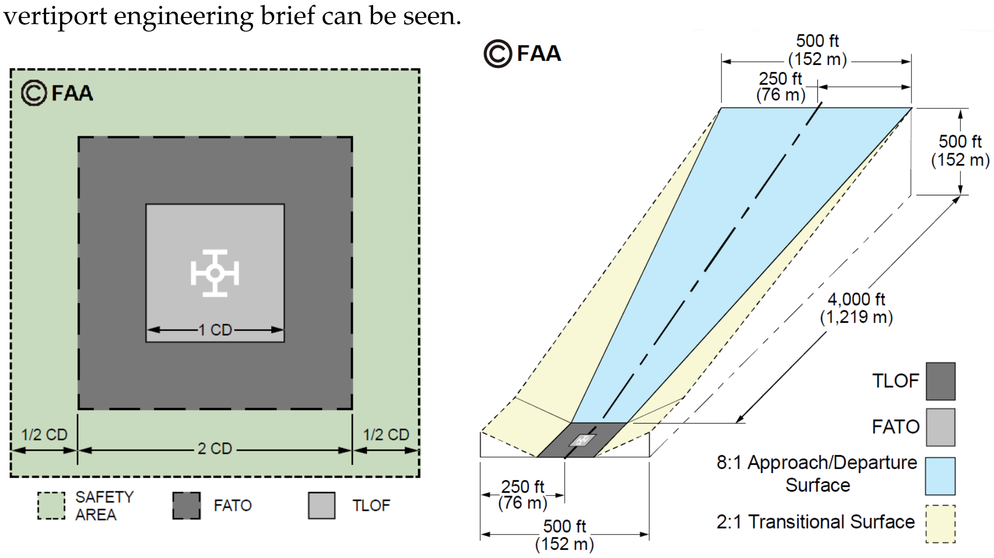


Figure 8. Dimensions of pad and approach/departure slope according to FAA engineering brief on vertiport design [18], ©FAA.

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.

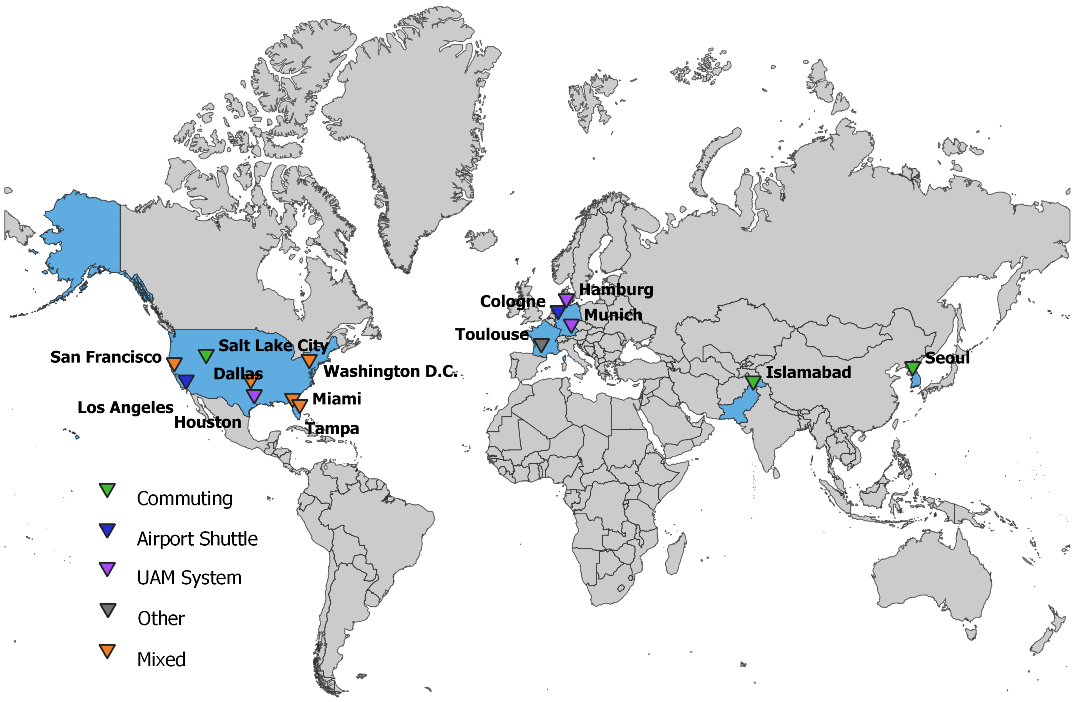


Figure 9. Vertiport network locations covered by selected scientific publications. Use-case is expressed through color-code.

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.

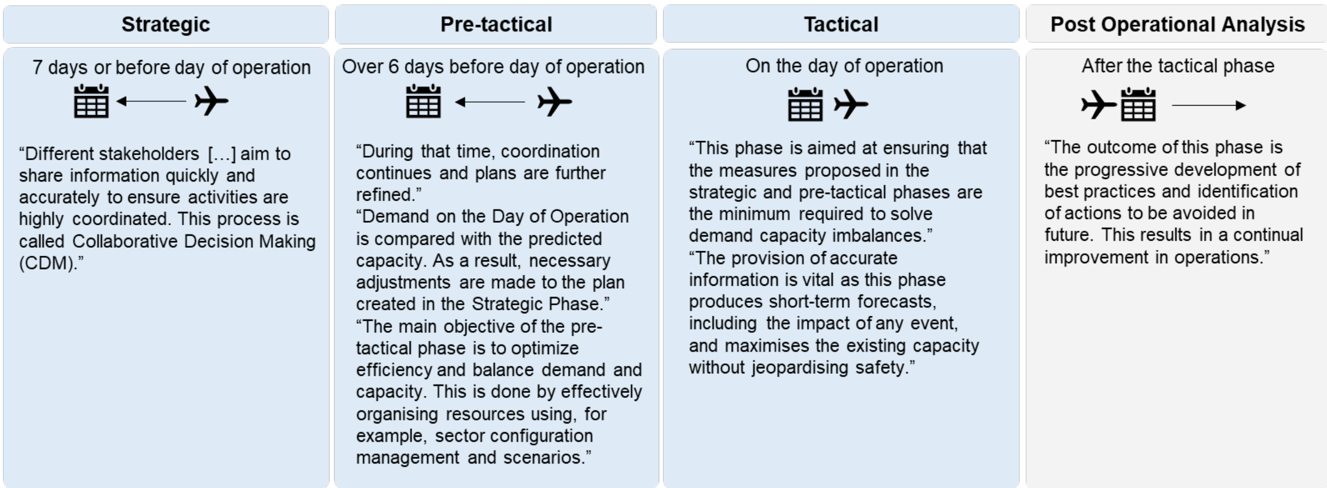


Figure 12. Air traffic flow and capacity management phases for commercial aviation according to [154]; all quotations by [154]; own depiction.

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.), [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 AM to 6 PM, 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

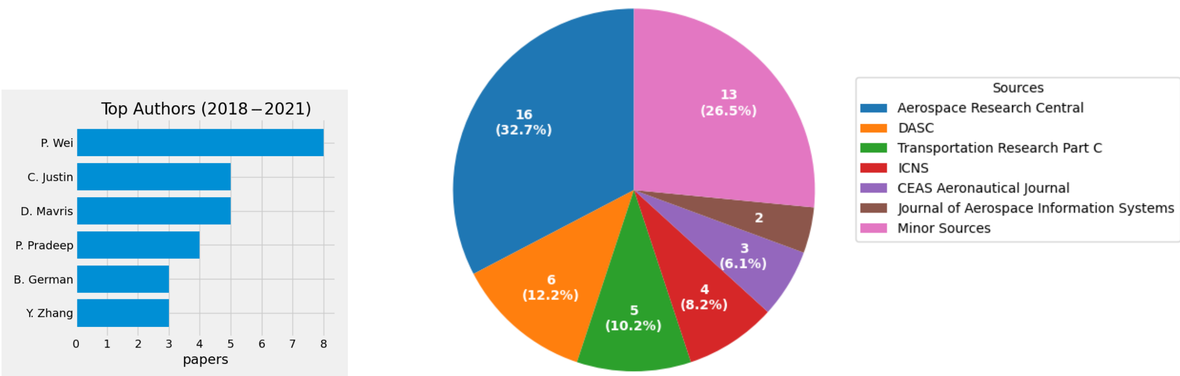
TLOF	touchdown and lift-off area
UAM	urban air mobility
UAS	unmanned aerial system
UTM	unmanned aircraft system traffic management
VFR	visual flight rules
VTOL	vertical take-off and landing

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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4.2 Vertiport Model and Agent-Based Framework (Publication #2)

Title: *Vertiport Operations Modeling, Agent-Based Simulation and Parameter Value Specification*

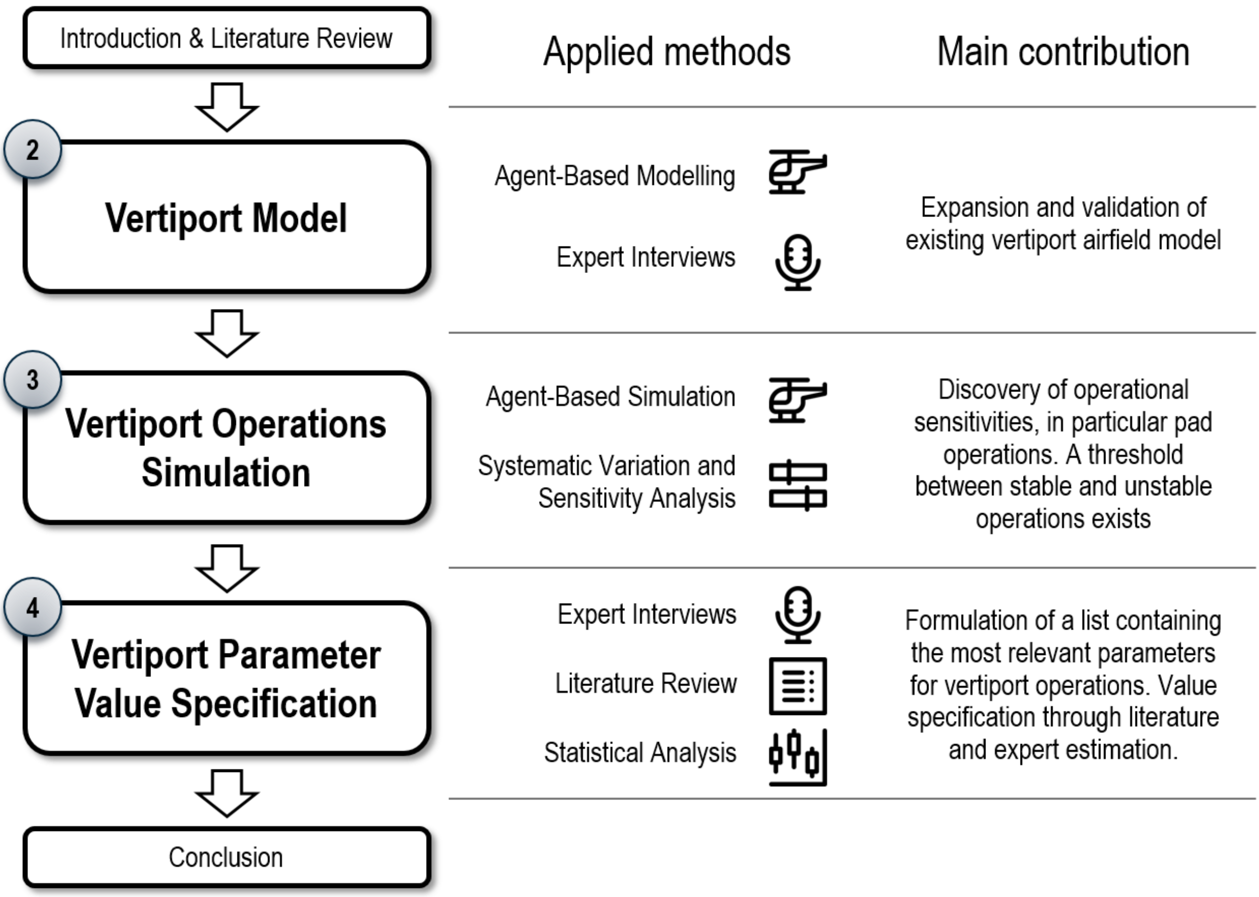

Figure 4.2 Graphical abstract of publication #2: "Vertiport Operations Modeling, Agent-Based Simulation and Parameter Value Specification".

4.2.1 Summary

Urban air mobility (UAM) is the idea of creating a future mobility market through the introduction of a new mode of aerial transport with substantial travel time advantages. A key factor diminishing travel time savings is vertiport processes. So far, vertiport throughput capacity has only been studied in a static manner using analytical methods, which has been found to be insufficient. This paper wants to increase the level of understanding of operational dynamics on vertiport airfields by being the first to apply agent-based simulation. For this purpose, an existing vertiport model consisting of pads, gates and stands was refined through two means. First, a sensitivity study with over 100 simulations was executed shedding light on the driving processes on a vertiport airfield. Second, an expert interview series with 17 participants was conducted, letting the experts evaluate the model and specify relevant parameter values. Three main results should find mention here: (1) Pad operations were identified to be most impactful on passenger delays. (2) Pad and gate processes have a threshold capacity beyond which delays increase exponentially. (3) A refined vertiport model is presented, including the 27 most relevant parameters and their value specification. In conclusion, this paper finds that optimized vertiport airfield design is crucial to UAM operations, and dynamic passenger and vehicle interactions cannot be neglected.

4.2.2 Contributions

Conceptualization, L.P. and M.H.; Methodology, L.P.; Software, L.P.; Resources, M.H.; Data Curation, L.P.; Writing—Original Draft Preparation, L.P.; Writing—Review and Editing, L.P. and M.H.; Visualization, L.P.; Supervision, M.H.

L.P.: Lukas Preis (BHL)

M.H.: Mirko Hornung (BHL)

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Article

Vertiport Operations Modeling, Agent-Based Simulation and Parameter Value Specification

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Abstract: Urban air mobility (UAM) is the idea of creating a future mobility market through the introduction of a new mode of aerial transport with substantial travel time advantages. A key factor diminishing travel time savings is vertiport processes. So far, vertiport throughput capacity has only been studied in a static manner using analytical methods, which has been found to be insufficient. This paper wants to increase the level of understanding of operational dynamics on vertiport airfields by being the first to apply agent-based simulation. For this purpose, an existing vertiport model consisting of pads, gates and stands was refined through two means. First, a sensitivity study with over 100 simulations was executed shedding light on the driving processes on a vertiport airfield. Second, an expert interview series with 17 participants was conducted, letting the experts evaluate the model and specify relevant parameter values. Three main results should find mention here: (1) Pad operations were identified to be most impactful on passenger delays. (2) Pad and gate processes have a threshold capacity beyond which delays increase exponentially. (3) A refined vertiport model is presented, including the 27 most relevant parameters and their value specification. In conclusion, this paper finds that optimized vertiport airfield design is crucial to UAM operations, and dynamic passenger and vehicle interactions cannot be neglected.

Keywords: urban air mobility; vertiport; agent-based simulation; expert interview

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1. Introduction and Literature Review

Urban air mobility (UAM) has received much attention in recent years, in both academia and the industry, with the potential of introducing a novel mode of transport into urban settings. The trend of urbanization in recent decades [1] has led to increased traffic problems and congestion, which in turn affects travel times, the environment and the overall quality of city life. UAM promises to be a fast [2] and clean [3] mode of transport. Some reports even indicate that UAM could alleviate congestion [4], while most estimations are more careful and do not expect a significant impact on the overall transportation network. A recent study even claims that the opposite could be true: when including access and egress trips to vertiports, the number of cars on the road might increase [5]. Market shares are conceivable to range between marginal significance [6] all the way up to 8% in the long haul [7]. Various market studies have tried to capture the global market potential [8–13] in the 2030s; estimates are located in tens of billions USD. This would be a relevant future mobility market, which has the potential to offer a variety of novel, intermodal services. For comprehensive and recent summaries of UAM topics, see publications by Niklaß et al. [14], Straubinger et al. [15] and Garrow et al. [16].

Should inner-city air travel become a reality, and if UAM becomes affordable to a relevant portion of the population, there could be fleets of thousands of aircraft in single metropolitan areas. This development would require highly performant infrastructure. UAM vehicles are envisioned to be fully or hybrid electric and have vertical take-off and landing (VTOL) capability (electric VTOL vehicles (eVTOLs). The infrastructure for eVTOLs, which is commonly referred to as vertiports, will need to cater throughputs in the magnitude of commercial airports [17] on the surface areas of large heliports [18]. Space in cities is costly [19], and airspace management will pose additional difficulties [20]. Vertiports will need to handle this highly constrained environment, which makes vertiport design and operations ambitious undertakings. Early modeling of the impact of UAM on cities and spatial structures was conducted by Straubinger [19]. She found out that the surface area demand of vertiports has a strong negative effect on the overall welfare of the population. Accordingly, designing vertiports with small footprints is an important goal.

Vertiports have been studied to some degree, but there are crucial gaps in the knowledge when it comes to proposed real-life operations. In 2019, the world's first vertiport was built by Skyports for an exhibition in Singapore [21,22]. Yet, this and similar projects [23] are comparative in size to existing helipads [24] and so far only for exhibitory purposes. Vertiport layout design and current considerations are discussed in detail by Preis [25]. As there are no real-life vertiports operating as of today, there is also no experimental research at this point.

Some work has been conducted concerning the airspace management, looking at equipment to increase safety during landing for small airports [26], airport-specific weather forecasts [27] or dynamic airspace sectorization [28]. These are all valuable considerations on the path to enabling safe air traffic management in the dense airspace surrounding a vertiport. Yet, these studies do not look at VTOL, but rather conventional take-off and landing, and do not consider airfield operations. When looking at VTOL, groundbreaking research was conducted around vertiport capacity envelopes by Vascik et al. [29]. Further, Zelinski's work on vertiport surface topologies [30] should find mention, as well as Schweiger et al. investigating the level of service a vertiport layout can deliver [31]. What remains is a gap in the current literature around operational dynamics on vertiports and, in particular, the vertiport airfield, which is the main focus of the presented work.

This paper wants to inform applied operations research in academia and start-ups in the industry who concern themselves with vertiport design; it aims to help develop both use cases and best urban mobility practices. Toward this goal, the fidelity of vertiport research will be raised from previous analytical approaches to an agent-based simulative approach. Next to the classical four-step approach of transport modeling (see for example Ref. [32]), agent-based modeling has become increasingly popular for transport simulation in recent decades [33] and has already been applied to simulating UAM [34]. Therefore, this simulation approach seems fitting. Simulation of vertiports goes beyond existing research and presents the highest possible level of fidelity, as real-life experiments are not an option at the moment, as discussed earlier. A high-fidelity vertiport airfield model will be presented throughout the paper, including a careful selection of relevant parameters and an informed determination of their values. The relevant information is drawn from the literature review and an expert interview series. The agent-based modeling and simulation (ABMS) framework in which the model is implemented was first published by Preis et al. [35] and has since been expanded.

The structure of the paper is as follows. In Section 2, the vertiport model will be briefly re-iterated, including all elements, agents and the assembled simulation environment. The refinement of the model through expert feedback will be highlighted. In Section 3, a sensitivity study of over 100 simulations will be presented with the aim of identifying driving operational processes. These processes encompass vehicle approach and departure, passenger boarding and de-boarding, number of pads and gates, initial fleet size of vehicles and the accumulated daily demand. In Section 4, all conceivable parameters are listed. The driving parameters are identified through expert interviews and insights from the sensitivity study. A final short list of parameters is presented, and each parameter value is determined according to values found in the literature and derived from expert interviews. Lastly, in the Appendices A–E, additional material on the vertiport model, the expert interview series conducted for this paper, the list of parameters and the statistical interpretation of the parameter values can be found.

2. Vertiport Model and Simulation Method

The vertiport model consists of elements, which are composed into a virtual environment and agents moving within this environment. There are three main elements (pads, gates and stands) and three additional elements (lanes, terminal and airspace). Two types of agents move within the environment: passengers and vehicles. Further, the controller plays a key role in coordinating all agents. In Appendix A, the characteristics of all elements and agents and how they are composed into the virtual environment will be described. Except for the terminal and the airspace, all other elements can only be occupied by one agent at a time. Both the early model and the implementation of the software code have been published before [35] and will, therefore, only be re-iterated briefly. Since the first publication, the model has been expanded and validated.

2.1. Vertiport Airfield Environment

In Figure 1, a schematic sketch of the environment can be seen. All pads, gates and stands are connected through lanes or taxiways and represent the airfield on the ground. The *airspace* is the system boundary on the side of the pads. Vehicles enter the environment through the airspace and need a certain approach time until they stand on a pad, which is differentiated into multiple steps. When vehicles take off from a pad, they need a certain time of departure while they are in the air before they leave the airspace and thus, the simulation boundary. The *terminal* is the system boundary on the side of the gates. Passengers arrive at the terminal, which can be imagined as a holding place near the gates, after processing (ticket scan, luggage drop-off, security screening). Passenger processing in the terminal is not considered in the environment, as will be explained in Section 2.2. Instead, passengers enter the environment at the point of arriving at the holding area. From the terminal, passengers walk toward a gate, enter the gate and start boarding a vehicle. After de-boarding a vehicle, passengers immediately walk toward the terminal and leave the simulation environment the moment they arrive at the terminal. Unused and empty vehicles are sent to a stand to clear space for other operations. Processes in the airspace and terminal were not part of the original model and were introduced for this paper. Further, a mechanism was introduced to prevent deadlock situations when the capacity limit of the vertiport is reached.

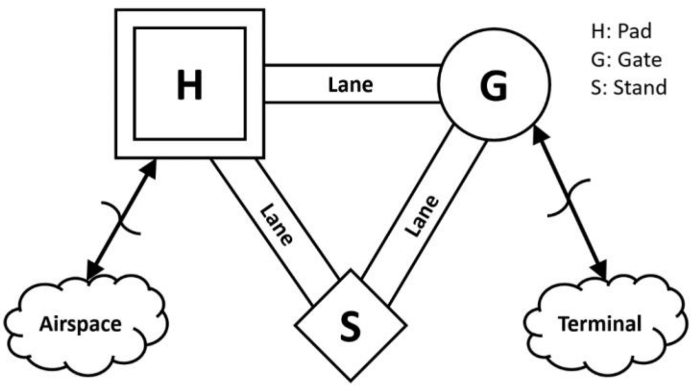

Figure 1. Vertiport environment composed of pads, gates and stands, including connecting lanes and interfaces to airspace and terminal [35].

2.2. Vertiport Model Refinement

This model was presented to 17 experts, and three main points were criticized (the expert interview series will be explained in detail in Section 4.1). The points are listed below, and an explanation is given on how they will be accounted for:

1. **Airspace operations**. Several experts expected the main operational bottlenecks in the airspace. Additionally, sending eVTOLs into holding loops for extended times, which is done to prevent deadlocks, might not be possible. Currently, these questions are being addressed in cooperation with the German Aerospace Center (DLR) [36]. Bauhaus Luftfahrt (BHL) will focus on vertiport airfield operations. A well-defined interface between both models on the airside (DLR) and groundside (BHL) will allow a holistic view.
2. **Passenger processing**. Some experts criticized the choice to neglect passenger processing and, in particular, ticket scan, luggage drop-off and security screening, because these are essential and time consuming in today's commercial aviation. First, these processes might and even must change dramatically in their duration to make UAM viable, wherefore they are not yet easily captured in an accurate model. Second, passenger processing has already been studied extensively for commercial airports [37], which allows adding empirical values to the results of the simulation during post-processing steps to account for pre-terminal passenger processing. The need for real-time simulation is not high. Lastly—and this answer comes from one of the experts on passenger boarding—passenger processing follows very different dynamics than vehicle taxiing. Both things may be difficult to harmonize into one unified environment and should rather be simulated independently.
3. **Energy management**. Other experts pointed out the need to include energy management in the model, in particular vehicle batteries, charging ports and an interface to the electric grid. As will be pointed out in Appendix A.1, this feedback was considered and included in the model. A detailed discussion of the model extension through an energy module will be presented in a separate publication to maintain a realistic scope of this paper. The parameter value determination of key energy-related parameters will still be considered in this paper, but the focus is on general vertiport airfield operations, unconstrained through energy limitations.

This section re-iterated the initial vertiport airfield model and highlighted early updates around the areas of the terminal and airspace. Two further aspects will now be considered to refine the model: first, the model improvements as desired from the 17 experts, which were discussed above. Second, a sensitivity study encompassing over 100 simulations, which will be described in the following Section 3. The goal is to identify the driving process and understand which parts of the model need further differentiation to capture all the relevant elements. Combining expert feedback and insights about the sensitivities will inform the refinement of the vertiport airfield model in Section 4.

3. Vertiport Operations Simulation Results and Identification of Driving Processes

With the updated vertiport model and the implementation in the ABMS simulation framework, which are described in Section 2, the first sensitivity study was undertaken. The goal is to understand the driving processes of vertiport operations, which will inform the following refinement of the model. In the course of the sensitivity study, over 100 simulations will be executed, distributed over six parameter variations. The following six processes or characteristics are expected to play a significant role and will be varied systematically:

- Initial fleet size of vehicles parked on the vertiport at the start of simulation;
- Accumulated demand over a day of operation;
- Approach and departure time of vehicles;
- Boarding and de-boarding time of passengers;
- Number of pads;
- Number of gates.

3.1. Definition of Simulation Sensitivity Study

The sensitivity study did not aim to look at realistic scenarios, but rather decouple the effects and variation of input parameters to understand the impact of individual processes. A 16 h day of operations was assumed. Demand profiles were randomly created from a normal distribution, with its peak in the middle of the operational time (see Figure 2). A normal distribution was chosen over a uniform distribution to understand the effects of peak and off-peak operations. Each distribution has the same accumulated number of vehicles arriving through the airspace and passengers arriving through the terminal, which leads to an identical number of parked vehicles at the start and end of each simulation. Asymmetric demand was judged to be an advanced question at the current stage and therefore not considered.

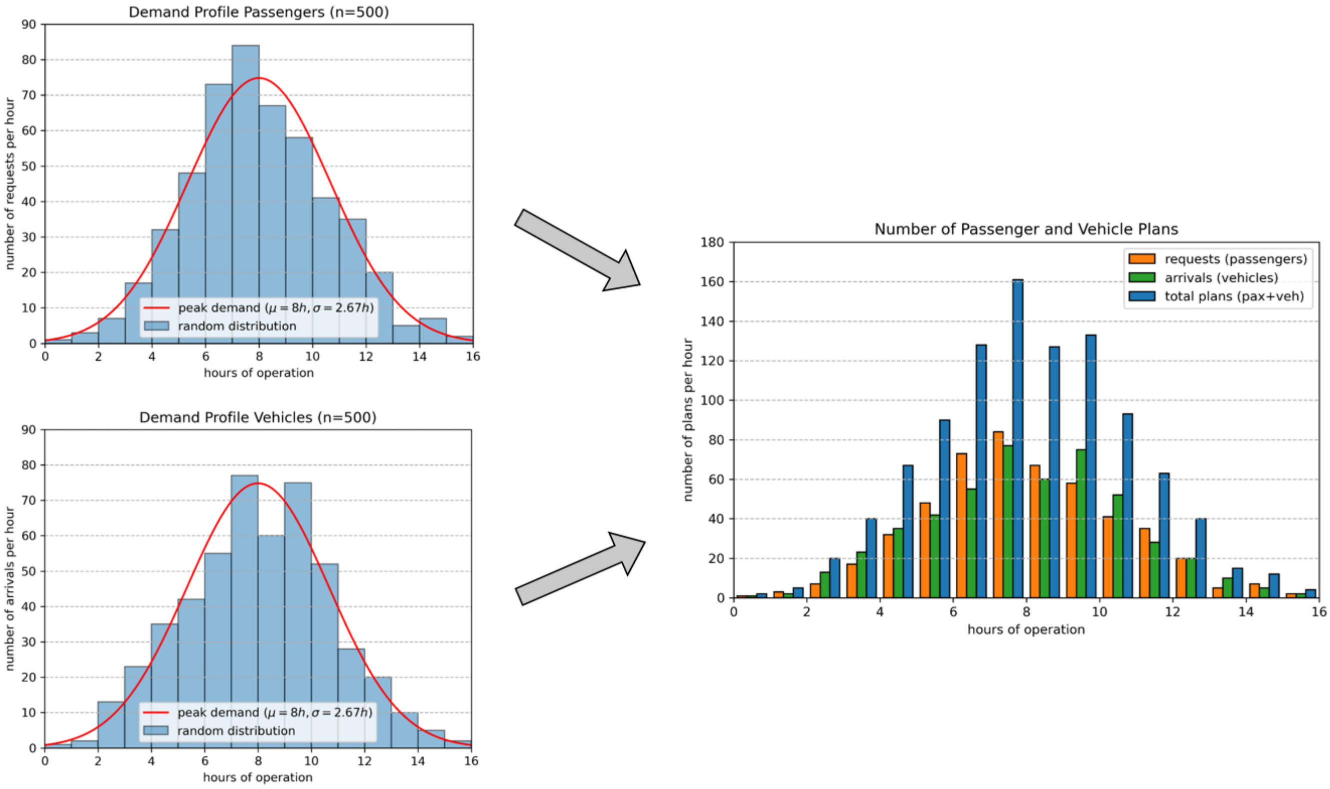

Figure 2. Passenger and vehicle demand profile for baseline scenario, randomly generated from normal distribution, spanning a 16 h operational day (example of variation A).

The baseline scenario is composed of 500 arrivals and requests, 20 vehicles of initial population and a vertiport layout with 4 pads, 12 gates and 20 stands. "Plans" is used as a term to describe both vehicle arrivals and passenger requests; there are, accordingly, a total of 1000 plans in the baseline scenario. Approach and departure times for vehicles are set to 60 s; walking time from the terminal to the gate and reverse for passengers is set to 20 s; boarding and de-boarding time is 120 s; and the speed of vehicle taxiing is 2.2 m/s. Five variations of the demand profiles (baseline profile shown in Figure 2, profiles B-E shown in Figure 3) were created in a Monte Carlo approach to account for stochastic effects. Next to the baseline scenario, 30 other sets of parameters were created with each 3–5 random samplings of the demand profile, resulting in a total of over 100 simulation scenarios (see Table 1). In the following, the average delay time per passenger over variations of parameters will be discussed.

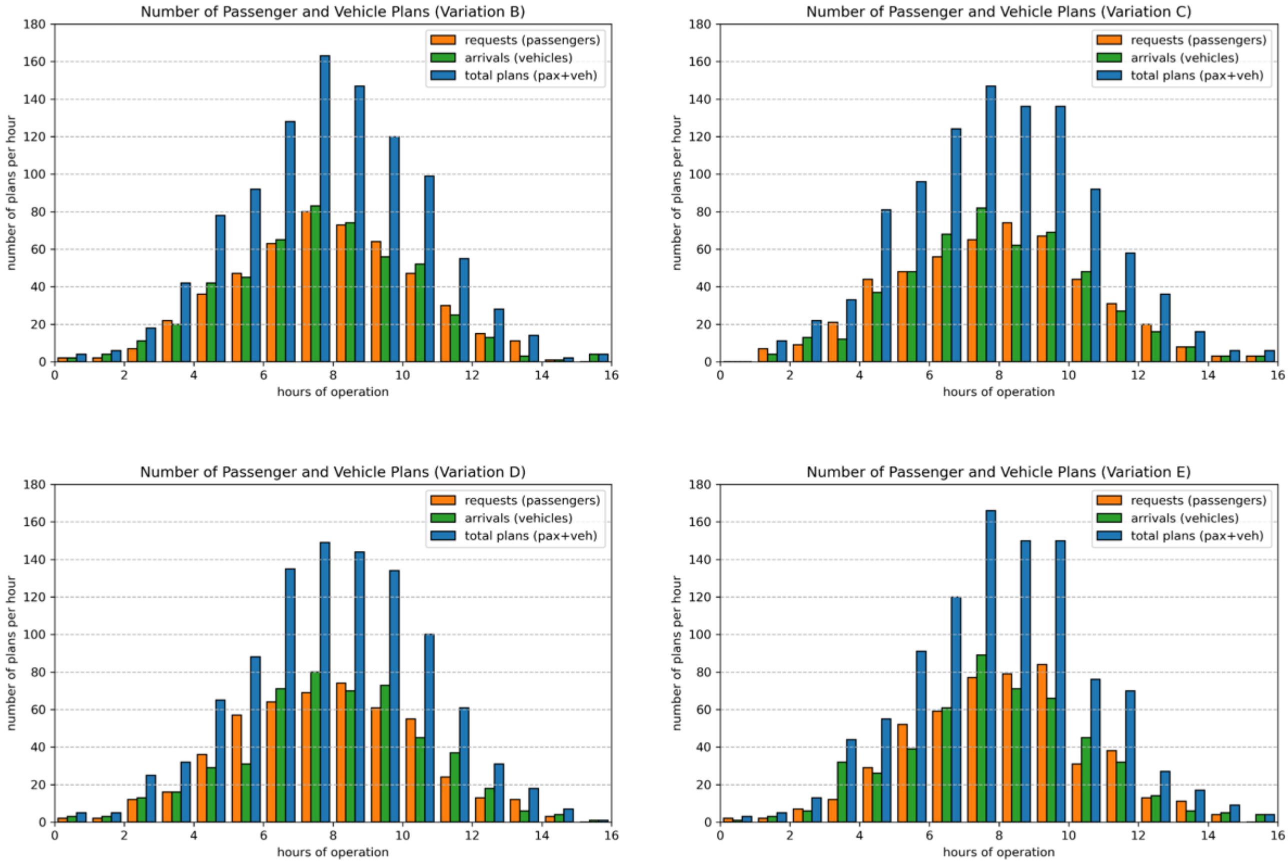

Figure 3. Variations B-E of demand profiles generated through Monte Carlo approach.

Table 1. Overview of parameter variations for simulations of the sensitivity study.

Aspect to Be Varied	Demand Variations Included	Varied Values (Baseline Marked)	Description
Fleet Size	A-C	0, 8, 12, 16, **20**, 24, 32	Number of vehicles initially parked at vertiport
Demand	A-E	750, **1000**, 1200, 1250, 1300, 1500	Accumulated demand over day of operations
Approach and Departure	A-C	30, **60**, 75, 90, 105, 120	Time vehicle needs to land or take off (in seconds) before next operation is possible
Boarding	A-C	1, **2**, 3.5, 4, 4.5, 5	Time passenger needs to board or de-board a vehicle (in minutes)
Pads	A-C	2, 3, **4**, 5	Number of pads included in airfield layout
Gates	A-C	6, 7, 8, 9, 10, **12**, 16	Number of gates included in airfield layout

3.2. Performance Indicator of Average Passenger Delay

The vertiport performance of any given simulation scenario in the sensitivity study will be expressed through a value, which is labeled "average (passenger) delay". This value is defined as the involuntary or idle waiting time of n passengers, which is caused by non-optimal operations. In other words, the delay of passenger i is the difference between actual operations t_i*(actual operations)* and optimal operations t_i*(optimal operations)* (see Equation (1)). Delay can occur while a passenger is waiting in the terminal to have a vehicle assigned to them or while waiting at the gate when the assigned vehicle has not yet arrived at the gate. Delay can also occur while the passenger is sitting in the vehicle and the vehicle is forced to wait, both on the ground and in the air.

$$average\ delay = \frac{1}{n} * \sum_{i}^{n} [t_i(actual\ operations) - t_i(optimal\ operations)] \quad (1)$$

Throughout the sensitivity study, it will be observed that there are, generally speaking, two regions for each variation. First, there is a region of low average passenger delay (less than 5 min), where a variation of parameter has little impact. Second, there is a region of high passenger delay (more than 5 min), where variations of the parameter lead to an exponential increase in passenger delay. The first type of region will be considered "stable" operations, the second type of region will be considered "unstable" operations.

3.3. Simulation Results of Sensitivity Study

3.3.1. Fleet Size

The fleet size or initial population at the start of simulation is set to 20 vehicles in the baseline scenario. A quadratic fit approximates the data well (see Figure 4), showing an optimal spot around the center (16 vehicles) when half of the vertiport parking capacity is used initially (32 vehicles maximum capacity, 20 at stands and 12 at gates). Depending on the demand profile, the optimum shifts more toward an initially fuller vertiport (shift to the right) or an emptier vertiport (shift to the left). The explanation might be a temporal excess of requests or arrivals, respectively. Average delays of passengers vary between 0 and 5 min, showing that the initial population has very little impact on the delay.

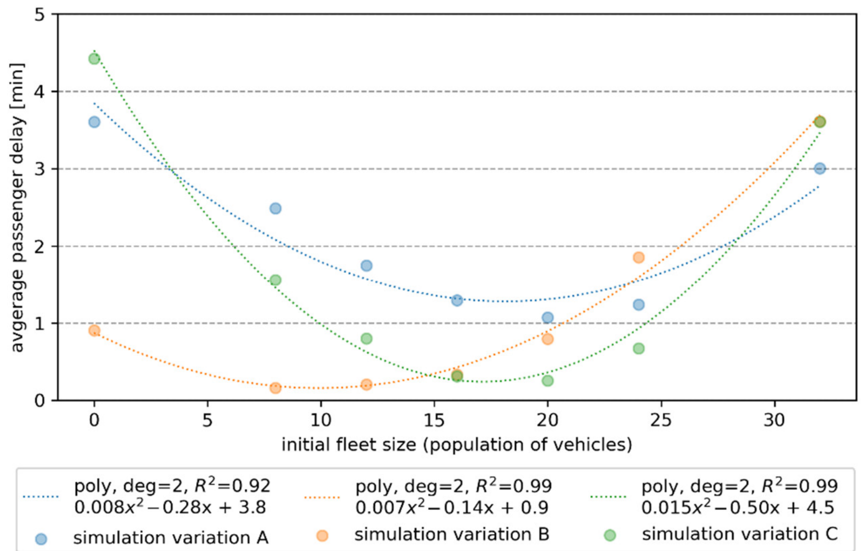

Figure 4. Average passenger delay with varying initial population of vehicles.

3.3.2. Demand Magnitude

The accumulated demand of the baseline scenario consists of 500 vehicles arriving through the airspace with each one passenger on board and 500 passengers arriving through the terminal, resulting in 1000 passengers over the course of one day. For each demand magnitude from 750 to 1500 passengers, five random samples were created (see Figure 5). In particular, for an accumulated demand of 1200 passengers and more, the variation is strong, which suggests the interpretation that with increased demand, the system becomes unstable. Further, temporal peaks in demand probably affect the average delay of passengers more strongly than the accumulated demand over a day of operations. Average delays of passengers vary between 0 to 10 min. In summary, it can be said that the demand has a moderate impact on the delay, but the accumulated number of passengers is not a reliable indicator to predict passenger delay.

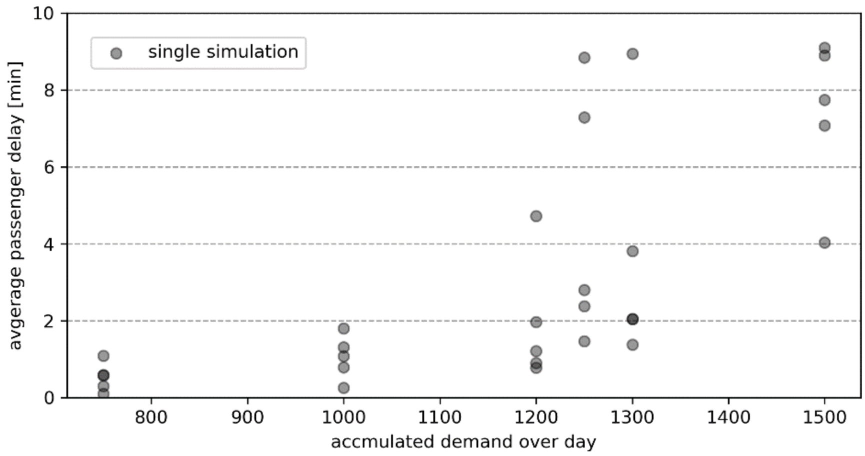

Figure 5. Average passenger delay with varying demand (accumulated over one day).

3.3.3. Approach/Departure and Boarding Times

The approach and departure time of the baseline scenario is each 60 s. An exponential fit approximates all three randomly sampled demand profiles nearly perfectly (see Figure 6). It can be seen that approach and departure times of up to 75 s have almost no impact on the average passenger delays. For more than 75 s, the average passenger delay then increases rapidly up to around half an hour for 120 s, which is twice the approach and departure time of the baseline scenario. Vertiports operate stably under a stretch of approach and departure times, but operations become unstable and delays increase rapidly once a threshold is crossed. Average delays of passengers vary between 0 and more than 30 min, which shows the major impact approach and departure times have on the delay.

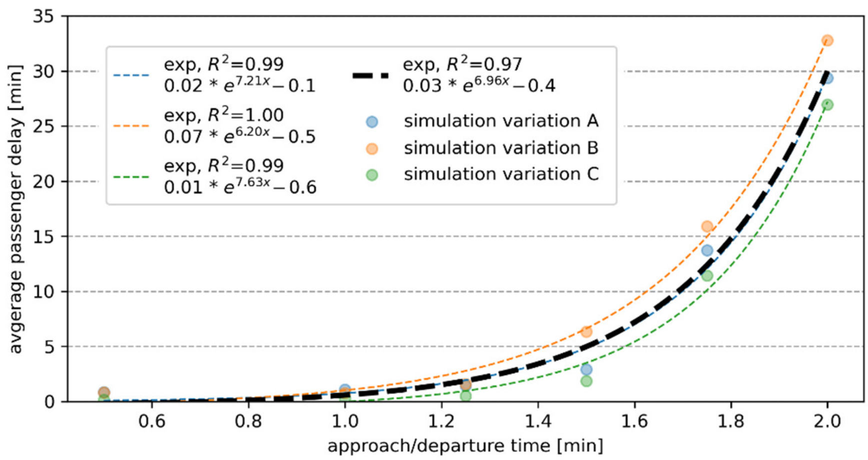

Figure 6. Average passenger delay with varying vehicle approach and departure time.

The boarding and de-boarding time of the baseline scenario is each 2 min. An exponential fit approximates the results well (see Figure 7). Similarly to the approach and departure time, there is a long stretch of stable operations up until around 3.5 min. Afterward, the average passenger delays rise exponentially. The effect is not as strong as for the approach and departure time; at twice the boarding time of the baseline scenario of 4 min, the delays are still below 5 min. An interpretation can be that increased boarding time will lead to unstable operations and exponentially increasing delays, but the boarding time is not as critical as approach and departure time. Average delays of passengers vary between 0 and 20 min, showing a substantial impact on the delay.

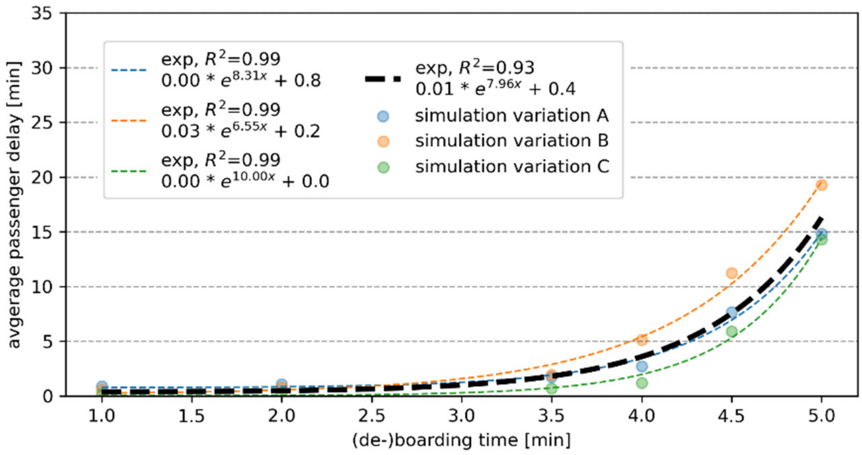

Figure 7. Average passenger delay with varying passenger boarding time.

3.3.4. Number of Pads and Gates

The number of pads is four for the baseline scenario. An exponential fit approximates the results nearly perfect (see Figure 8). Only discrete variations of the number of pads are possible, which limits the resolution along the x-axis. At three pads, the average passenger delay times have increased, but operations seem to be stable. At two pads, a tipping point in delays is seen, pointing to a highly critical relationship between stable vertiport operations, expressed in low average passenger delays, and a minimum number of pads. Average delays of passengers are below 5 min for three or more pads and are around 45 min for two pads. From the observed factors, the number of pads has the strongest impact on the delay.

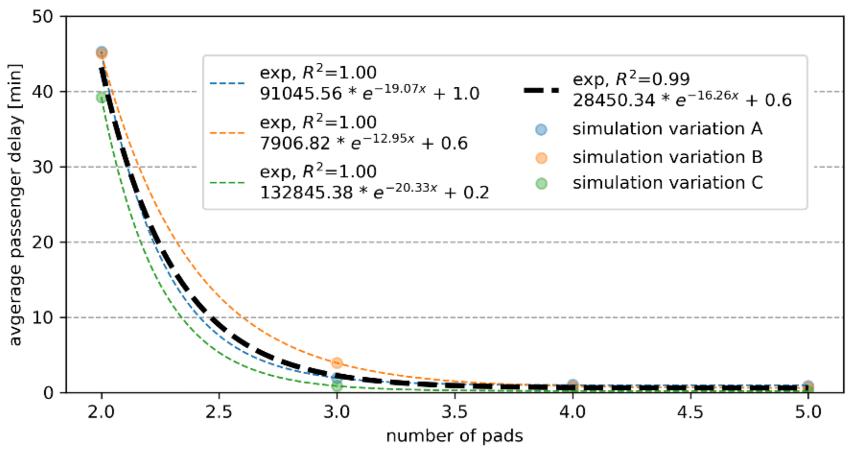

Figure 8. Average passenger delay with varying number of pads.

The number of gates is 12 for the baseline scenario. An exponential fit approximates the results for individual demand profiles nearly perfectly (see Figure 9). This concludes that the particular demand profile has an effect on how efficiently the number of gates operate. For 10 or more gates, operations are stable; between 8 and 9 gates, average passenger delays start increasing and then rise exponentially for lower numbers of gates. Similarly to the number of pads, the number of gates shows a region of low delays and then experiences an exponential increase after a threshold toward a region of unstable operations. Average delays of passengers are below 2 min for 10 or more gates and increase to over 20 min for as few as 6 gates. The number of gates has a substantial impact on passenger delay.

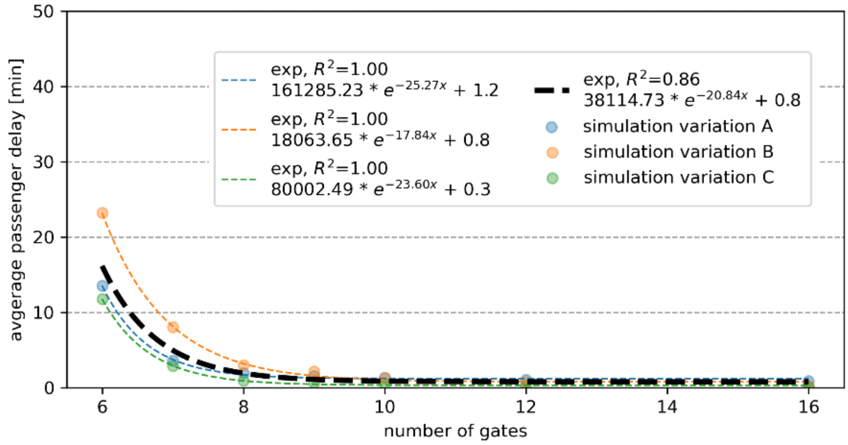

Figure 9. Average passenger delay with varying number of gates.

3.4. Summary of Driving Processes in Vertiport Operations

Vertiport operations are highly sensitive to a variation in the presented driving parameters, typically showing a region of stable operations with low average passenger delays and an unstable region with exponential increase in delays. The initial fleet size at the start of a simulation has an optimal point at half capacity (half of all stands and gates are occupied by available vehicles) of the vertiport and has very little impact on the average passenger delay. The accumulated demand over a day results in scattered results, suggesting that temporal peaks in demand have a larger impact than the overall demand. This finding suggests that vertiports need to be designed toward a peak hour, not toward accumulated demand.

Both processing times and vertiport sizes show exponential growth in average passenger delays after crossing a certain threshold. Vehicle approach and departure time and the number of pads appear to be more sensitive than passenger boarding and de-boarding time and the number of gates. The central focus in designing vertiports should therefore be placed on optimal placement and handling of pads. Selecting the ratio between the number of pads and the number of gates, also accounting for the processing times, is also critical to plan an efficient vertiport layout. Once a vertiport layout is planned, it can handle a certain amount of demand, but not much more; due to the tipping point characteristic, it will quickly enter unstable operations, and average passenger delays will increase exponentially.

In this section, the previously published software implementation of the ABMS [35] was applied. Over 100 simulations were executed to understand the sensitivities of vertiport airfield operations. The focus of the initial publication lay on the software architecture, whereas this paper focuses on the application of the framework to generate new insights.

4. Discussion of Vertiport Parameters and Values

In this section, the list of parameters that are incorporated in the refined vertiport model are introduced, including the evolution of the list and the current short list of most relevant parameters. The model was refined based on the responses of experts presented in Section 2.2 and the insights from the simulation sensitivity study presented in Section 3.4. Initially, a list of parameters was formulated with a total of 82 entries assembled into 10 groups. Through expert interviews and literature review, the list was expanded and individual parameters were differentiated or aggregated where necessary, resulting in a full list of 95 parameters. Irrelevant parameters were dropped to form a long list of 55 parameters, and from these, the most relevant 27 parameters were chosen and assembled into 5 new groups. The full list of parameters can be seen in Appendix C and the short list of parameters in Appendix D. In the following sections, the expert interviews and selection process will be discussed in further detail.

4.1. Expert Interview Approach

As UAM, in its proposed magnitude, is a novel field of transportation, the scope and confidence of parameters for vertiport ground operations are strongly limited in current literature, wherefore expert interviews were chosen as a method for gathering data. The interviews followed a semi-structured approach with a list of questions related to UAM, the vertiport model and vertiport parameters. Each interview lasted 30–60 min and was conducted through video calls. Experts were selected according to their expertise and experience; each expert was interviewed in person and filled out a questionnaire about specific parameter values after the interview. The questions of the interview questionnaire can be found in Appendix B. The interview series took place between October 2020 and July 2021. All responses are anonymized for protection of privacy and confidentiality of the answers. For this reason, only the aggregated values can be shown in this paper.

In total, 17 experts took part in the interview series with backgrounds in research, the aviation industry, aircraft operations and architecture. The experts were from the USA, Great Britain and Germany and had an average experience in their field of 10.6 years (median experience 7 years). A total of 19 qualitative remarks toward the vertiport model were given, which are incorporated in Section 2.2. Forty-nine qualitative responses concerning the definition of parameters were gathered during the interviews. This information was incorporated in the refinement process of the parameter list presented in the following section.

4.2. Identification of Relevant Parameters

For the vertiport model, a total of 97 parameters in 10 groups were considered, out of which a short list of the most relevant parameters was formed, including 27 entries separated into 5 groups. There were four stages of the parameter list: the initial list (82 entries), the expanded full list (97 entries), the refined long list (57 entries) and the selective short list (27 entries). The responses from the expert interviews helped to expand the initial list toward the full list through adding new parameters or differentiating existing parameters. Further, the expert responses aided in forming the long list by aggregating multiple parameters into single parameters and dropping irrelevant parameters. The short list (see Section 4.3) was finally formed by looking at the expected driving processes (discussed in Section 3.4) on a vertiport and reducing the list of parameters to account for the most relevant aspects.

In Table 2, the initial 10 groups of parameters are shown and the number of parameters from the initial list, the full list, the long list and the short list.

Table 2. Evolution of list of parameters and division into initial groups.

ID	Initial Group	Initial List	Full List	Long List	Short List
A	Vertiport Elements	9	9	5	4
B	Passenger Processing	9	12	7	2
C	Passenger Boarding	16	16	4	4
D	Vehicle Taxiing	6	8	6	5
E	Take-Off and Landing	5	5	3	2
F	Flight Approach and Departure	11	14	14	6
G	Battery Charging	10	11	9	3
H	Battery Swapping	8	10	3	1
I	Vehicle Maintenance	6	8	2	0
J	General Vertiport Operations	2	4	4	0
	Total	**82**	**97**	**57**	**27**

4.3. Final Short List of Parameters

A short list of 27 parameters, which capture the most relevant processes in a vertiport, is shown in Appendix D. The IDs are coherent over the evolution of the parameter list (see all parameters considered in Appendix C). The short list of parameters is separated into five new groups and given a new index:

- Vertiport elements (no index)
- Flight approach and departure (indices A and D)
- Passenger boarding and de-boarding (index B)
- Energy management (index E)
- Vehicle taxiing (index T)

Group *vertiport elements* was shown to be impactful in Section 3.3.4, where the number of pads and gates in a vertiport layout impacted the average passenger delay significantly. Groups *boarding* and *approach and departure* were both highlighted by the experts in Section 2.2 and shown to be relevant for vertiport operations in Section 3.3.3. Group *energy* was also highlighted by the experts in Section 2.2. Lastly, group *taxiing* was added due to the potential impact of different taxiing concepts, which have not yet been studied in depth.

All groups that have operational character (all except for *vertiport elements*) will be considered in the parameter value determination in Section 4.4. For group *vertiport elements* (which includes the dimensions of pads, gates, stands and taxiways), the values can be extracted with good confidence from existing heliport standards (see heliport manuals by FAA [38] or ICAO [18]). In addition, this group does not have any operational character in the same sense as the other four groups, but rather determines the possible vertiport layouts, which have to be designed prior to simulating a day of operations. Parameter groups *boarding*, *taxiing*, *approach and departure* and *energy* will be explained in the following and are visualized in Figure 10.

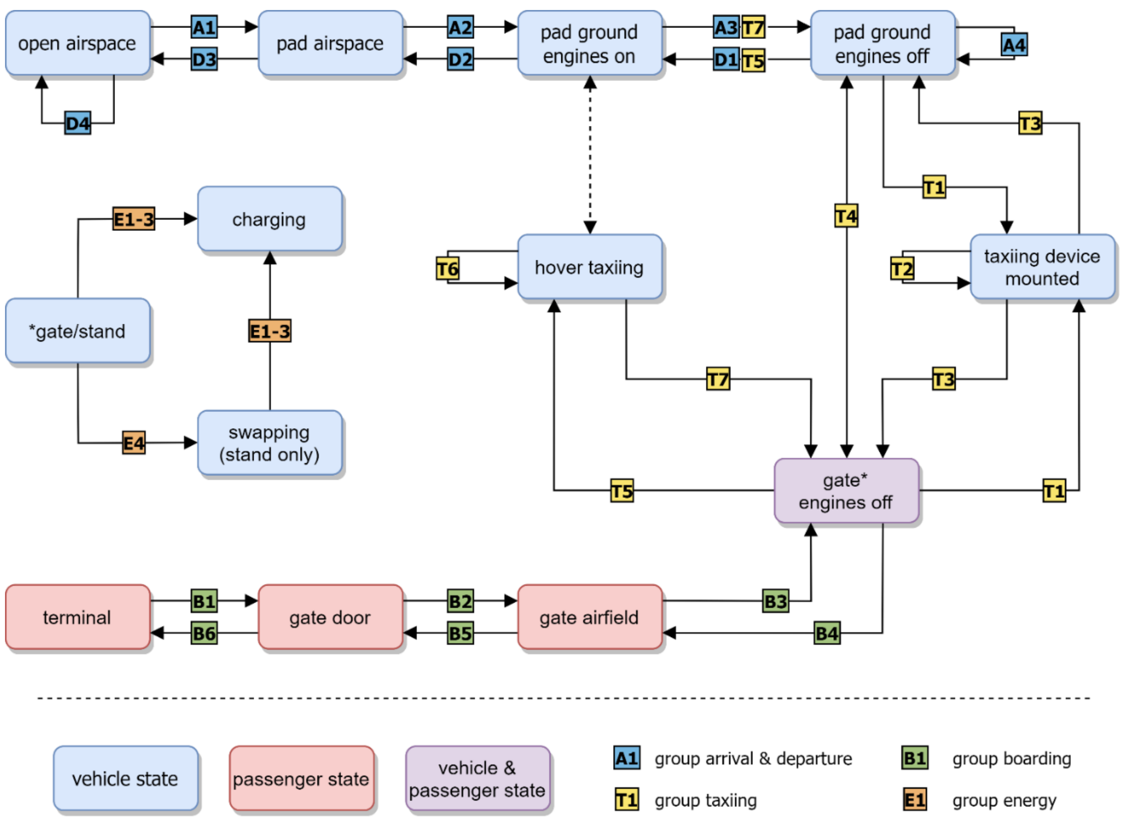

Figure 10. Refined model, including parameters from final short list grouped into approach and departure, boarding, taxiing and energy.

4.3.1. Flight Approach and Departure

Parameter group *approach and departure* starts with a vehicle being in the controlled airspace of the vertiport and starting final approach. It enters the physical airspace above the pad (A1), transitions into a final hover over the center of the pad (A2), touches the ground and shuts down the engines (A3), if the taxi mode is other than hover taxi. The pad needs a time to "cool down" after an operation (A4) to account for wake vortices and separation minima between vehicles. In reverse order, the vehicle starts its engines (D1), unless the taxi mode is hover taxi, lifts off and hovers (D2), and transitions into forward flight leaving the physical airspace of the pad (D3). Analog to the approach process, the pad needs a "cool-down" time (D4) before the next operation can be initiated.

4.3.2. Passenger Boarding and De-Boarding

Parameter group *boarding* starts with a passenger arriving or waiting at the holding place in the terminal. Once a vehicle is assigned, the passenger walks toward the gate (B1) and enters the gate (B2), which can be imagined as stepping through a door into the immediate proximity of a vehicle, in order to step into the vehicle and board it (B3). In reverse order, the passenger de-boards the vehicle (B4), leaves the proximity of the vehicle, steps through the gate door (B5) and subsequently walks toward the holding place in the terminal (B6) to exit the simulation.

4.3.3. Energy Management

Parameter group *energy* contains parameters for both charging or swapping vehicle batteries. As in the case of swapping, the batteries still need to be charged. Charging is essential for both types; for battery swapping, the charging process occurs remotely. The battery swapping time (E4) is aggregated into one parameter encompassing the entire swapping procedure. The battery has a certain capacity (E2), which corresponds to the usable capacity, not the full physical capacity of the battery. Therefore, a depth of discharge reserve needs to be subtracted beforehand. The batteries can be charged with a certain charging speed or charging power (E3), which is assumed constant as a first approximation. During the charging process, some energy is lost due to inefficiencies in the charging process. The losses are given as relative losses to the overall processed energy (E1).

4.3.4. Vehicle Taxiing

Parameter group *taxiing* encompasses three modes of taxiing: "hover" taxi, "passive" taxi and "active" taxi. The "passive" taxi mode facilitates a taxiing device, which is first mounted to the vehicle (T1), then the device moves over the airfield (T2), and at the destination, the device is de-mounted (T3). It could be pushing, pulling or carrying the vehicle, performed by a movable platform, through ropes or a bot, respectively. The "active" taxi mode facilitates auxiliary electrical motors at the wheels of the vehicles (skids are not possible in this scenario) through which the vehicle can taxi (T4) without using the main engines or an external device. The "hover" taxi mode facilitates the main engines to hover near the surface (eVTOLs with skids) or touch the ground and roll (eVTOLs with wheels) (T6). If the engines are off at the start of taxiing or have to be off after taxiing, the engines are started (T5) or stopped (T7), respectively.

4.4. Parameter Value Determination

After selecting and defining the essential parameters for the vertiport model in the previous sections, the parameter values are now going to be determined. As no vertiports in the envisioned dimension are operating at the time of writing, no direct experimental data are available. Some parameter values can be borrowed from similar applications, for example, the parameter values in group *elements* can be determined according to existing heliport guidelines [38]. Yet, for most parameters, value determination poses a substantial challenge. In order to attempt an initial value determination of the presented vertiport model and its parameters, two sources will be included in the following: parameter values determination from other authors' statements captured in the literature and the estimations given by the experts during the interviews presented in Section 4.1.

From the literature review, a total of 135 datapoints were identified of which a subset of 47 parameter values is included in this paper. The other datapoints were either values in an aggregated form, had differently defined parameter boundaries or corresponded to parameters, which are not included in the final short list of parameters (see Section 4.2 for the selection of parameters). The experts answered a total of 186 datapoints, of which 77 correspond to one are another parameter of the final short list.

In Table 3, the value specification of all parameters identified as crucial for the vertiport model are shown (please find the definition of all parameters in the final short list in Appendix D). In Appendix D, a more detailed discussion of the statistical aggregation and confidence of value determination is presented.

Table 3. List of parameter values in the refined vertiport model, including references.

ID	Parameter	Value	Unit	# Experts	# Literature	References
B1/B6	Terminal to/from gate	31.9	s	3	0	
B2	Enter gate	19.7	s	5	0	
B3	Boarding	73.0	s	4	5	[8,30,39–41]
B4	De-boarding	65.8	s	4	4	[8,30,40,41]
B5	Leave gate	26.7	s	2	0	
T2	Passive taxiing	2.63	m/s	6	0	
T1/T3	(De-)mounting passive taxiing device	27.0	s	3	0	
T4	Active taxiing	2.15	m/s	5	1	[42]
T6	Hover taxiing	3.25	m/s	3	3	[30,36,43]
T5/D1	Start engine	4.50	s	2	0	
T7/A3	Stop engine	5.00	s	2	0	
A1	Enter airspace	46.3	s	6	2	[8,44]
A2	Final hover	22.9	s	5	5	[43,45–48]
D2	Initial hover	13.5	s	5	5	[43–46,48]
D3	Leave airspace	28.7	s	6	1	[44]
A4/D4	"Cool-down" after landing/take-off	30.0	s	3	3	[49–51]
E3	Charging speed	311	kW	4	7	[42,44,45,48,52–54]
E2	Battery capacity	133	kWh	4	3	[46,48,55]
E1	Energy loss	7.17	%	3	3	[44,48,52]
E4	Swapping time	349	s	2	5	[11,52,56–58]

5. Conclusions and Future Work

Urban air mobility promises to enrich the current transportation system with a new and fast mode of transport. Advances in the required infrastructure, in particular, vertiports, are necessary to realize the promises UAM offers. As of today, no vertiports are operating, and experimental data are, except for related research on heliports, non-existent. Through expert interviews and agent-based simulation, this paper attempted to raise the fidelity of vertiport operations modeling to a higher level.

A vertiport model, consisting of pads, gates and stands, was introduced. The model was implemented in an ABMS framework, with passengers and vehicles as agents. Experts were asked to evaluate the model and recommend refinements. Their answers on airspace operations, passenger boarding and energy management were discussed. Next, a simulation sensitivity study was conducted, showing that vertiports have a region of stable operations and a threshold beyond which operations become unstable, causing passenger delays to increase exponentially. In particular, the number of pads and length of approach and departure time of vehicles were identified as design drivers. This study further guided the focus of model refinement. Lastly, through expert interviews (n = 17) and results from the sensitivity study, the early model (initially presented by Preis et al. [35]) was refined, and 27 driving parameters were identified. These parameters were grouped into vertiport elements, vehicle approach and departure, passenger boarding and de-boarding, energy management and vehicle taxiing. Through the literature review and expert estimations, the parameter values were specified.

The work of this paper can aid the wider scope of research in at least three ways. First, the updated vertiport model (Section 2) may be used as a reference for general research around infrastructure for UAM. Second, the results of the sensitivity study (Section 3.4) give valuable insights into the design drivers for vertiport operations and will be helpful when planning vertiport layout and operations in highly constrained urban environments. Third, the list of parameters (Section 4.3 and Appendix D) and, in particular, the specified parameter values (Section 4.4) can be used in part or as a whole for studies in the area of UAM. There is not much consensus in the UAM community on the parameter values, which makes this specification especially valuable. A further strength is the combined approach of literature review and expert estimations.

In the future, the ABMS framework will be used to further investigate the effects on vertiports, in particular the questions of taxiing modes, energy sources and charging vs. swapping of batteries. An ongoing refinement of the parameter values will also be performed as new research is conducted throughout the community. Lastly, a stochastic extension to the vertiport model is planned to account for variations, in particular, between passengers in real life.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

UAM	Urban Air Mobility
eVTOLs	Electric Vertical Take-Off and Landing Vehicles
VTOL	Vertical Take-Off and Landing
ABMS	Agent-Based Modeling and Simulation

Appendix A. Vertiport Model Elements and Agents

Appendix A.1. Elements of Vertiport Airfield

Pads are physical areas for take-off and landing of eVTOLs. They present the interface between ground and air operations and are connected through lanes with the rest of the vertiport airfield. Before landing or after take-off, pads have a so called “cool-down” time before the next operation can take place to account for separation minima due to wake vortices and safety buffers.

Gates are both a physical area where vehicles park during turnaround, as well as interfaces to the terminal to allow for boarding and de-boarding of passengers. One vehicle and multiple passengers can be at the gate at the same time. Charging eVTOLs can be possible at gates but is not mandatory. Small inspection or maintenance tasks can be accounted for through a fixed turnaround time. Gates are connected through lanes with the rest of the vertiport airfield.

Stands are physical areas for parking vehicles during low demand and for charging and/or swapping of batteries. At stands, larger maintenance tasks can be performed, which are modeled through a state "busy", which can be interrupted upon request. Stands are connected through lanes with the rest of the vertiport airfield.

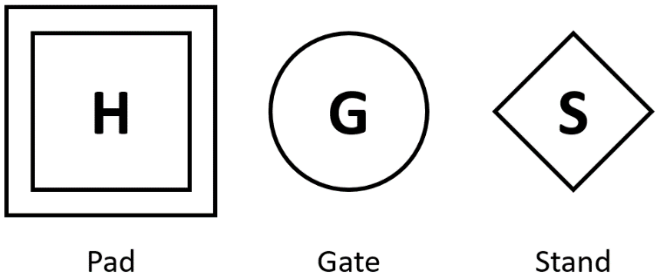

Figure A1. Main vertiport elements: pad, gates and stand.

Lanes are non-physical or physical connections between pads, gates and stands. There are two capabilities included in the model. First, an open airfield with no distinct areas for lanes. All the main elements are connected with all the other main elements of a different type through beeline connections. Physical collision of agents, which might occur on intersecting lanes, is not accounted for. Second, a defined taxiway layout, where taxi nodes are included to create a network of lanes. Lanes are aggregated into taxiways, and each taxi-way can only be occupied by one vehicle at a time. Beyond vehicles taxiing on the lanes, it is also conceivable that there will be no vehicle movement on the ground, but rather passengers walking from the gate to the pad for boarding. In this case, passenger lanes are defined.

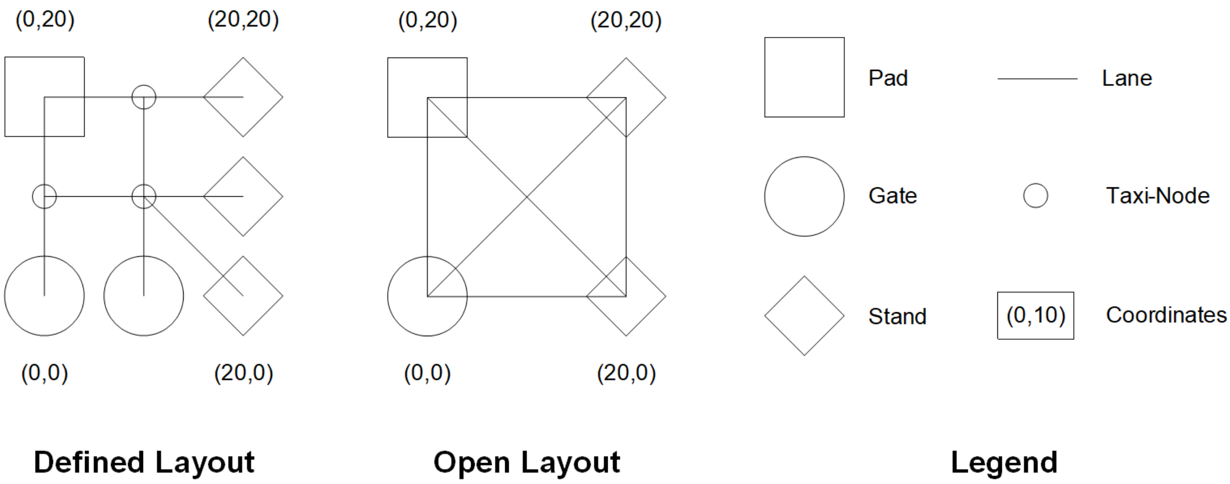

Figure A2. Layout variations implemented in the ABMS framework: defined and open.

The *terminal* is a non-physical space and can be imagined as a holding area inside the vertiport facility near the gate. Here, passengers enter the simulation environment and stay while they are waiting for a vehicle. Once a vehicle is assigned, passengers need a short time to walk toward the gate. Passenger processing (ticket scan, luggage drop-off, security screening) is not considered, but the terminal is implemented in a way to be expandable into separate physical areas. The terminal can hold an unlimited number of passengers and has a direct, equally long connection to each gate.

The *airspace* is a non-physical space representing the physical airspace surrounding the vertiport. Vehicles arrive in the airspace and start approaching a pad, if available, or are forced into a holding state in the airspace. The airspace can hold an unlimited number of vehicles. The airspace is connected to all pads with the same distance but can be differentiated into airspace segments (e.g., representing different directions from which vehicles arrive), and pads can be connected to only one or some of these airspace segments. When a vehicle approaches a pad or departs from a pad into the airspace, the pad is occupied for the entire process, even before the vehicle would physically occupy the pad, to account for separation minima. Included in the approach or departure operation is a distinct cool-down time before the pad is available for the next operation.

Appendix A.2. Agents in Vertiport Simulation

Passengers arrive either by foot through the terminal to request a vehicle or on board of a vehicle arriving through the airspace to be dropped off at a gate. When arriving at a vertiport by foot, passengers enter the terminal and either wait in this holding area or walk toward the gate, where their assigned vehicle is located. When departing the vertiport, they walk from the gate to the terminal after de-boarding the vehicle. When they reach the terminal, they leave the simulation environment. Passengers have a walking speed and/or need distinct amounts of time to walk between the terminal and the gates, enter and exit the gates and board or de-board a vehicle.

Vehicles are either stationed at the vertiport at the start of the operations or arrive at the vertiport through the airspace. If they find an available pad, they start the approach; if not, they are forced into a holding loop in the air. An approach consists of entering the physical pad airspace, a final hover, touch-down and a cool-down time. Depending on the mode of taxiing (hovering, using supplemental motors at wheels, being pulled by taxiing bot) the engines are potentially stopped. The departure process contains the same steps in reverse order. Vehicles either taxi to an available stand to be parked or to a gate to drop off passengers. Either way, the pad must be left immediately, and mechanisms are implemented to assure at least one free stand or gate. Vehicles carry batteries, which can either be swapped or charged at stands or potentially gates. The batteries have a capacity, charging speed and charging inefficiencies. The model currently only allows for single-seater vehicles. Vehicles with multiple seats increase the operational complexity substantially. Questions arise such as pooling passengers, energy constraints, varying passenger destinations and other factors that need to be considered. All these lie outside the system boundaries of the model's environment.

The *controller* is representative of an all-knowing air traffic controller who has perfect knowledge of all passenger and vehicle states and locations. They work through all requests, assigning vehicles to arriving passengers, and through all arrivals, assigning destinations to both passengers and vehicles. The controller becomes aware of a vehicle arriving in the airspace and a passenger arriving at the terminal at the moment of arrival with no prior notification. Therefore, the controller reacts to the given situation and cannot plan ahead. Next to processing all new vehicle arrivals and passenger requests, the controller monitors all waiting agents and serves them according to the first-in-first-out principle.

Appendix B. Expert Interview Questionnaire

In the following, an excerpt of questions is shown from the expert interview series conducted for the purpose of refining the vertiport model and determining the parameter values. The experts received an interview guide including the questions ahead of time. Not all questions were answered every time, accounting for the individual backgrounds of the experts and their partial inability to pass on information due to confidentiality reasons. The expert interview series was conducted between October 2020 and July 2021 and encompassed 17 experts with divers backgrounds.

P3Q1: Within the current model, what would you assume to be the critical path or design driver?

P3Q2: Which elements or processes are you missing?

P3Q3: For which processes would you see the greatest optimization potential?

P3Q4: Where do you anticipate the biggest operational safety threats?

P4Q1: What is your estimated value for each of the parameters below? What would be a minimal value? A maximal value? How sure are you (1 = very sure, 2 = sure enough, 3 = educated guess)?

P4Q2: Which parameters of the above list would you define as most important?

P4Q3: What other parameters would you find interesting or critical?

Appendix C. Parameter List Evolution

In the following, the evolution of the parameter list, which is discussed in Section 4 is visualized in detail. The colors correspond to the individual lists (gray: full list, blue: long list, green: short list). The font corresponds to the evolution of the parameters. Regular font means the parameter was present in the initial list. Crossed-out font means the parameter was aggregated with other parameters into a supra-parameter or differentiated into multiple sub-parameters. Red font means the parameters were added later on and were not part of the initial list.

Group	ID	Parameter Description
Vertiport Elements	A1	Dimensions of pad
	A2	~~Dimensions of pad safety area~~
	A3	Dimensions of gate
	A4	~~Dimensions of gate safety area~~
	A5	Dimensions of stand
	A6	~~Dimensions of stand safety area~~
	A7	Dimensions of taxi-way
	A8	~~Dimensions of taxi-way safety area~~
	A9	Dimensions of terminal
Passenger Processing	B1	Path facility entry door to ticket scan
	B2	Ticket scan
	B3	Path ticket scan to security check
	B4	Security check
	B5	~~Path security check to luggage drop off~~
	B6	Luggage drop off
	B7	Path luggage drop off to gate door
	B8	~~Stepping through gate door to vehicle proximity~~
	B9	~~Leaving vehicle proximity~~
	B10	Path security check to holding place in terminal
	B11	Passenger walking from holding place in terminal to gate
	B12	Passenger walking from gate to holding place in terminal

Group	ID	Parameter Description
Passenger Boarding	C1	Passenger ~~step into helicopter~~ board helicopter
	C2	~~Sit down & buckle up~~
	C3	~~Passenger loosen buckle & get up~~
	C4	Passenger ~~step out of helicopter~~ de-board helicopter
	C5	Passenger leave ~~pad (see Processing Parameters)~~ gate
	C6	Passenger enter ~~pad (see Processing Parameters)~~ gate
	C7	~~Helicopter open door~~
	C8	~~Helicopter close door~~
	C9	Safety instruction of passenger
	C10	Variation with multiple passengers
	C11	Store Luggage
	C12	Unloading luggage & pick-up by passenger
	C13	Turn off electronic devices
	C14	Verbal exchange with flight crew
	C15	Deploy staircase/entry aid
	C16	Extract staircase/entry aid
Vehicle Taxiing	D1	Walking speed of passenger
	D2	Speed of hover taxiing on Taxiway
	D3	~~Time for starting and stopping rotors for active taxiing~~
	D4	Speed of passive taxiing device on Taxiway
	D5	Time to mount ~~and de-mount~~ passive taxiing device
	D6	~~Time leaving/entering Pad/Gate/Stand~~
	D7	Time to de-mount passive taxiing device
	D8	Speed of active taxiing with motors at wheels

Group	ID	Parameter Description
Take-Off and Landing	E1	Starting Rotors
	E2	Stopping Rotors
	E3	~~Transition time of Rotor speed from approach to active taxiing~~
	E4	~~Transition time of Rotor speed from active taxiing to departure~~
	E5	Visual Inspection by pilot/sensors for surrounding contingencies
Flight Approach and Departure	F1	Initial hover
	F2	Final hover
	F3	Leaving Pad airspace
	F4	Entering Pad airspace
	F5	Diameter/~~Height~~ of controlled vertiport airspace
	F6	Descend speed within controlled vertiport airspace
	F7	Descend angle within controlled vertiport airspace
	F8	Climb speed within controlled vertiport airspace
	F9	Climb angle within controlled vertiport airspace
	F10	Descend/~~Climb~~ path detour from diagonal beeline
	F11	Cooldown after landing due to wake vortices
	F12	Cooldown after take-off due to down wash
	F13	Height of controlled vertiport airspace
	F14	Climb path detour from diagonal beeline

Figure A3. *Cont.*

Group	ID	Parameter Description
Battery Charging	G1	Connect charging cable + safety check
	G2	Disconnect charging cable + clean up area
	G3	Charging speed (with non-constant effect?)
	G4	Ampere ~~and Voltage~~ levels ~~+ dimensioning of cables & plugs~~
	G5	Battery capacity of vehicle
	G6	Apply thermal management device
	G7	Power needed of cooling device
	G8	Preferred charging level
	G9	Minimal discharged level
	G10	Energy loss due to inefficiency
	G11	Voltage Levels during charging
Battery Swapping	H1	Physical dimensions of battery pack
	H2	Number of standards
	H3	~~Distance of battery pack storage to swapping area~~
	H4	~~Deployment/Extraction speed of battery back~~
	H5	~~Time for safety check before and after swapping~~
	H6	~~Unplugging of old battery back~~
	H7	~~Moving away/in of old/new battery pack~~
	H8	~~Plugging in of new battery pack~~
	H9	Swapping Time
	H10	Area with swapping possibility (gate? Stand!)

Group	ID	Parameter Description
Vehicle Maintenance	I1	Visual inspection for damage
	I2	Cockpit checklist (avionics, navigational, communication)
	I3	Cleaning interior
	I4	Cleaning windscreen and windows
	I5	Oil check
	I6	Warming up vehicle after parking at stand (pendant to de-icing)
	I7	Routine vehicle maintenance necessary after number of flight
	I8	Duration of routine vehicle maintenance
General Vertiport Operations	J1	Cleaning Taxiways
	J2	Cleaning Pads
	J3	Number of operations before cleaning taxiway is necessary
	J4	Number of operations before cleaning pad is necessary

Colorcode list
Full list
Long list
Short List
Colorcode action
Part of initial list
~~Aggregated/differiantiad after expert interviews~~
Added after expert interviews

Figure A3. Evolution of parameter list.

Appendix D. Parameter Short List

In the following table, the essential parameters for vertiport operations are described. The "initial ID" corresponds to the IDs used throughout the evolution of the parameter list (see Appendix C). The "new group" and "new ID" correspond to the group definition in Section 4.3. All parameters have a descriptive title, and all time-based parameters are additionally described in terms of their initial and final state.

Table A1. Parameter definition of final short list.

Initial ID	New Group	New ID	Parameter	Time Starts	Time Ends
A1	Elements	-	Dimensions of pad	-	-
A3	Elements	-	Dimensions of gate	-	-
A5	Elements	-	Dimensions of stand	-	-
A7	Elements	-	Dimensions of taxiway	-	-
B11	Boarding	B1	Terminal to gate	Passenger starts walking from waiting area in the terminal	Passenger arrives at door connecting the terminal and the airfield
B12	Boarding	B6	Gate to terminal	Passenger starts walking from door connecting the airfield and the terminal	Passenger arrives at waiting area in the terminal

Table A1. *Cont.*

Initial ID	New Group	New ID	Parameter	Time Starts	Time Ends
C6	Boarding	B2	Enter gate	Passenger steps through the door between terminal and airfield	Passenger arrives at immediate proximity of the vehicle
C5	Boarding	B5	Leave gate	Passenger starts walking away from the vehicle	Passenger steps through door, leaving the airfield, and enters the terminal
C1	Boarding	B3	Boarding	Passenger steps into the vehicle	Passenger is buckled up and ready for takeoff
C4	Boarding	B4	De-boarding	Passenger unbuckles and begins to gather belongings	Passenger exits the vehicle and steps onto the ground
D5	Taxiing	T1	Mounting passive taxiing device	Vehicle is stationary at mount location, and passive taxiing device is ready to be mounted	Passive taxiing device is mounted to vehicle
D4	Taxiing	T2	Passive taxiing	-	-
D7	Taxiing	T3	De-mounting passive taxiing device	Vehicle is stationary at mount location, and passive taxiing device is ready to be de-mounted	Passive taxiing device is de-mounted from vehicle
D8	Taxiing	T4	Active taxiing	-	-
D2	Taxiing	T6	Hover taxiing	-	-
F4	Approach and Departure	A1	Enter airspace	Vehicle is in final approach and about to enter physical airspace of the pad	Vehicle finishes descent or forward movement
F2	Approach and Departure	A2	Final hover	Vehicle stopped descent or forward movement	Vehicle wheels or skids touch the ground
E2	Approach and Departure/Taxiing	T7/A3	Stop engine	Engine power is on idle	Engine is off
F11	Approach and Departure	A4	Cool-down (landing)	Vehicle taxied off the pad	Next operation can be initiated: entering physical airspace of the pad during approach or taxiing onto pad from the airfield
E1	Approach and Departure/Taxiing	T5/D1	Start engine	Engine is off	Engine is ready for takeoff or taxiing
F1	Approach and Departure	D2	Initial hover	Vehicle wheels or skids stop touching the ground	Vehicle begins ascent or forward movement
F3	Approach and Departure	D3	Leave airspace	Vehicle begins ascent or forward movement	Vehicle exits physical airspace above the pad
F12	Approach and Departure	D4	Cool-down (take-off)	Vehicle left the physical airspace of the pad	Next operation can be initiated: entering physical airspace of the pad during approach or taxiing onto pad from the airfield

Table A1. *Cont.*

Initial ID	New Group	New ID	Parameter	Time Starts	Time Ends
G10	Energy	E1	Energy loss	-	-
G5	Energy	E2	Battery capacity	-	-
G3	Energy	E3	Charging speed	-	-
H9	Energy	E4	Swapping time	Vehicle rests at swapping facility ready for swapping, old battery pack on board	Vehicle is ready to leave swapping facility, new battery pack on board

Appendix E. Notes on Confidence of Parameter Value Determination

In the following, the statistical considerations during the determination of the parameter values are presented, including an interpretation of the confidence of the determination. In the table below, all parameters (index i) of the short list (see Appendix D for the definition of the parameters) are presented, including the number of datapoints from expert interviews and the literature. Both groups, expert responses v^i_{exp} and the literature v^i_{lit}, are treated separate at first: the median v^i_{med} and average v^i_{avg} values of both groups are calculated individually. For the literature group, both median $v^i_{lit,med}$ and average $v^i_{lit,avg}$ values for each parameter are unweighted. For the expert group, the median values $v^i_{exp,med}$ are unweighted, and the average values $v^i_{exp,avg}$ are weighted according to the confidence levels the experts gave during the interviews (see Appendix B). As a measure of agreement between values from experts and the literature, the variance Δv^i between the two groups is defined according to Equation (A1). The variance is calculated for the median Δv^i_{med} and average Δv^i_{avg} values. The values are then calculated separately for median $v^i_{cal,med}$ and average $v^i_{cal,avg}$ according to Equation (A2). The value whose absolute variance $\left|\Delta v^i\right|$ is smaller is then chosen to be the final value v^i.

$$\Delta v^i = \frac{v^i_{exp} - v^i_{lit}}{v^i_{lit}} \tag{A1}$$

$$v^i_{cal} = \frac{v^i_{lit} + v^i_{exp}}{2} \tag{A2}$$

To find a further measure of agreement, this time, between all values, the concept of a normal distribution is applied, which is defined through its expected value μ and its standard deviation σ. μ is defined to be the final value v^i and σ is calculated according to Equation (A3), with n^i being the number of datapoints for parameter i and v^i_k denotes an individual datapoint. Analysis of a normal distribution shows that about two-thirds of all values lie with $\pm 1\sigma$ of the expected value.

$$\sigma^2 = \frac{1}{n^i} \sum_{n=1}^{k} \left(v^i_k - \mu \right)^2 \tag{A3}$$

Three criteria of confidence are defined to determine the overall confidence of the value determination for each parameter. If all three criteria are met, the confidence is considered high. If two criteria are met, the confidence is considered medium. If one ore no criteria are met, the confidence is considered low. The definition of the criteria is as follows:

1. The parameter i has five or more total datapoints.
2. The absolute variance $\left|\Delta v^i\right|$ of both median and average is below a value of 0.5.
3. The quotient of two times the standard deviation and the expected value $\frac{2*\sigma}{\mu}$ is below a value of 1.0.

ID	Parameter	Unit	# Experts	# Literature	# Total	Median experts	(weigthed) Average experts	Median literature	Average literature	Varianz median	Varianz average	Calibrated median	Calibrated average	Standard deviation sigma	2 x sigma / mu	Confidence
B1/B6	Terminal to/from gate	s	3	0	3	15.0	31.9	-	-	-	-	15.0	31.9	21.2	1.33	low
B2	Enter gate	s	5	0	5	15.0	19.7	-	-	-	-	15.0	19.7	19.8	2.02	low
B3	Boarding	s	4	5	9	45.0	73.3	60.0	72.7	-25%	1%	52.5	73.0	59.7	1.64	medium
B4	De-boarding	s	4	4	8	42.5	56.7	60.0	75.0	-29%	-24%	51.3	65.8	34.9	1.06	medium
B5	Leave gate	s	2	0	2	35.0	26.7	-	-	-	-	35.0	26.7	25.0	1.88	low
T2	Passive taxiing	m/s	6	0	6	2.64	2.63	-	-	-	-	2.64	2.63	2.08	1.58	low
T1/T3	(De-)mounting passive taxiing device	s	3	0	3	60.0	27.0	-	-	-	-	60.0	27.0	25.9	1.92	low
T4	Active taxiing	m/s	5	1	6	2.78	3.44	1.52	1.52	82%	125%	2.15	2.48	1.43	1.33	low
T6	Hover taxiing	m/s	3	3	6	5.00	4.78	1.34	1.72	273%	178%	3.17	3.25	2.18	1.35	low
T5/D1	Start engine	s	2	0	2	4.00	4.50	-	-	-	-	4.00	4.50	1	0.44	low
T7/A3	Stop engine	s	2	0	2	5.00	5.00	-	-	-	-	5.00	5.00	0	0.00	low
A1	Enter airspace	s	6	2	8	40.0	33.8	52.5	52.5	-24%	-36%	46.3	43.2	25.9	1.12	medium
A2	Final hover	s	5	5	10	15.0	17.4	30.0	28.4	-50%	-39%	22.5	22.9	15.6	1.37	low
D2	Initial hover	s	5	5	10	15.0	17.5	12.0	23.6	25%	-26%	13.5	20.5	16.5	2.45	medium
D3	Leave airspace	s	6	1	7	25.0	27.4	30.0	30.0	-17%	-9%	27.5	28.7	21.6	1.50	medium
A4/D4	Cooldown after landing/take-off	s	3	3	6	30.0	37.1	30.0	50.0	0%	-26%	30.0	43.6	26.1	1.74	medium
E3	Charging speed	kW	4	7	11	225	225	450	396	-50%	-43%	338	311	181	1.17	low
E2	Battery capacity	kWh	4	3	7	100	142	126	124	-20%	14%	113	133	56.3	0.85	high
E1	Energy loss	%	3	3	6	5.00	6.00	10.00	8.33	-50%	-28%	7.50	7.17	2.91	0.81	medium
E4	Swapping time	s	2	5	7	398	438	300	234	33%	87%	349	336	150	0.86	medium

criterium met · criterium not met · final calibrated value

Figure A4. Statistical analysis of parameter value specification and confidence.

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4.3 Vertiport Simulation Results and Design Heuristic (Publication #3)

Title: *A Vertiport Design Heuristic to Ensure Efficient Ground Operations for Urban Air Mobility*

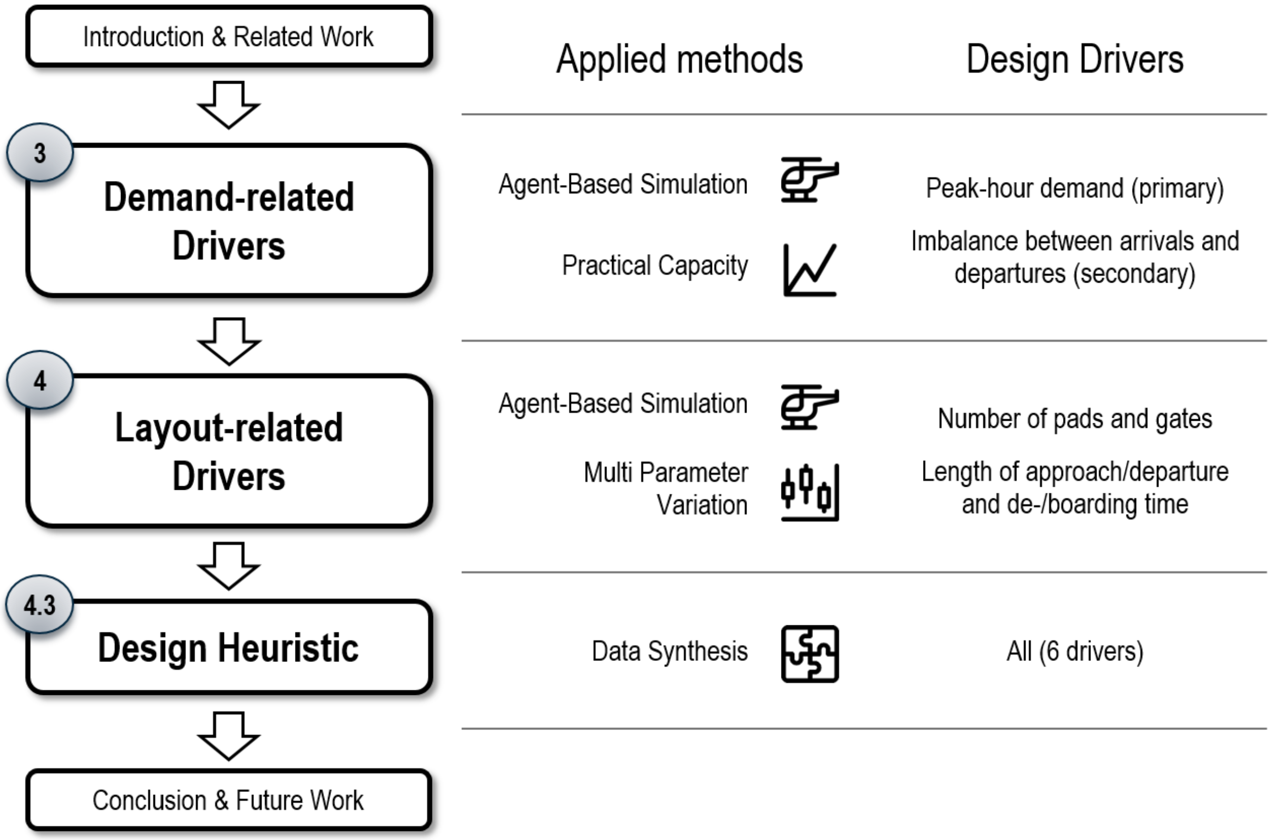

Figure 4.3 Graphical abstract of publication #3: "A Vertiport Design Heuristic to Ensure Efficient Ground Operations for Urban Air Mobility".

4.3.1 Summary

Urban Air Mobility is a novel concept of transportation with unknown market potential. Even in conservative estimates, thousands of operations could be expected on a single vertiport. This exceeds known heliport operations, which is the most comparable existing mode of transport—by far. Vertiport operations, in particular the dynamics on the airfield, are not well understood; in the following article, we want to address this research gap. By using means of agent-based simulation, the following design drivers were identified: peaks in demand, imbalance between arrivals and departures, pad operations and gate operations. We calculate a practical hourly capacity of 264 movements for our baseline scenario consisting of 4 pads, 12 gates and 20 stand. We are further able to shown that avoiding this peak and staying below a maximum imbalance between arrivals and departures of less than 33 ensures an average passenger delay of less than 3 min. Lastly, we present a parameter study varying the number of pads and gates, the length of approach/departure and boarding/de-boarding and the level of demand. The results of this study are aggregated into a graphical design heuristic displaying the interchangeability of the mentioned aspects.

4.3.2 Contributions

Conceptualization, L.P. and M.H.; methodology, L.P.; software, L.P.; resources, M.H.; data curation, L.P.; writing—original draft preparation, L.P.; writing—review and editing, L.P. and M.H.; visualization, L.P.; supervision, M.H.

L.P.: Lukas Preis (BHL)
M.H.: Mirko Hornung (BHL)

4.3.3 Citation

L. Preis and M. Hornung, “A Vertiport Design Heuristic to Ensure Efficient Ground Operations for Urban Air Mobility,” MPDI Applied Sciences, vol. 12, no. 13, p. 7260, 2022. DOI: 10.3390/app12147260

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Article

A Vertiport Design Heuristic to Ensure Efficient Ground Operations for Urban Air Mobility

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Abstract: Urban Air Mobility is a novel concept of transportation with unknown market potential. Even in conservative estimates, thousands of operations could be expected on a single vertiport. This exceeds known heliport operations, which is the most comparable existing mode of transport—by far. Vertiport operations, in particular the dynamics on the airfield, are not well understood; in the following article, we want to address this research gap. By using means of agent-based simulation, the following design drivers were identified: peaks in demand, imbalance between arrivals and departures, pad operations and gate operations. We calculate a practical hourly capacity of 264 movements for our baseline scenario consisting of 4 pads, 12 gates and 20 stand. We are further able to shown that avoiding this peak and staying below a maximum imbalance between arrivals and departures of less than 33 ensures an average passenger delay of less than 3 min. Lastly, we present a parameter study varying the number of pads and gates, the length of approach/departure and boarding/de-boarding and the level of demand. The results of this study are aggregated into a graphical design heuristic displaying the interchangeability of the mentioned aspects.

Keywords: urban air mobility; vertiport; agent-based simulation; design heuristic; operational delay; practical capacity

check for updates

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1. Introduction

The question of potential demand for Urban Air Mobility (UAM) is one of the key factors in designing the UAM-system. Demand considerations range from marginal significance all the way up to establishing a new mode of transport: a mode that could be affordable to a substantial part of the population. At this point in time, it is difficult to predict the market potential of UAM as can be seen by the differing results of two major market studies commissioned by NASA in 2018 [1,2]. Ploetner et al. published five scenarios for UAM demand in the Munich metropolitan area for the year 2030. The scenarios range from conservative to progressive assumptions [3]. It is worth to observe that even, in the more pessimistic scenarios, there are 5000 and 38,000 trips per day in a network of 24 vertiports. This would lead to daily demands of potentially thousands of vehicles for the busier vertiports and, thus, far exceed current operational experience and capacity.

While conventional modes of individualized ground-based traffic (e.g., cars) can easily cope with these volumes of demand, the minimal expected demand of a mature UAM system surpasses known helicopter operations by at least one magnitude. For example the heliports at Chicago O'Hare International Airport and Chicago Midway International Airport had around 50,000 annual operations in the year 1960, a time of high demand, which equals an average of around 140 operations per day [4]. Helicopters are the mode of transport that many say is most similar to how UAM is going to operate [5,6]. This is due to the shared Vertical Take-Off and Landing (VTOL) capability. When considering the necessary ground infrastructure this presents a major problem. Other aspects of this new mode of transport might be ready for launch and add value to the transport system;

however, the operations on the ground are not only unknown but also difficult to anticipate. Therefore, every effort must be made to understand vertiport operations in general and airfield operations in particular before UAM can take-off.

Both vertiport Air Traffic Management (ATM) and general vertiport layout capacities have been studied to some extent, but (dynamics of) operations on the airfield have been neglected so far. For the vertiport ATM, the questions of arrival management and queuing of vehicles when the capacity limit is reached seems to be of special interest. Various strategies for approaching vehicles have been proposed such as concentric circles for holding loops [7], a rolling horizon to buffer the arrival time [8] or spiral-shaped approach and departure paths above the vertiport [9]. In addition the throughput of vertiports was analyzed in terms of vertiport capacities [10] and airfield topologies [11]. Though these are valuable first steps, the studies take a system-level approach and do not consider dynamics of vertiport airfield operations and in particular conflicts between individual participants of the operations. Schweiger et al. was the first to simulate vertiport operations with a discrete-event modeling approach [12]. However the purpose of the study was the development of a vertiport airside concept of operations and was limited to one vertiport scenario. Further mention is due to Rimjha et al. who also uses discrete-event simulation [13], yet the number of operations is limited to 325 per day and the scenarios, therefore, do not reach the expected complexity of operations. The sensitivities of vertiport operations and the dynamics of vertiport airfield operations remain unknown according to the current state of literature.

This article wants to increase the level of understanding around vertiport design through agent-based simulation and identify and quantify the main drivers of operations. The main gap of understanding, as identified above, lies first with the vertiport airfield (airside-ground). Second, it lies with the operational dynamics including peaks in demand and conflicts between actors involved in the operations. This leads to the following research question:

Is it possible to predict the operational efficiency of a given vertiport based on limited knowledge of the proposed layout and expected demand?

The main contributions of this work are fourfold: (1) the main drivers of operational inefficiency (throughout this article measured as "passenger delay") will be identified. (2) By applying the concept of "practical capacity" borrowed from airport operations (see Section 3) the thresholds for efficient vertiport operations will be be quantified. (3) A variation of vertiport layouts and processes will be studied alongside varying demand to understand the impact of pad and gate operations (see Section 4). (4) The results of pad and gate studies will be aggregated into a graphical display to enable transfer of insights between a range of vertiport layouts and operational specifications (see Section 4.3). Thus, the above-stated research question will be answered through establishing a design heuristic, which captures all top-level drivers of vertiport operations.

2. Related Work

This article wants to shed light on vertiport airfield operations and show its dynamic sensitivities. For these purposes, a customized Agent-Based Modeling and Simulation (ABMS) framework will be facilitated, which focuses on vertiport airfield operations while including passenger terminal and airspace operations on the system's boundaries. The model and parameter value specifications are described in [14] and the software implementation in the programming language *Python* is described in [15]. The methodological foundation is laid in [14], which is a publicly available article: it was originally published in a MDPI *Electronics* Special Issue on "Urban Air Mobility" and can be downloaded under https://www.mdpi.com/2079-9292/11/7/1071 (accessed on 29 May 2022). Below, we only include a brief summary of the main elements of the model and in order to avoid repetition want to refer the reader to the original article. The advancement of the ABMS method is not an objective in this article, but rather the application of the existing method and the creation of quantified and transferable results.

The basic model consists of three types of elements: (1) pads for vertical take-off and landing, which are the interface towards the airspace surrounding the vertiport. (2) Gates for boarding and de-boarding of passengers, which are the interface towards the terminal where the pre-flight passenger processing happens. (3) Stands for parking vehicles during off-peak times. These three elements are connected through (4) taxi lanes. In this virtual environment, two types of agents can move and interact: (I) vehicles and (II) passengers. To simulate one day of operations, the simulation needs four types of inputs: (A) a vertiport layout given by the coordinates of the centers of the three elements described above; (B) a list of plans, which consists of requests of passengers and arrivals of vehicles; (C) an initial population, which are the vehicles parked on the vertiport at the start of the simulation; (D) a list of parameter values defining the length of individual processes occuring on the airfield. Together, inputs A–D make up a scenario. The elements, agents, environment and inputs are depicted in Figure 1. In the visualizations throughout this article, any specific result (e.g., average passenger delay) of one simulation scenario is depicted as a dot.

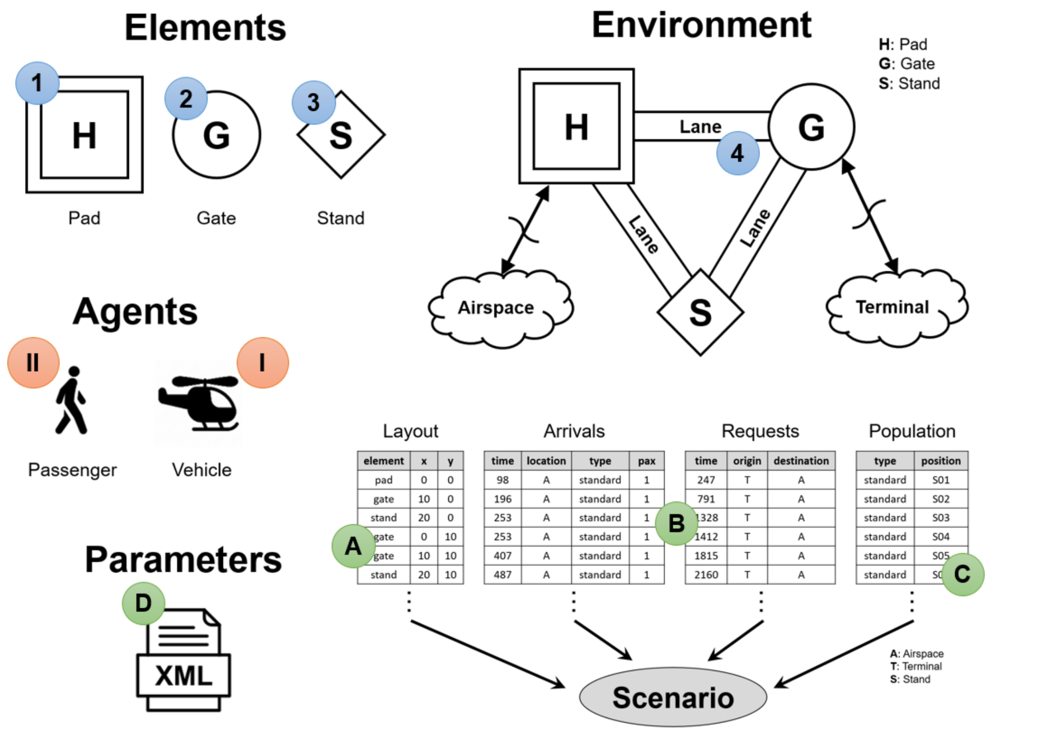


Figure 1. Depiction of elements, agents and environment of the agent-based simulation framework for vertiport operations; further including inputs needed for one simulation scenario.

In previous publications [14,16], the following insights were presented (as depicted in Figure 2), which will be expanded in this work:

1. Operations on gates (e.g., passenger boarding) can be a bottleneck to operations and, therefore, should be considered in vertiport capacity planning. This diverts from conventional airport planning where the runways are the main limiting factor considered in the capacity planning process (see for example [17,18]).
2. Increasing/decreasing the time of processes on pads or gates (e.g., approach or boarding time, respectively) has a similar effect as reducing/expanding the number of pads or gates. Both increased process times and reduced number of elements beyond a certain threshold yield an exponential increase in delay.
3. The accumulated daily demand is generally not a reliable indicator for operational efficiency; instead, using the peak-hour demand yields more reliable predictions about delay. Analysis of peak-hour demand is typical for airports, but not for heliports. It

can, therefore, be assumed that heliports do not operate at capacity limit. Previous simulations showed that the peak-hour demand is the strongest driver of delay.

4. The imbalance of arrivals and departures has a substantial impact on passenger delay. This phenomenon can be explained by a state when a vertiport is either drained of all vehicles, forcing passengers to wait for arriving vehicles, or when the vertiport is fully stocked and arriving vehicles have no gates or stands they can taxi to.

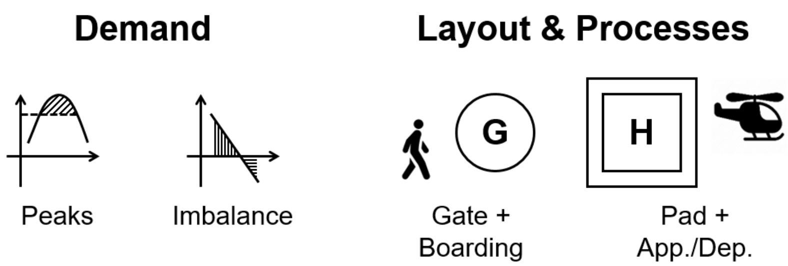


Figure 2. Depiction of design drivers for vertiport operations.

This article advances the state of research from the two previous publications in the following ways: First, it synthesizes the demand-related [14] and layout-related [16] drivers of vertiport operations into a holistic framework. Second, the number of simulation studies increased from 138 in [14] and 105 in [16] to over 750 in this article to cover a wider range of possible designs. Third, "practical capacity" (see Section 3.1) is introduced as a method to quantify delays. Forth, through the design heuristic presented in Section 4.3, results become transferable to other layouts and scenarios and the interchangeability of driving aspects is graphically displayed.

3. Demand-Related Drivers of Vertiport Operations

This section explores the effect different magnitudes and shapes of demand profiles have on the efficiency of vertiport airfield operations. Inefficient operations are measured in terms of average passenger delay as defined in Section 3.3. As was mentioned in Section 2, previous work has given reason to expect a threshold between efficient and inefficient operations. By using the concept of "practical capacity" borrowed from airport's capacity planning (see Section 3.1), this threshold will be quantified. The two main demand-related design drivers, peak-hour demand and imbalance between arrivals and departures, will then be separated and their effects described independently. It will be shown that avoiding both drivers ensures low delays and confirms that operational inefficiency is adequately described by these two effects.

3.1. Practical Capacity

Airport capacity planning uses a concept called "practical (hourly) capacity" (PHCAP) to determine the threshold between regular and congested operations. With increasing (hourly) demand also the average delay of each aircraft increases; typically in an exponential fashion. A threshold time of maximum allowable average delay is defined and the hourly capacity below this threshold is considered the "practical capacity" (see Figure 3). Operations beyond this hourly demand might be possible (referred to as "technical capacity"), but due to the exponential increase in delay the objectives of efficient traffic cannot be sustained. Typical threshold times extracted from standard works on airport design and other publications are shown in Table 1. For the purpose of this article, we chose the practical capacity to be 2–4 min as vertiport operations will be more time-sensitive than airport operations.

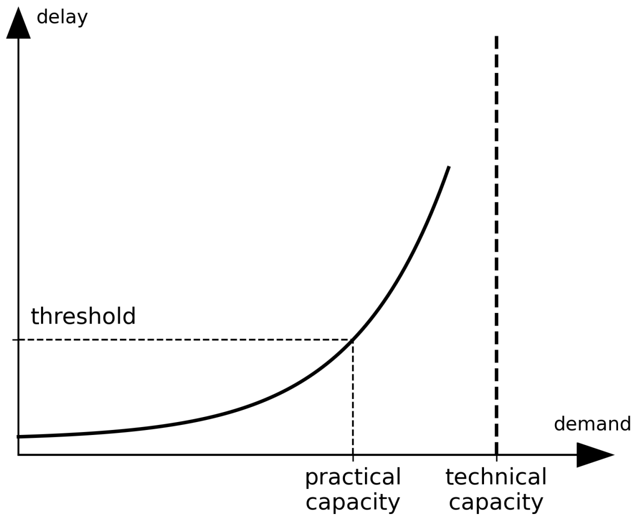


Figure 3. Concept of practical capacity, defined by a threshold of acceptable (average) delay.

Table 1. Practical capacity for airport capacity planning in the literature.

Author	Description	Time
Ashford [17]	Hourly capacity	3–10 min
Mensen [19]	Practical hourly capacity	-
Neufville [20]	Practical hourly capacity (PHCAP)	4 min
Wells [21]	Maximum acceptable delay for practical capacity	4–9 min
Bubalo [22]	Practical capacity under pre-defined Level-of-Service	5 min
OTA [23]	Practical capacity	5 min

3.2. Study Design

In this section, the concept of practical capacity will be applied to a baseline scenario to first understand the drivers of delay and second to quantify the practical capacity for the depicted scenario. The layout of the vertiport consists of 4 pads, 12 gates and 20 stands with 16 stands being occupied by vehicles at the start of simulation. From academia and industry various vertiport layouts have been suggested, some of which are reviewed in Appendix A; our proposed baseline layout is a compromise between these suggested layouts and our reasoning for this choice is elaborated on in the mentioned appendix. Approach and departure time are set to 45 s and boarding and de-boarding time are set to 95 s, both based on the parameter value specification in [14]. Operating time is assumed to go from 6 a.m. to 10 p.m., a 16-hour time window. In a parameter variation study the following three characteristics will be varied: (1) the shape of demand profile (see Figure 4 for an example of each shape); (2) the accumulated passenger demand over the course of the day of operations (16 h); (3) multiple variations of each demand profile (each variation is a random sample created from the combination of uniform and normal distributions as shown in Figure 4). The design of the study is presented in Table 2.

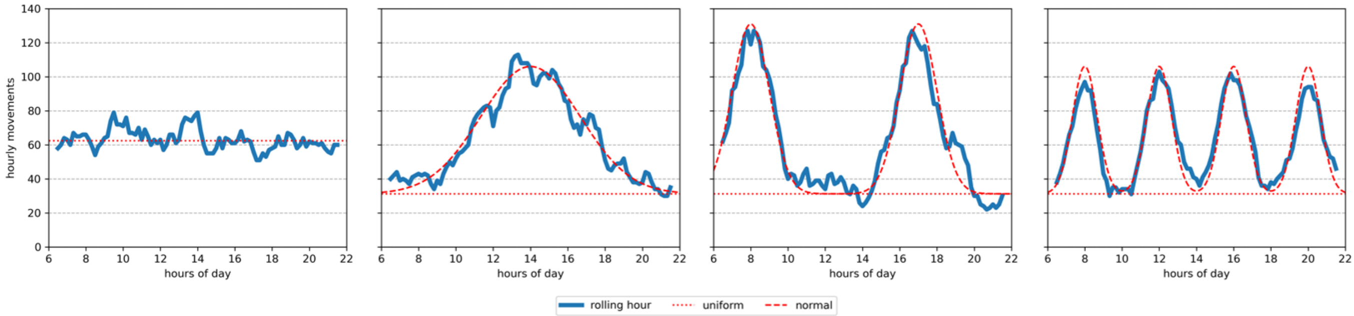


Figure 4. Examples of four shapes of randomly sampled demand profiles: uniform, single peak, bi-modal and four peaks (left to right).

Table 2. Study design for demand-related drivers of operations.

Demand Profile Characteristic	# of Variations	Description
Shape of demand profile	4	Uniform, single peak, bi-modal, four peaks
Accumulated daily passenger demand	21	1000 to 3000 in steps of 100
Random samples	3	Variations A–C
Total simulation scenarios	252	

3.3. Analysis of Daily Demand

Figure 5 shows the results of the study described in the previous section. Passenger delay is defined as the delta between the time a passenger spends on the airfield during optimal operations and actual operations. The average passenger delay is the average across all individual passenger delays. For more details on the definition of average passenger delay, please refer to the vertiport model description [14]. Next to the individual simulation results, exponential fits of each shape individually and all shapes collectively are portrayed. It can be seen that the residual error varies substantially, which confirms previous findings that the accumulated daily demand is not a reliable measure of expected delay. The best fit can be observed for the bi-modal shape ($R^2 = 0.95$), meaning that bi-modal distributions allow for the best prediction of delay; therefore, this shape will be used in the following study in Section 4.

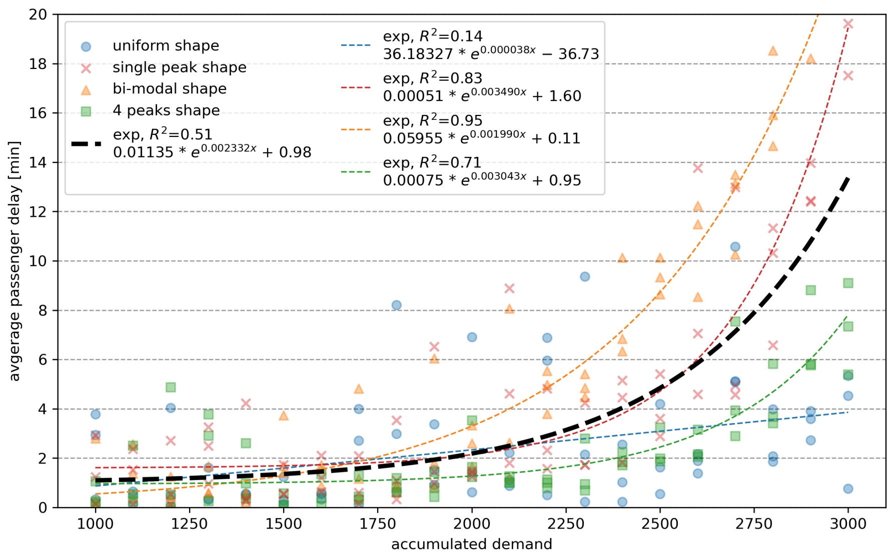


Figure 5. Analyzing the effect of accumulated daily demand on the average passenger delay.

3.4. Drivers of Delay

Instead of using the accumulated daily demand, the peak-hour demand will now serve as indicator. In Figure 6, it can be seen that the overall residual error improved from $R^2 = 0.51$ to $R^2 = 0.76$, showing that the peak-hour demand predicts delay better than the accumulated daily demand. Using 4 min as the threshold for the practical hourly capacity, the baseline vertiport layout shows $PHCAP = 264$. While the exponential fit is more accurate, there are still many outliers for peak-hour demands lower than the threshold. In a next step, all scenarios with peaks higher than 264 will be removed in order to investigate the source of the outliers.

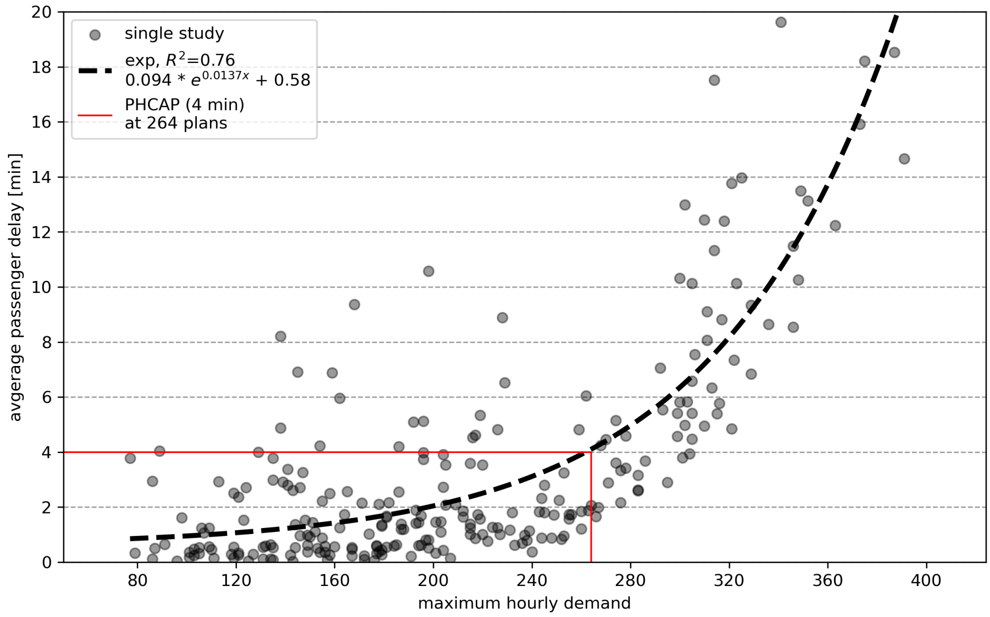


Figure 6. Analyzing the effect of peak-hour demand on the average passenger delay and identification of the practical hourly capacity PHCAP.

It has been proposed that imbalance between arrivals and departures, filling up or draining the vertiport of vehicles, is the second strongest driver of delay after peak-hour demand. In Figure 7, the average passenger delay is plotted over the maximum imbalance reached during the day for the remaining scenarios. Vehicle stock means the current number of vehicles present in the simulation environment minus the current number passengers present in the simulation environment is larger than the initial number of vehicles (16 for the baseline scenario). Passenger stock means this number is smaller than the initial number of vehicles. How vehicle and passenger stock evolve over the course of a day of operations is shown exemplary in Figure 8. For each scenario the higher value between vehicle stock and passenger stock is selected and visualized in Figure 7 including individual linear regressions and a combined linear regression. With a residual error of $R^2 = 0.77$, the quality of the regression is similar to the exponential fit for peak-hour demand. The imbalance of arrivals and departures has a lower impact on delay than peak-hour demand, but it is unclear how much lower the impact is. Therefore, a threshold of 2 min is chosen, which is half the threshold of 4 min that was applied earlier to the peak-hour demand. The threshold of 2 min is applied as an analogue to the practical capacity concept. This results in a "practical imbalance capacity" (PICAP) of $PICAP = 33$.

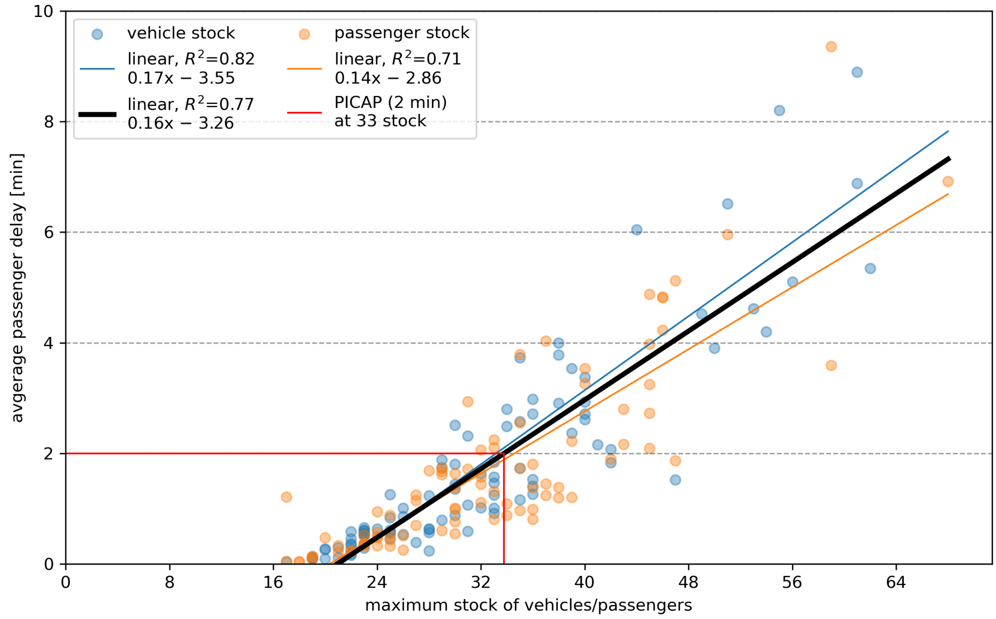


Figure 7. Analyzing the effect of vehicle/passenger stock on the average passenger delay and identification of the practical imbalance capacity PICAP.

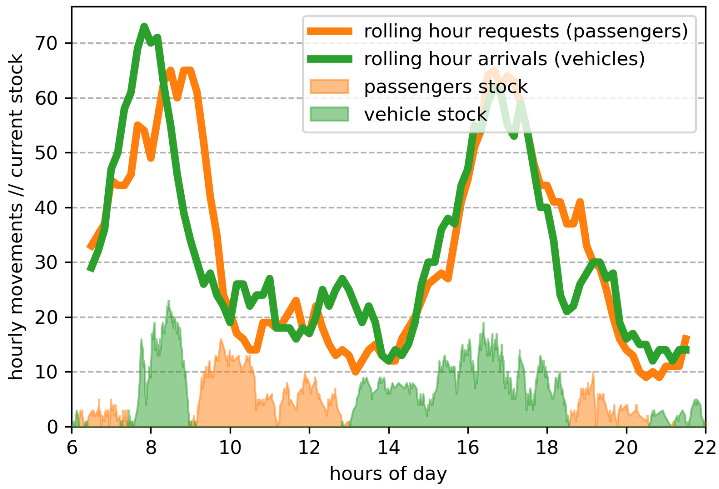


Figure 8. Illustration of vehicle and passenger stock resulting from imbalances in arrivals and departures.

To better decouple the two effects of peak-hour demand and maximum stock, the scenarios are split into four groups corresponding to the two thresholds. In Figure 9, the variation of average passenger delay for the four groups can be seen, including the size *n* of each group. As expected, when looking at scenarios which stay below both thresholds, the average passenger delays are low: 36 s median delay and below 3 min maximum delay, to be precise. This not only confirms that peak-hour demand and maximum stock are the two main design drivers, but also that the delay can accurately be predicted by abstracting the demand-profile to these two factors. It is further confirmed that peak-hour demand has the larger impact, as the group above the PHCAP threshold and below the PICAP threshold results in greater delays than the group below the PHCAP threshold and above the PICAP threshold. Furthermore, when excluding the effect of imbalance, the residual error of the exponential fit improves from $R^2 = 0.76$ to $R^2 = 0.87$ (see Appendix B). This affirms the accuracy of the PHCAP to predict delay.

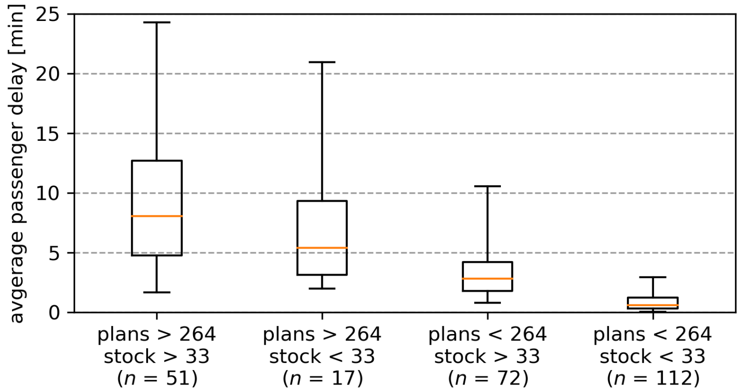
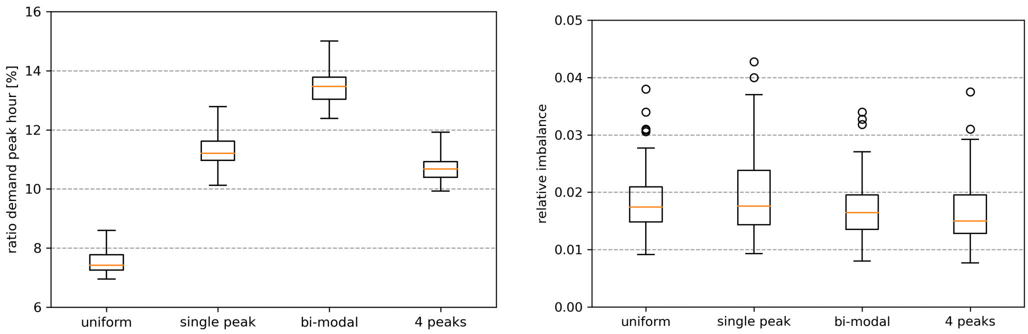


Figure 9. Four groups of scenarios based on their position related to the thresholds of PHCAP (plans = 264) and PICAP (stock = 33); the number n of scenarios falling into each category is listed in brackets.

3.5. Further Effects

For the scenarios above one ore both thresholds can be crossed while still leading to comparatively low average passenger delays. The cause for this cannot be explained by the proposed two factor analysis. In Figure 9, about a quarter of all scenarios, which exceed both thresholds, still result in average passenger delays of 5 min or less. Therefore, it may be concluded that avoid crossing the thresholds of peak-hour demand and maximum stock will prevent delays; but the opposite does not hold true: crossing both threshold delays does not need to increase the delay. One reason for this could be an oversimplification of both factors. The peak-hour demand only indicates the tip of the peak, but not how broad the curve is. Similarly, the stock only indicates the maximum level of imbalance, but not for how long this imbalance is maintained. We believe that simplification is justified for the current state of the art while all vertiport operation data is based on simulation and not experiments. In the future both factors might need to be expanded.

Lastly, to trace the peak-hour demand and maximum stock back to the accumulated daily demand, where the starting point was, we included Figure 10. When knowing only the accumulated daily demand and the shape of the demand profile, the peak-hour demand can be derived with reasonable confidence as can be seen in Figure 10a. We will facilitate this relationship in the following Section 4.2; here, the accumulated daily demand will be used to create discrete variations of plots. Yet, this is not true for the maximum stock: There seems to be insufficient correlation to predict the imbalance based on the accumulated daily demand and the shape of the demand profile (see Figure 10b).



(**a**) (**b**)

Figure 10. Reconstructing peak-hour demand and maximum stock based on knowledge of the accumulated daily demand and the shape of the demand profile. (**a**) Relation of peak hour demand to daily demand. (**b**) Relation of largest imbalance to daily demand.

4. Layout-Related Drivers on Vertiport Operations

This section will expand the previous study from Section 3 where only one vertiport airfield layout was considered and vary layouts and the length of processes taking place on pads and gates. It was shown that processes on pads and gates are design drivers [14] wherefore both number of pads and number of gates will be varied in a sensitivity study. Correspondingly, the length of approach and departure time and the length of boarding and de-boarding time will be varied alongside the number of pads and gates, respectively. For the shape of the demand profile a bi-modal distribution will be chosen for three reasons: first, bi-modal demand distributions are common in transportation with a morning and an afternoon peak. Second, as was shown in Section 3.3, bi-modal distributions allow for the best prediction of delay depending on the accumulated demand. Third, the main demand-related driver of delay is the peaks as shown in Section 3.4 and the peaks are most prominent for the bi-modal distribution.

4.1. Study Design

The number of pads and gates in combination with the approach and departure time and boarding and de-boarding time will be varied as presented in Tables 3 and 4. Further, three demand magnitudes of accumulated daily demand will be included. While it was shown that the daily demand is generally not a good indicator to predict delay, the peak-hour demand can be derived with reasonable accuracy from the daily demand (see Section 3.5), and the bi-modal distribution has the best correlation between daily demand and average passenger delay (see Section 3.3). The reason to choose accumulated daily demand in this study is to provide discrete sets of results for better visualization. Lastly, for each demand magnitude in the study three random samples will be included.

Table 3. Study design for pad-related drivers of operations.

Variation of Inputs	# of Variations	Description
Number of pads	4	2–5 pads in steps of 1
Approach and departure time	9;7;5	20–120 s in steps of 12.5 s
Accumulated daily demand	3	1000–2000 in steps of 500
Random samples	3	Variations A–C
Total simulation scenarios	252	

Table 4. Study design for gate-related drivers of operations.

Variation of Inputs	# of Variations	Description
Number of gates	4	6–12 pads in steps of 2
Boarding and de-boarding time	9;7;5	60–200 s in steps of 17.5 s
Accumulated daily demand	3	1000–2000 in steps of 500
Random samples	3	Variations A–C
Total simulation scenarios	252	

4.2. Analysis of Layout and Processes

Figures 11 and 12 show the results of the multi-parameter variation study for pads and gates respectively. Exponential fits are applied alongside the concept of practical capacity (see Section 3.1) with a threshold of 4 min. The time values for approach and departure and boarding and de-boarding corresponding to the 4 min threshold are written in each subplot. The columns represent studies with equal accumulated demand; the rows represent studies with equal number of pads or gates. For each subplot the residual error R^2 is given and the following general trend is observed: with higher demand or fewer pads/gates, R^2 is higher. Exponential growth of delay is, therefore, more clearly observed in cases were the capacity of the vertiport airfield is more strongly exceeded.

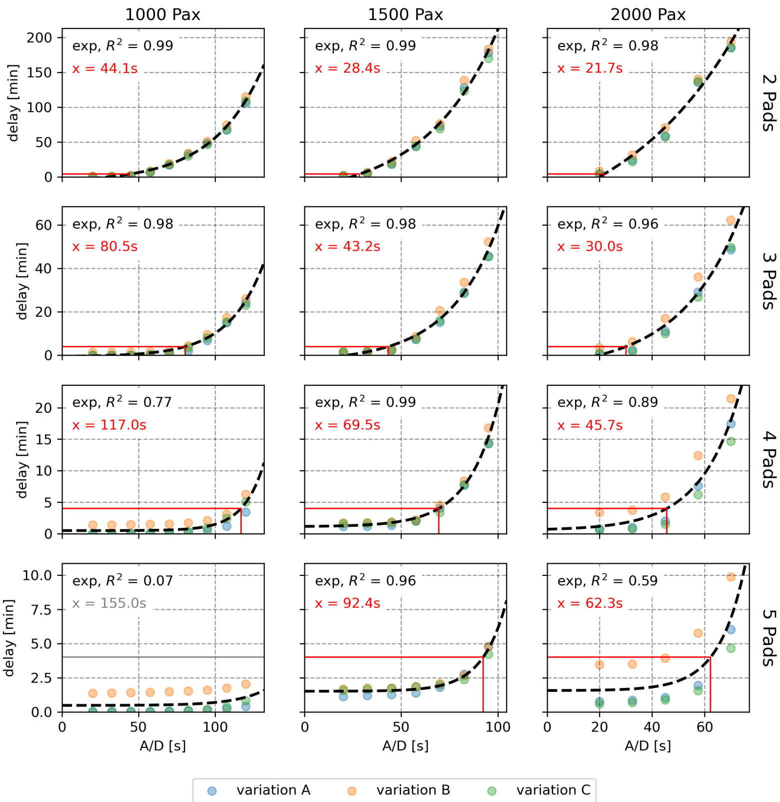


Figure 11. Simulation study under variation of demand, number of pads and approach and departure time (A/D).

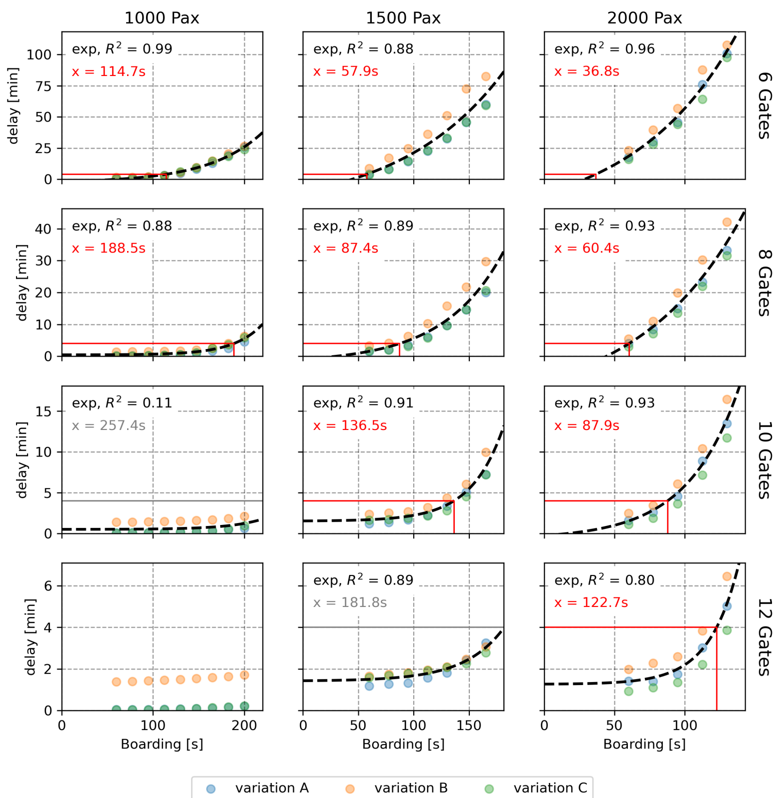


Figure 12. Simulation study under variation of demand, number of gates and boarding and deboarding time.

4.3. Design Heuristic

Using the threshold values from Section 4.2 a design heuristic is formulated to quantify the interchangeability between demand capacity, number of pads or gates and approach/departure or boarding/de-boarding time. Figure 13a,b provide a graphical solution to the design heuristic concerning pads and gates including related processes. Each point in the visualization yields the same result of an average passenger delay of 4 min. The relationship between number of elements (pad/gate) and the respective length of the processes taking place on the element are well estimated through a linear regression. The slope of the regressions flattens with the increase of demand. Two examples of how to use the design heuristic are shown in Appendix C.

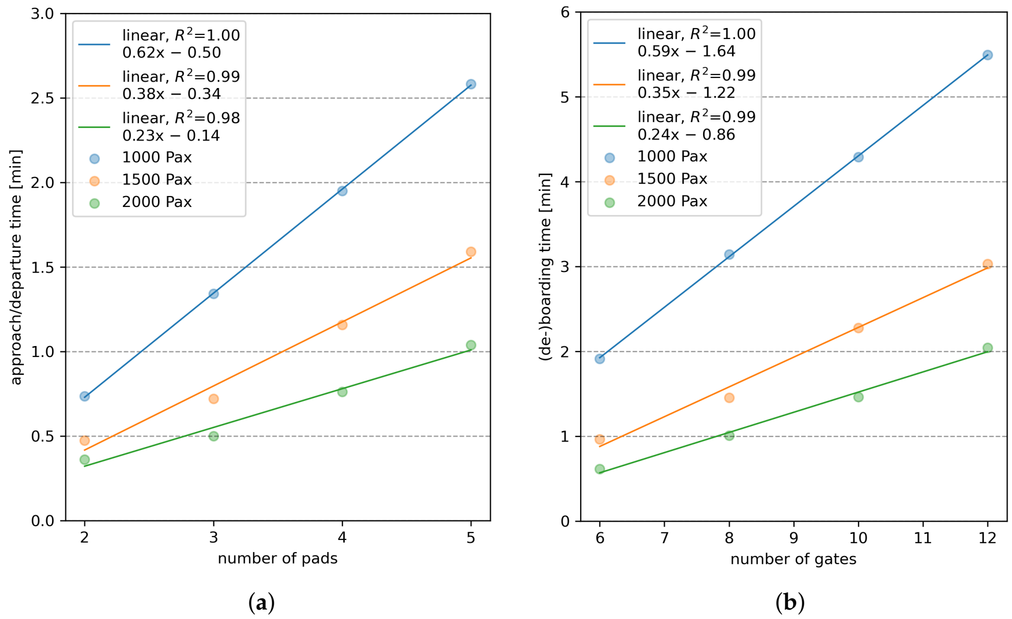


Figure 13. Graphical display of the interchangeability of demand capacity, number of elements and related processes. (**a**) Design heuristic for pad operations. (**b**) Design heuristic for gate operations.

5. Conclusions

Potential UAM demand is expected to lead to thousands of daily operations on a single vertiport. This exceeds the volume of past helicopter operations, which is the most comparable existing mode of transport by far. While vertiport airside-air operations have been studied to some extent, a gap in research has been identified around airside-ground operations on vertiport airfields. Furthermore, in a preceeding publication it was shown that operational dynamics on vertiports can not be neglected [16], which renders past static or system-level analysis of vertiport capacities insufficient. Before UAM can take-off, this gap of knowledge needs to be addressed.

For this article a custom-tailored ABMS framework [15] was fascilitated to investigate operational dynamics on vertiport airfields. It builds on preliminary insights on the drivers of delay around demand profiles [16] and vertiport layouts [14]. The main contributions of this article are fourfold: (1) The identified drivers of operational inefficiency have been confirmed. Looking at demand-related drivers, it was possible to prove that if the peaks of a demand profile and the imbalance between arrivals and requests stay within certain limits the average passenger delay is guaranteed to be low (below 3 min with a median of 36 s in the baseline scenario; see Section 3.4). (2) The mentioned thresholds between efficient and inefficient operations were quantified for the baseline scenario of 4 pads and 12 gates by using the concept of "practical capacity" (see Section 3.1). Defining thresholds of acceptable average delay of 4 min for peak-hour demand yielded $PHCAP = 264$; and of 2 min for the maximum imbalance of arrivals and departures yielded $PICAP = 33$ (see Section 3.4). (3) Looking at layout-related drivers, all of the following have shown high operational sensitivity expressed in exponential increase of delay: number of pads, number of gates, approach and departure time and boarding and de-boarding time. A multi-parameter variation of these factors including a variation of demand showed these sensitivities to hold true over a wide range of values, particularly for highly constrained scenarios as shown in Section 4.2. (4) The insight from 1–3 were aggregated into a design heuristic in order to transfer insights between scenarios and predict operational efficiency based on just a few characteristics (see Section 4.3).

The claim of this article is that the presented insights will allow to quantify the expected delay on a vertiport by knowing only the following six values:

1. Peak-hour demand;
2. Maximum imbalance between arrivals and departures;
3. Number of pads;
4. Number of gates;
5. Approach and departure time;
6. Boarding and de-boarding time.

This design heuristic can be applied in the broader context: Vertiport planners can use the design heuristic to create a vertiport airfield that will match the given constraints in terms of demand, available area and acceptable delay. Furthermore, vehicle designers and regulatory agencies can use the sensitivities presented in this article to optimize their work around processes on pads in particular but also on gates. Lastly, the UAM research community can use insights around delay in at least two ways: first to study its impact on operational procedures on the ground and in the air; second to model the effect of delay on demand and with that on market potential of UAM.

6. Limitations and Future Work

The design heuristic presented in this article is limited in range and granularity. In the simulation study in Section 4 we investigated a design space of 2–5 pads and 6–12 gates which shows linear behaviour according to the design heuristic. This might allow for extrapolation beyond the limits of the studied design space, but the consistency is unknown. Furthermore, we looked at 1000, 1500 and 2000 daily passengers, which is a rather coarse resolution; more granularity would allow for more precise application of the design heuristic. Another limitation worth mentioning is that we assumed uniform characteristics across all agents (e.g., all passengers have the same walking speed). While both passengers and vehicles will have varying characteristics in the real world, it was shown in a related study that this effect plays a negligible role [24].

Future work, as indicated in Section 3.5, should entail a more detailed analysis of peaks and imbalances of demand. Staying below the defined thresholds of $PHCAP = 264$ and $PICAP = 33$ guarantees low delays; but exceeding the thresholds does not necessarily lead to high delays (see also Figure 9). We propose future work on demand peaks to include not only the tip of a peak, but also the breadth. In this way statements can be made about how long the capacity threshold is exceeded. Similarly, we propose future work on imbalances to not only include the maximum imbalance, but also how long a high imbalance is maintained.

Another aspect worth considering is vehicle down-time at the gates or stands (e.g., for charging). Currently, the vertiport simulation operates in a touch-and-go fashion, meaning that vehicles are available for their next mission right after de-boarding is finished. In future real world operations, this assumption will only be true of some vertiports, while a down-time exceeding the boarding process can be expected for most vertiports. How this impacts vertiport operations needs to be investigated in the future.

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Abbreviations

The following abbreviations are used in this manuscript:

ABMS	Agent-Based Modeling and Simulation;
ATM	Air Traffic Management;
PHCAP	Practical Hourly Capacity;
PICAP	Practical Imbalance Capacity;
UAM	Urban Air Mobility;
VTOL	Vertical Take-Off and Landing.

Appendix A. Review of Vertiport Layouts

Various vertiport layouts have been proposed by academia and the industry. In Table A1, a review of sources defining vertiport layouts is presented. The focus hereby lies on the number of pads (for take-off and landing) and gates/stands (for boarding of passengers and parking of vehicles). In our article, gates have the function of allowing passengers to board and de-board the vehicle, while stands are used to park idle vehicles. In contrast, most of the presented sources do not differentiate between gates and stands.

Table A1. Review of vertiport layouts.

Source	Publication Type	# of Pads	# of Gates/Stands
McKinsey [25]	report	1–10	2–20
Lilium [26]	website	1–2	2–8
Volocopter [27]	website	1–4	-
DLR [28]	journal article	1/4	8/36
NASA [11]	conference paper	4	20–24
Virgina Tech [13]	conference paper	1–3	8–24
Purdue [29]	conference paper	4	14

As stated in Section 3.2, we chose a baseline vertiport layout of 4 pads, 12 gates and 20 stands. Four pads were chosen both by DLR (Germany) and NASA (U.S.), which we assumed to be the most trustworthy sources. Furthermore, using only one or two pads might not allow for more complex interactions to occur on the airfield, thereby rendering ABMS superfluous and preventing the results to be transferable to larger vertiport sizes. Four pads can be placed in the four corners of a square and allow for clear sectioning of the airspace; for more than 4 pads the airspace operations are not as straightforward anymore. For these reasons we chose four pads for our baseline layout, but varied the number from 2 to 5 pads, as shown in Section 4.1, to understand the broader design space.

Next, we chose the number of gates corresponding to the number of pads. The lengths of approach and departure time (45 s) and boarding and de-boarding time (95 s) were derived from the preceding publication [14]. To match the theoretically possible throughput on one pad (and while assuming the pads to be the initial bottleneck of operations) there would be a need of three gates. This results in 12 gates for four pads as gates are grouped around pads. Stands were then lined up around gates, which results in 5 stands per pad and accordingly 20 stands for the baseline vertiport layout. The geometric arrangement of one group is displayed in Figure A1.

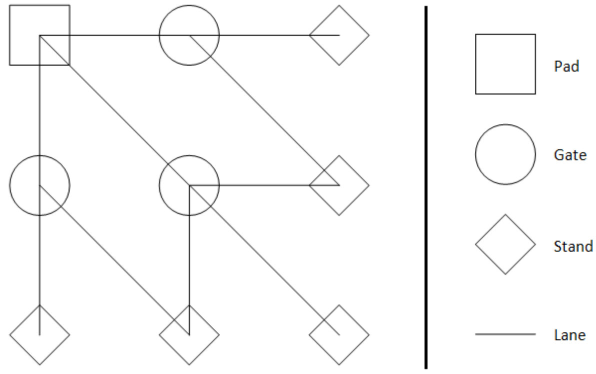

Figure A1. Schematic representation of one group of vertiport elements: 1 pad surrounded by 3 gates and 5 stands.

Appendix B. Isolating Driver of Practical Hourly Capacity

In Section 3.4, the drivers of delay are analyzed and de-coupled. It was shown that the peak-hour demand is the primary driver while the imbalance of arrivals and departures is the secondary driver. The hypothesis was formulated that outliers in Figure 6 can be explained by the stock of vehicles/passengers. In Figure A2, all scenarios were excluded, which have a maximum imbalance higher than the threshold of $PICAP = 33$. It can be seen that this improves the residual error of the exponential fit from $R^2 = 0.76$ to $R^2 = 0.87$ and thereby affirms the hypothesis.

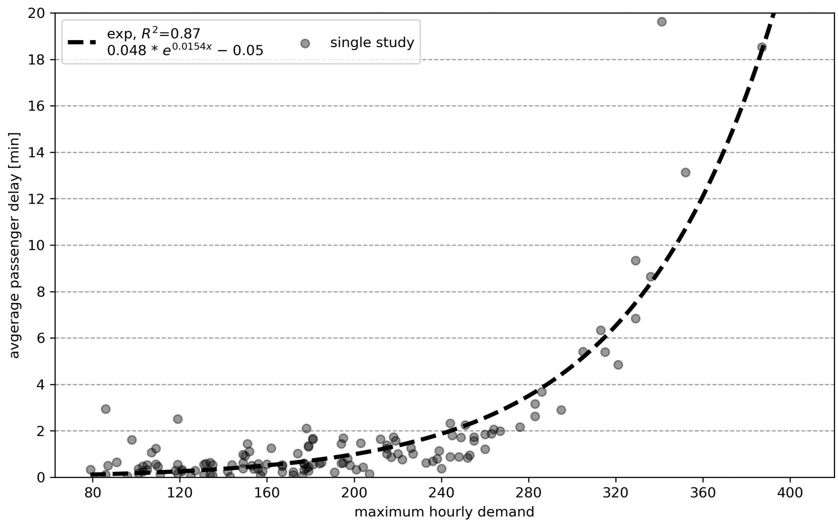

Figure A2. Refined analysis of the effect of peak-hour demand on the average passenger delay (excluding all scenarios surpassing the PICAP threshold).

Appendix C. How-To Apply the Design Heuristic

The design heuristic presented in Section 4.3 can be applied in numerous ways. As described, each point in the diagrams corresponds to the same behavior in the system (e.g., in the presented scenarios an average passenger delay of 4 min). Therefore, the pad-related diagram describes the interchangeability of number of pads, approach and departure time and demand. Analogously, the gate-related diagram describes the interchangeability of number of gates, boarding and de-boarding time and demand. In Figure A3 two examples of how to apply the design heuristic are shown to illustrate the usage. On the left hand side, a scenario with 90 s of approach and departure time and 1000 daily passengers is assumed. If the daily demand rises to 2000 passengers while the same quality of operations wants to be assured, the approach and departure time needs to be reduced to around 37 s. On the right hand side, a scenario with 1000 daily passengers being processes on six gates is shown. In order to process 1500 passenger daily, while again maintaining the same quality of operations, the number of gates would need to be increased to nine.

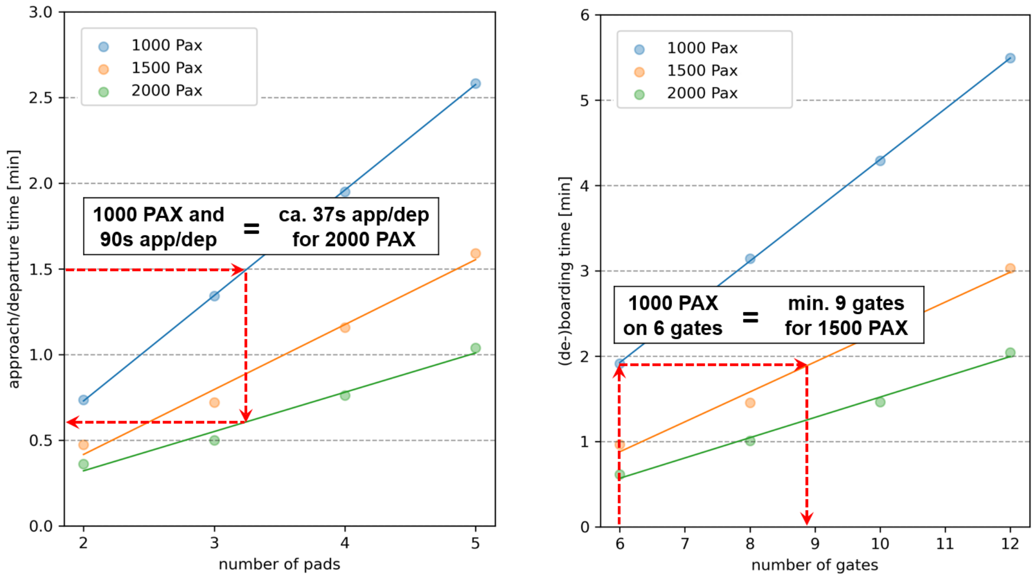

Figure A3. Application examples illustrating the use of the vertiport design heuristic.

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4.4 Further Publications on Vertiport Design and Operations

Next to the the three journal articles described above there is a list of conference papers and master's theses that were published and written in the context of this doctoral thesis. The citations to the publications are listed below and the full documents are available on demand; please contact the following address if interested: `lukas.preis@tum.de`.

4.4.1 Conference Papers

K. Lippoldt, L. Preis, and K. Bogenberger, "Preliminary Study of nation-wide Urban Air Mobility Demand and Vertiport Network Study on Germany," in Transportation Research Arena Conference, Lisbon, Portugal, 14-17 November, 2022.

L. Preis and S. Cheng, "Simulation of Individual Aircraft and Passenger Behaviour and Study of Impact on Vertiport Operations," in AIAA Aviation 2022 Forum, Chicago, IL, USA, 27 June-1 July, 2022. DOI: 10.2514/6.2022-4074

L. Preis, M. Husemann, M. Shamiyeh, and E. Stumpf, "Time and Energy Saving Potential of Efficient Urban Air Mobility Airspace Structures," in AIAA Aviation 2022 Forum, Chicago, IL, USA, 27 June-1 July, 2022. DOI: 10.2514/6.2022-3545

L. Preis and M. Hack Vazquez, "Vertiport Throughput Capacity under Constraints caused by Vehicle Design, Regulations and Operations," in Delft International Conference on Urban Air-Mobility, Delft, Netherlands, 22-24 March, 2022.

L. Preis and M. Hornung, "Identification of Driving Processes for Vertiport Operations Using Agent-Based Simulation," in AIAA SciTech 2022 Forum, San Diego, CA, USA, 3-7 January, 2022. DOI: 10.2514/6.2022-0215

K. Lippoldt, L. Preis, and K. Bogenberger, "Vertiport Placement Method Based On Mobility Survey Data," in 32nd Congress of the International Council of the Aeronautical Society, Shanghai, China, 14-18 September, 2021.

L. Preis, "Quick Sizing, Throughput Estimating and Layout Planning for VTOL Aerodromes – A Methodology for Vertiport Design," in AIAA Aviation 2021 Forum, virtual event, 2-6 August, 2021. DOI: 10.2514/6.2021-2372

L. Preis, A. Amirzada, and M. Hornung, "Ground Operation on Vertiports – Introduction of an Agent-Based Simulation Framework," in AIAA Scitech 2021 Forum, virtual event, 11-15 & 19-21 January, 2021. DOI: 10.2514/6.2021-1898

4.4.2 Master theses

A. Amirzada, "Implementation of a Simulation Framework for Vertiport Ground Operations in the Context of Urban Air Mobility," master thesis, Technical University of Munich, Munich, Germany, 2021.

S. Cheng, "Parameter Calibration and Stochastic Model Extension for an Agent-Based Simulation of Vertiport Ground Operations," master thesis, Technical University of Munich, Munich, Germany, 2021. URL: `https://mediatum.ub.tum.de/node?id=1633724`

M. Hack Vazquez, “Vertiport Sizing and Layout Planning through Integer Programming in the Context of Urban Air Mobility,” master thesis, Technical University of Munich, Munich, Germany, 2021. URL: https://mediatum.ub.tum.de/node?id=1624149

5 Conclusion

Urban Air Mobility derives its novelty from technological advancements in electrification and autonomy (Sections 2.1.2 and 2.1.3). Through these technologies eVTOLs are expected to be safer, quieter and cheaper than helicopters — their closest "relative" in the transport system (Section 2.1.1). The market potential is largely unknown, but median estimates project billions USD (annually and globally) in the short-term and tens of billions USD in the 2030s (Section 2.2). Hurdles that are not as easily solved are eVTOLs design, ATM, community acceptance (driven by noise) and infrastructure (Section 2.3). Vertiports, which are at the heart of UAM infrastructure, are thus one of few crucial elements in the UAM system. This thesis studies vertiport design and operations in a so far unparalleled level of breadth and detail and thereby makes a valuable contribution to seeing a new mode of transport take off.

The validity of UAM is the promise of fast travel with travel time savings compared to conventional ground-bound modes of transport. To account for true time savings the entire door-to-door chain needs to be considered. In the case of UAM the trip can be broken into (1) access and egress, (2) processing at the vertiports and (3) the flight leg as illustrated in Figure 5.1. In the remainder of this chapter, the contributions of this thesis to each of the three trip segments will be discussed in order of increasing focus. Previous research indicates that segment 2 (processing) has the highest impact on travel time savings, segment 1 (access and egress) a high impact and segment 3 (flight) a lower but still tangible impact. This understanding guided the prioritization of research and the focus of this thesis.

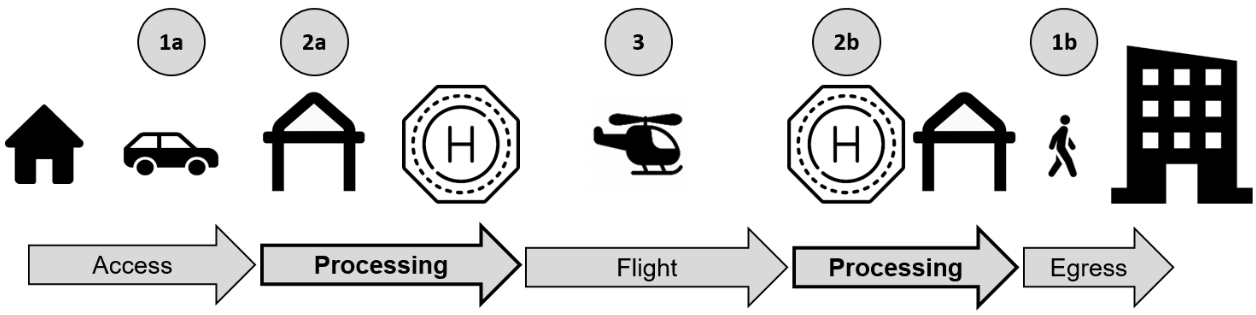


Figure 5.1 The UAM trip chain consists of access/egress, processing and flight.

The flight leg of a UAM trip (segment 3) is composed of maneuvers in the proximity of vertiports (takeoff and departure at the vertiport of origin and approach and landing at the vertiport of destination) and the cruise segment in between. The latter has surprisingly little impact on the overall trip time for short distances. Instead, it appears that once eVTOLs move significantly faster than ground-bound traffic[1] the further potential for time savings through increased cruise speed peters out quickly. Next to increasing cruise speed, time saving potential exists in optimizing vertiport approach and departure strategies as was shown in [127].

Access to and egress from vertiports (segment 1) is determined by the number and location of vertiports. If a vertiport network is denser (i.e. it has more vertiports per area), the average travel time to and from the nearest vertiport decreases. This is also true of optimized placement of vertiports so that the location corresponds to demand patterns of the particular city. In [110, 111, 9] a holistic appraoch for placing vertiports was developed. One unique feature was the combination of finding promising locations and then selecting suitable sites within the identified location by using a combination of quantitative GIS data analytics and qualitative expert judgment (see Section 3.1.1).

[1] When looking at average speeds in typical major of 30-50 km/h it could be sufficient to fly at around 100 km/h in the air (2-3 faster).

Processing at vertiports (segment 2) carries the largest potential for time savings wherefore the attention of the thesis is focused on this segment. Two streams of methods as depicted in Figure 5.2 were developed: mixed-integer programming for design of vertiports and agent-based modeling and simulation for operations at vertiports. While processes in the passenger terminal like ticket scanning and security screening lie on the critical path, these processes are rather easily optimized and play a minor role in the processing time (comparable to today's straightforward processes for business aviation at small regional airports). Based on this assumption the vertiport airfield has been selected as the main object of concern. In short, it can be said: profitable UAM operations need, first and foremost, smoothly operating vertiports followed by a well-designed and dense vertiport network while (for inner-city distances) a cruise speed of around 100 km/h suffices.

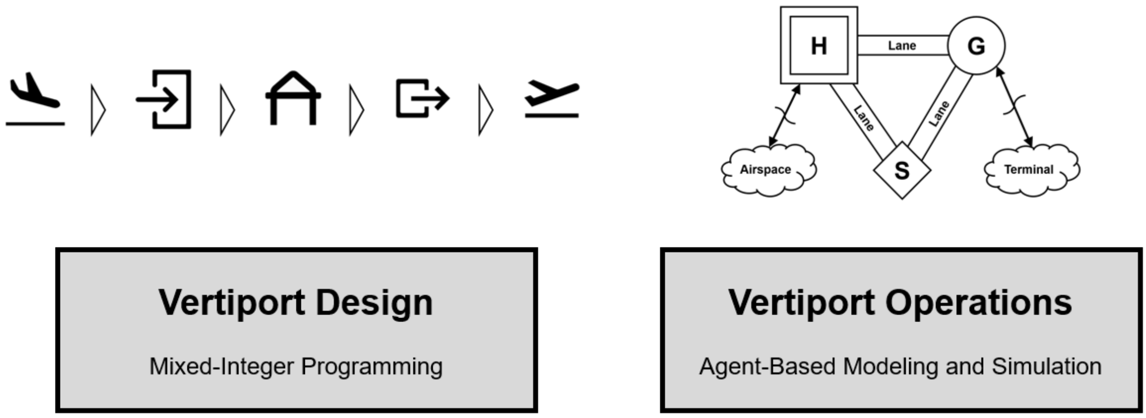


Figure 5.2 Methods used for vertiport layout design and vertiport airfield operations.

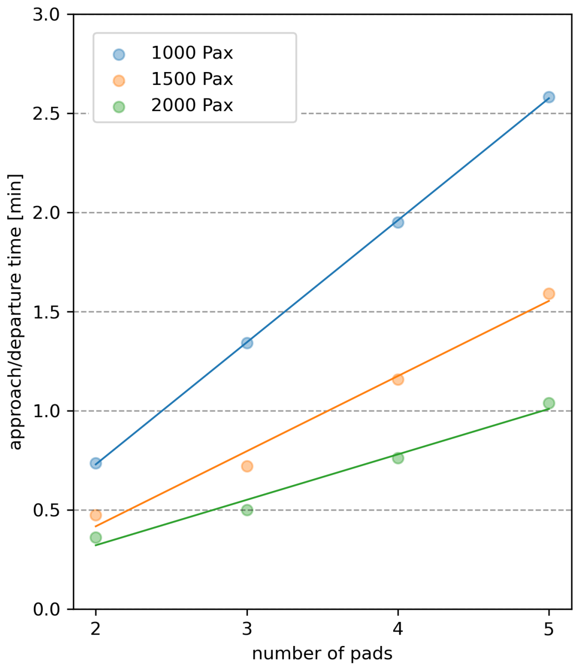
Vertiport designs in the context of this thesis are analyzed through MIP [9], a low-fidelity approach to primarily understand the relationship between possible throughput and required land area (see Section 3.1.3). Initial results in [1] indicate that compact multi-copters, such as the early *City Airbus* and *eHang 216*, will have the best performance on the ground in terms of passenger throughput on a given area. Rules-of-thumb (Table 3.8) and tabulated vertiport sizes (Appendix B.2) were creataed to help the research community do first-order estimations of space demand and throughput capacity. Depending on the vehicle design and shape of the area the vertiport airfield will need somewhere between $25{-}350\,m^2$ per passenger throughput per hour.

Vertiport operations in the context of this thesis are simulated through ABMS [10], a high-fidelity approach to illuminate dynamics of operations with special attention to peaks and imbalances in demand profiles (Section 3.2). In [3] it was shown that dynamics in vertiport operations, in particular local fluctuations of the demand profile, have major impacts on the operational efficiency and should not be neglected. This discovery fills a gap in the current scientific literature where peaks in demand are only regarded in selected UAM studies and considerations of imbalances in arrivals and departures are virtually absent. The analysis of dynamics in vertiport operations are the main contribution of this thesis.

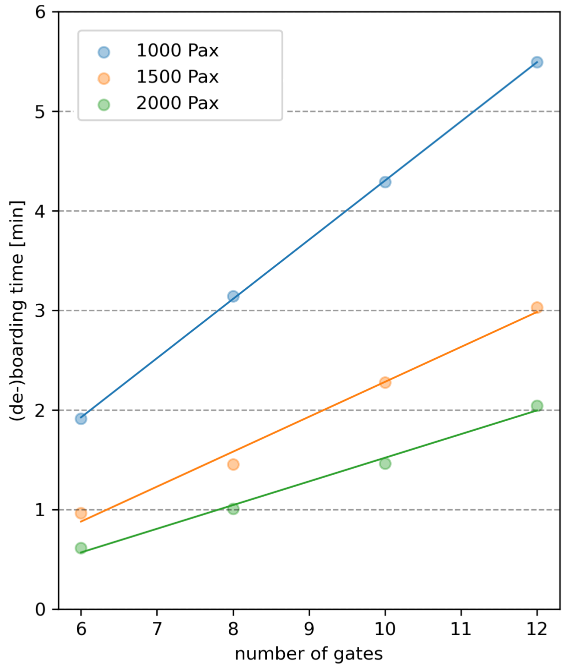
Drivers of vertiport airfield operations can be divided into layout-related and demand-related drivers. Concerning layout-related drivers publication #2 [2] showed that gates can be bottlenecks to vertiport operations and calls for a new way of determining aerodrome capacities. At the same time it needs to be highlighted that pads (which occur in lower number) react more sensitively to aggravation of capacity than gates (which occur in higher number). The same behavior can be observed between processes and elements, namely now lower number of pads impact operations more severely than longer approach and departure times (the same is true for gates and boarding times). This phenomenon is attributed to the discrete nature of the number of elements while process times are continuous. Further, the number of gates is higher than the number of pads, wherefore the discrete nature of number of pads is more tangible.

Demand-related drivers of vertiport operations are not as easily capture as layout-related drivers, which explains the evolution of publications (Section 3.2.5): in publication #2 [2] accumulated daily demand was identified as impactful on operations, but not suitable to predict delay; in [11] the refined analyses showed that peaks in demand and imbalances between arrivals and departures drive delay; and in publication #3 [12] it was possible to isolate and quantify these effects.

Combining all these insights, vertiport airfield operations can be reduced to six drivers, which predict the efficiency of vertiport operations within reasonable accuracy. The drivers of operations are (1) peak-hour demand, (2) maximum imbalance between arrivals and departures, (3) number of pads, (4) number of gates, (5) approach and departure time and (6) boarding and de-boarding time. In a final step all quantified design drivers were synthesized into one design heuristic, which is shown in Figure 5.3.



(a) Interchangeability of number of pads, approach/departure time and magnitude of demand.



(b) Interchangeability of number of gates, boarding time and magnitude of demand.

Figure 5.3 Vertiport design heuristic derived from agent-based simulation study as shown in publication #3 [12].

In summary, this thesis presents the necessary data to plan the design and operations of vertiports in various levels of detail. These efficiently planned vertiports will then help reduce process times, which is the main lever to reduce door-to-door travel time. Saved time, in turn, is the central promise of UAM. In the end, the hope is that this thesis will make a contribution to introduction and scaling of UAM services worldwide and thereby open a new chapter of aerial mobility.

6 Future Work

This thesis presents a treatment of vertiports in the highest currently available and reasonable level of detail. It has the highest *available* level of detail due its combination of high-fidelity simulation and a wide range of possible scenarios. All other published work is either limited to low-fidelity analysis of vertiport operations or a small number of scenarios (see Section 3.2 for more background on this argument). Further, this thesis has the highest *reasonable* level of detail due to the large unknowns in the UAM system. Especially in absence of experimental data, it can be argued that the presented simulation currently captures operations in the best possible way. Due to the large unknowns more detailed modeling is not likely to increase the quality of results. This statement is made specifically for the time of writing (early 2023) knowing that the availability of experimental data will increase soon with multiple vertiport companies working on launching their first commercial operations in the near future. Prominent examples are *Skyports*[1] and *Urban-Air Port*[2]. With that said, there are a handful of extensions of the ABMS framework that might become worthwhile in the near future: an energy module, a taxiing study, differentiation of parameters, passenger movement on the airfield, multi-vertiport studies, multi-seater vehicles and segmentation of airspace/terminal.

6.1 Energy Module

The implementation of an **energy module** into the framework is recommended. The model already exists as discussed in Section 3.2.1 and depicted in Figure 6.1 including all relevant parameters (see all parameters in Figure 3.8 and Table 3.10 and the energy-module specific parameters reiterated in Figure 6.2). The next step would be the implementation of the model according to the software structure shown in Figure 6.3. Further remarks on the implementation of missing parameters are given in Section 6.2.

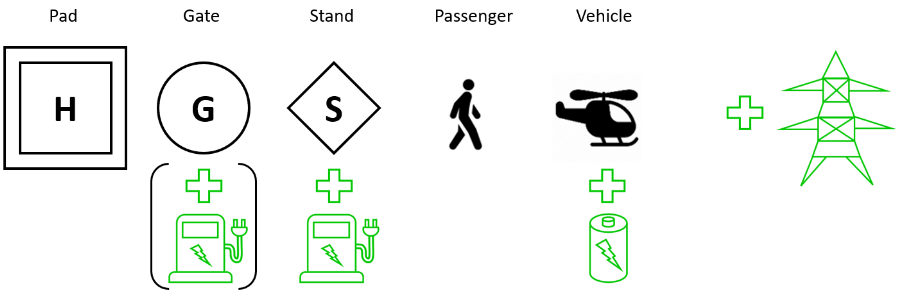


Figure 6.1 Depiction of energy module for ABMS framework.

The energy module would enable investigation of a range of new research questions. The following might be of particular interest:

1. How do eVTOLs charging at stands (or gates) impact the dynamics of vertiport operations? And what are the sensitivities of operations depending on charging times? (see Section 2.1.2)
2. How would optimal vertiport operations change when using direct charging, battery swapping or conventional re-fueling (i.e. using hydrogen for fuel cells)?
3. What is the impact of operations on the electric grid? More concretely, how would battery swapping enable peak-power-shaving and at what benefit?

[1]https://skyports.net/landing-infrastructure/ (accessed on 4.6.2020)
[2]https://www.urbanairport.com/ (accessed on 7.10.2021)

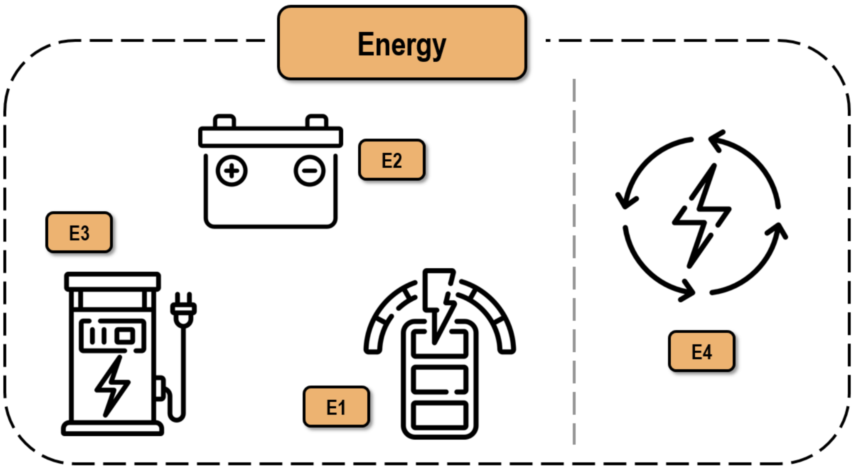


Figure 6.2 Illustration of energy module parameters.

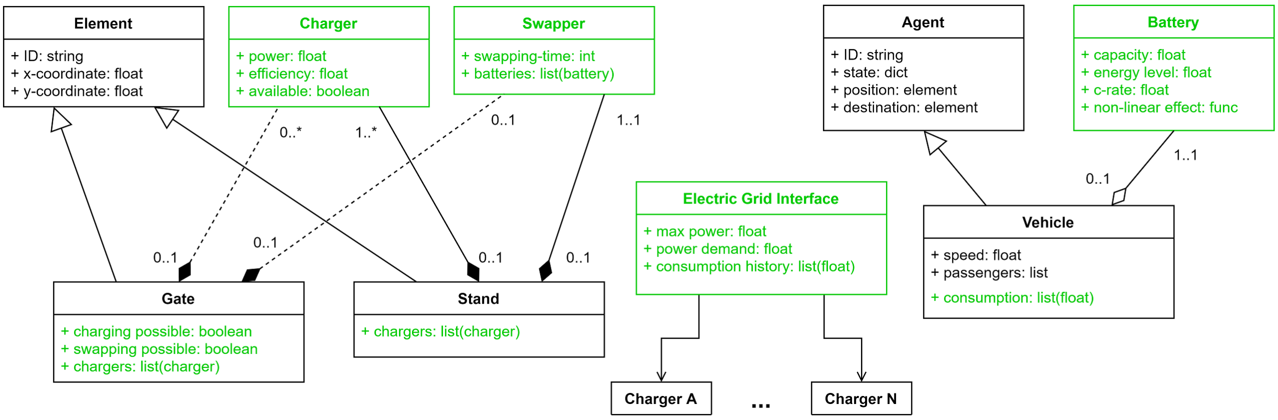
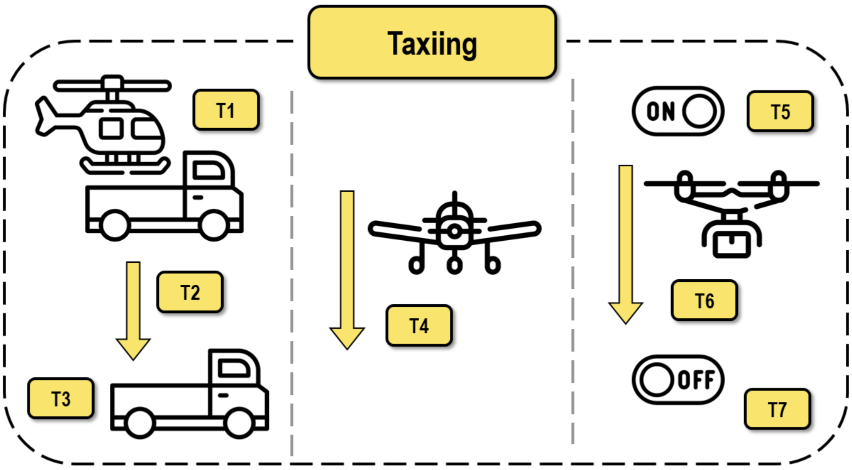


Figure 6.3 Suggested class structure for implementation of energy module.

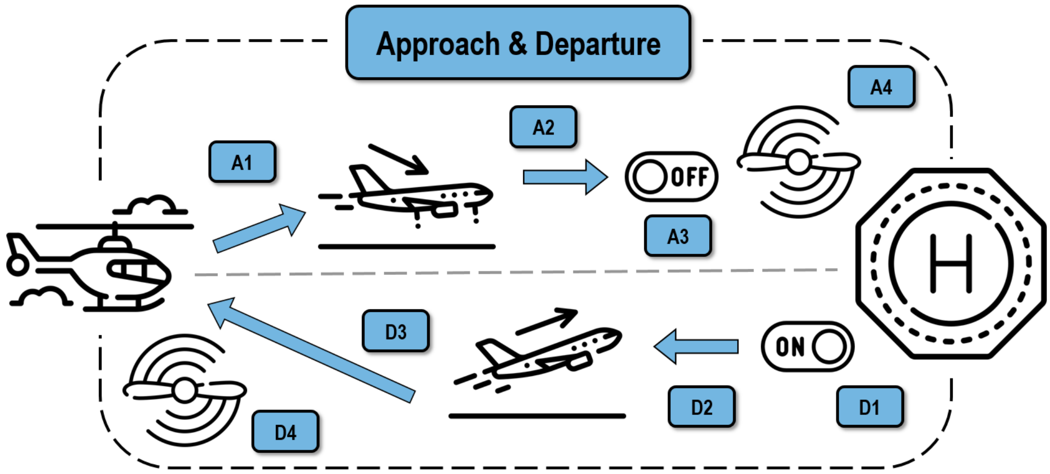
6.2 Vehicle Taxiing and Parameter Implementation

Investigating different eVTOLs **taxiing** approaches could be of interest not least to vehicle manufacturers. Ground taxiing will be a novel phenomenon for vertiports as discussed in publication #1. Here three types of ground taxiing are defined: hover taxiing, active ground taxiing and passive ground taxiing (see the respective section 4.2.2. "Ground Movement and Taxiing" on page 30) [77]. The different types of taxiing are illustrated in Figure 6.4a. This study would involve multiple branches of this dissertation: (1) the layout of a vertiport, in particular the width of taxiways, depends on the hover mode [9]; here the MIP approach from Section 3.1 can be applied to find optimal layouts for hover and ground taxiing. (2) The speed of taxiing and processes, as shown in Section 3.2.1, vary between taxiing modes; to apply this the **differentiation of parameters** would need to be implemented (for the differentiation of approach/departure and boarding/de-boarding see Figures 6.4b and 6.4c, respectively). (3) When including the energy module of Section 6.1, the energy consumption of the different taxiing modes could be tracked to see if this has a relevant effect on operations. Lastly, (4) **passenger movement on the airfield**[3] could be implemented to include another alternative to taxiing and allow for studying single-pad topologies (see Section 3.1.2). From unpublished material, it is known that passenger walking speed can be expected to be around $1.4 - 1.8\,m/s$. This last extension would be best located in the existing layout extension (see Appendix A.3.2).

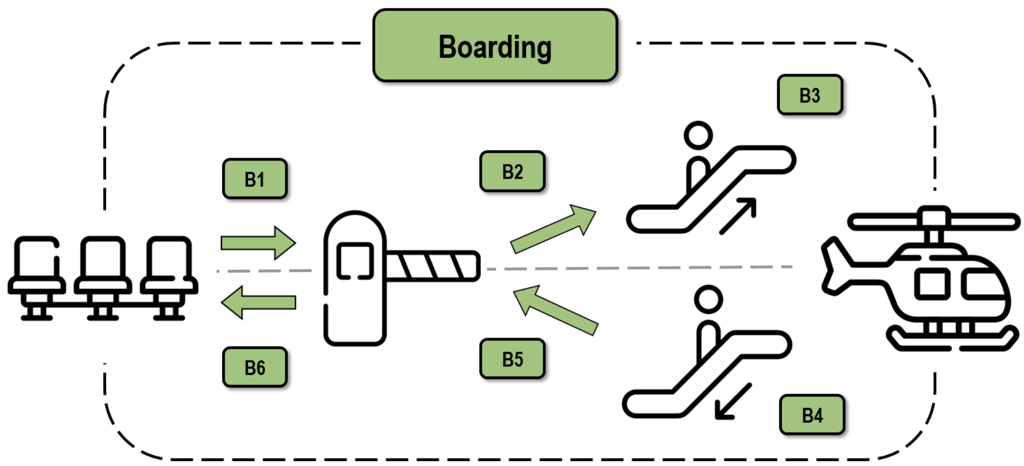
[3]The idea is that the passenger would walk from the gate to the pad and then board the vehicle, instead of a vehicle taxiing from a pad to the gate to pick up the passenger. This process is common practice in today's helicopter operations.



(a) Taxiing parameters: passive ground taxiing (left), active ground taxiing (center) and hover taxiing (right).



(b) Differentiation of approach and departure parameters.



(c) Differentation of boarding parameters.

Figure 6.4 Illustration of differentiated parameters in vertiport model (IDs matching Section 3.2.1).

Independent of the taxiing study it is an obvious next step to implement all the missing parameters included in the model as listed in Table 3.10 and shown in Figure 6.4 into the software. At the time of writing only aggregated parameters are implemented. For example, instead of "entering airspace", "final hover", "stop engines" and "cool-down after landing" there is only one parameter encompassing the whole chain of steps: "approach".

6.3 Multi-Vertiport Studies

A major limitation of this thesis is its system boundaries around one single vertiport. eVTOLs and passengers arrive and leave the vertiport, but it is unknown what happens before or after. It is therefore suggest to develop the software toward a **multi-vertiport study** framework. This could either be done by instantiating multiple vertiports and defining fixed travel times between them. It would be implementable within reasonable effort, but flights between vertiports are treated as a black box and therefore would not capture all relevant aspects of a UAM transport network. A better, but more time-intensive, way would be to include the vertiport model into the *MATSim* UAM extension of Rothfeld [47]. Here a transfer into the programming language *Java* would be required; or a repetitive simulation with both frameworks, where a simulation with one framework provides the output to be used as input for a simulation with the other framework and so forth.

Vertiport network studies open up the possibility of considering new operational aspects, two of which will be mentioned here. First, **multi-seater** vehicles could be implemented. The current version of the framework only allows single-seater vehicles, which does not match the passenger capacity of envisioned eVTOLs (see Section 3.1.3 for a list of prominent eVTOLs designs). Multi-seater vehicles will not only prolong the downtime during boarding, but they raise a set of new operational aspects (e.g. load factor) and operational strategies (e.g. pooling). Second, when considering eVTOLs and passengers coming from different directions, it makes sense to implement a **segmentation of airspace and terminal**. The software structure for segmentation is already present in the input-files shown in Figure A.3 as explained in Appendix A.2.

6.4 Miscellaneous

Two other avenues might be worthwhile to explore: first, an economic vertiport model and, second, an automated GIS-based evaluation of cities towards their suitability for vertiport sites.

An economic vertiport model would encompass real-estate acquisition, vertiport construction cost, vehicle cost and operational cost, in particular electricity. Some attempts have been made into this direction [128, 123, 129], but due to the large unknowns, it must be considered whether or not the time is ripe to develop a meaningful economic vertiport model.

Finding suitable cities for UAM introduction through a GIS approach might be an interesting viewpoint. It is, therefore, proposed to use *Open Street Map* data to extract all areas that are large enough to host at least a single-pad topology (see Section 3.1.2) and are not excluded by the list of suitable sites presented in Section 3.1.1 and Appendix B.1. Next, the number of suitable locations and their share of the total city land area can be calculated. Another qualitative step might be useful to exclude areas that are not captured by the described quantitative process, but are not suitable for other reasons. After identifying the list of sites, their possible throughput capacity could be estimated by MIP (see Section 3.1.3). Ultimately these values (number of vertiports, proportion of suitable landmass, vertiport locations, vertiport throughputs) could be combined into an index measuring the suitability of a city for UAM introduction and scaling. A global application of this approach would aid the selection of cities for future UAM studies.

A Agent-Based Modeling and Simulation Framework

A.1 Updates of Simulation Framework

The first functional version of the ABMS framework is described in Section 3.2.2 and the implementation was finished by Preis and Amirzada in early 2021 as documented in [13]. This version will be referred to as v1.0. Since then the framework was continuously updated towards the current v1.1 on which the studies are based that are presented in Section 3.2.5. Since the execution of the studies an overhaul of the code towards a future version v2.0 was started which is still ongoing at the time of writing. The delta between v1.0 and the future version v2.0 will be described in the following. A detailed description of the software architecture of v1.1 can be found in Appendix A.2.

A.1.1 Major Software Changes

There are five major changes to the software:

1. The rules on which agents base their decision-making and actions were moved from the main loop in *Controller.run()* to a separate *Rule_Machine*. The full list of rules are described in Appendix A.5. The main loop will only have a few simple functions to select and execute the fitting rule based on the momentary state of the environment and agent.
2. A booking-system was introduced, which is described in Appendix A.3.3. It was originally implemented to avoid deadlocks through allowing arriving vehicles to pre-book gates during their approach. It will further be updated to allow a choice between different booking strategies, which can be part of an operational strategy.
3. For the purpose of simulation studies the following scripts were created: “demand_machine.py” to automatically create defined multi-factor variations of demand profiles; “file_structure.py” to organize input files according to a given study design; and “multi_run.py” to batch-execute any given number of simulation scenarios.
4. The analysis capabilities of the framework were strongly expanded and can be categorized into three groups: (1) pre-simulation demand-related analysis as discussed in Section 3.2.3; (2) post-simulation scenario-related analysis, which are introduced in Section 3.2.4 and expanded in Appendix A.4.2; and (3) para-simulation study-related analysis. The latter is the analysis-part to the batch-execution of studies mentioned under point 3. It encompasses scripts for data evaluation (“custom_data.py” and “custom_filter.py”) and visualization (“custom_plot.py”). The study-related analysis is elaborated in Appendix A.4.3.
5. An interface for the stochastic extension (see Appendix A.3.1) was created. Though the changes in code for the interface are minor, the addition of the stochastic extension enabling the operator to assign individual characteristics to each agent is a major update. The core script of the stochastic extensions developed by Cheng is “population_generator.py” [4].

A.1.2 Minor Software Changes

Minor changes in the class-structure are as follows:

- Class *Agent* was updated by the attributes "type", "parameters" and "state"
- Class *Vehicle* was updated by moving the attribute "taxi_speed" into the inherited attribute "parameters" and eliminating the need for vehicle configurations; further, class *Vehicle* now has a number of functions to interact with boarded passengers, which were not explicitly described in the first version
- Class *Element* was update by the attribute "type"
- Classes *Airspace* and *Terminal* were added who both inherit from class *Element*; further, class *Taxi* was created, also inheriting from class *Element*, in the context of the layout extension (see Appendix A.3.2)
- Class *Lane* was updated by the attribute "type" and an assignment of a taxiway in the context of the layout extension (see Appendix A.3.2)
- Classes *Path*, *Router* and *Way* were created in the context of the layout extension (see Appendix A.3.2)
- Class *Layout* was update by the functions "read_lanes" in the context of the layout extension (see Appendix A.3.2), "create_terminal" and "create_airspace" for improved handling by the controller and "print_layout" to document auto-generated layouts; further, the functions "read_layout" and "get_elements" were aggregated into one function "read_elements"
- Classes *Plans* and *Population* were overhauled and now read *csv*-files as input (version v1.0 still worked with hard-coded test data)
- Class *Units* was update to allow a choice between default parameter values (as was the only option in v1.0) and reading parameter values from an *xml*-file (introduced for v1.1)
- Class *State_Machine* was updated by various functions for better handling of agents
- Class *Controller* was updated by various functions for more efficient controlling and logging, including the creation of classes *Event* and *CSVServices*

A.2 Software Framework Architecture and How-To-Simulate

A.2.1 File Structure

In this section the file- and class-structure of the simulation framework will be described including a step-by-step guide of how to run a simulation. The file-structure is shown in Figure A.1: "input" contains the files needed by the code stored in "src" to simulate a scenario and the product is stored in "results". After post-simulation analysis the files and visualizations are stored in the folder "output". In the folder "src" two files lie on the first level: "main.py" as the starting point of a simulation and "controller.py" which is the central operating class during the simulation. The controller is aided by the scripts in the folder "machines". Next, there are the folders "inputs", "plans" and "service" for handling data; and "agents", "elements" and "lanes" for creating the necessary objects for the simulation. Further, there are the folders "demand" and "analysis" for pre- and post-simulation analysis; and lastly, the folder "studies" that contains scripts to prepare, execute and evaluated simulation studies. Here the central script to execute a batch of simulations is "multi_run.py" which handles the inputs and results and calls the above-mentioned "main.py" script for each simulation. The class-structure of version v1.1 is shown in Figure A.2 as a *UML* class-diagram. Version v1.0 was documented in [13] and the updates that occurred since then are explained in Appendix A.1. The underlying model is explained in Section 3.2.1 and general remarks to the software and its design patterns are mentioned in Section 3.2.2.

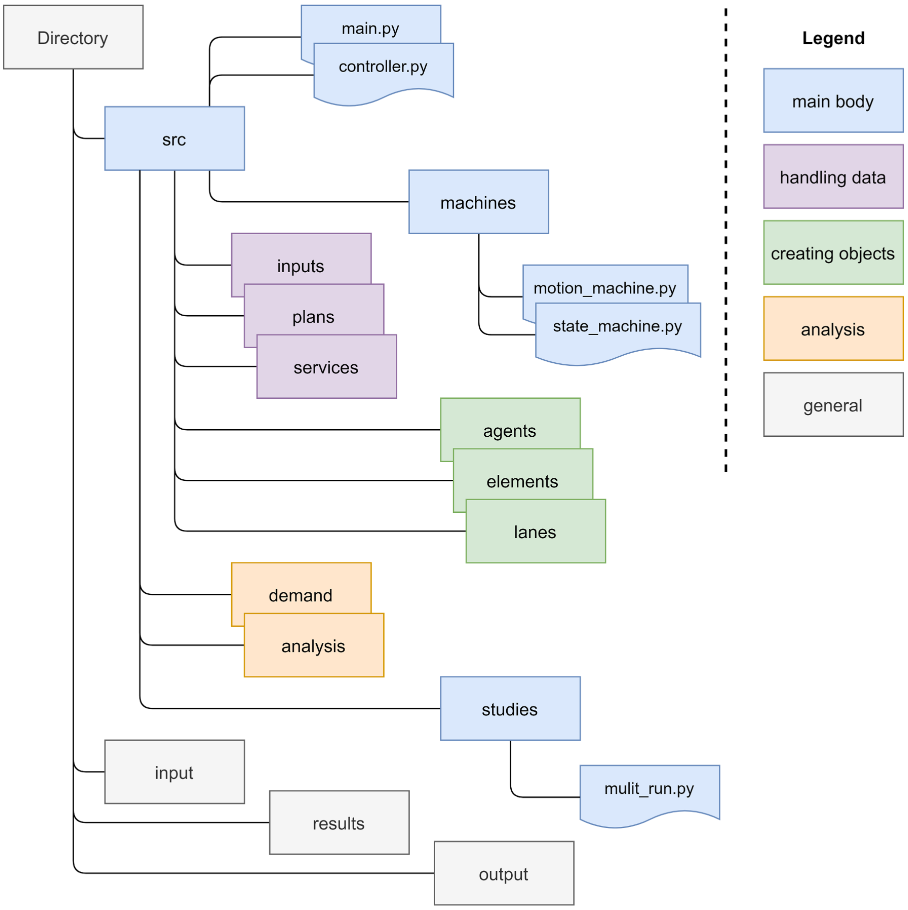


Figure A.1 File structure of ABMS framework.

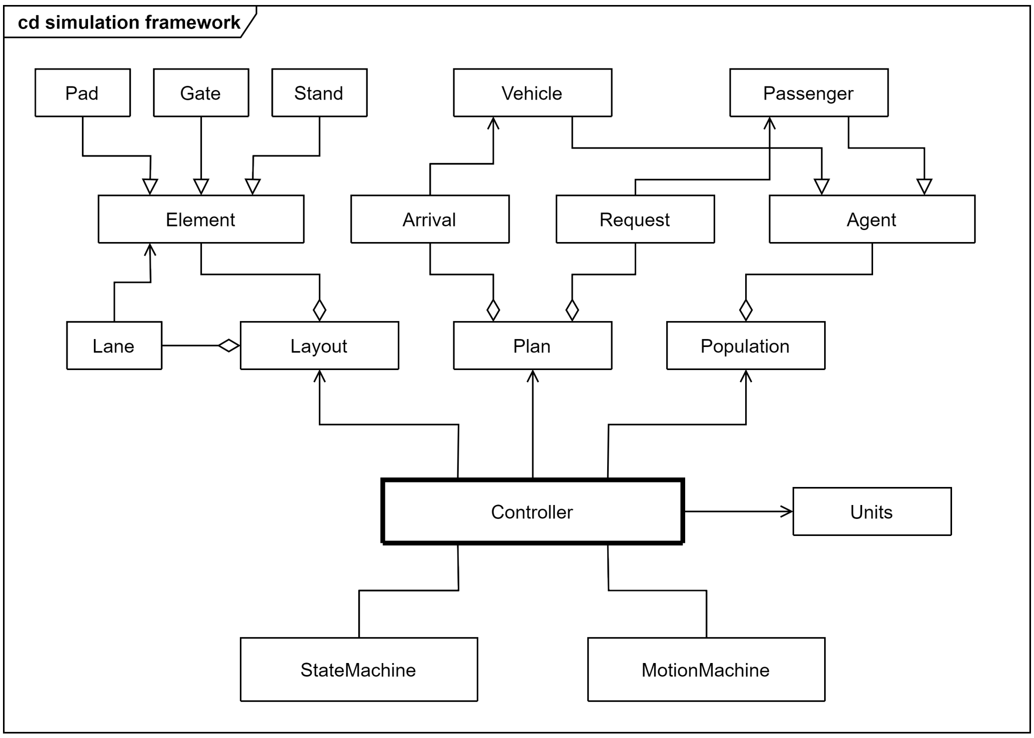


Figure A.2 Software architecture of ABMS framework visualized as *UML* class diagram (updated from [13]).

A.2.2 Simulation Input

One scenario simulation needs five inputs as illustrated in Figure A.3: (1) a vertiport layout composed of elements where each element is characterized by its type and the coordinates of its (spatial) center. (2) Arrivals of vehicles who are characterized by their type and number of passengers on board (in the version v1.1 only single-seater aircraft are possible). Each vehicle is further assigned an arrival time (in seconds after midnight) and an arrival location, which corresponds to a segment of the airspace. (3) Requests of passengers, which are characterized by their time of arrival at the vertiport, their section of the terminal they arrive in and the segment of the airspace they need to fly out of. Arrivals and requests have a similar structure and are summarized by the term “plans”. In version v1.1, both airspace (“A”) and terminal (“T”) are modeled each as one unified space, but the architecture does allow for segmentation. (4) Population, the vehicles present on the vertiport at the start of simulation, are characterized by their type and the element they stand on. (5) A list of parameters determining the lengths of actions. The parameters are given in the *xml*-format while all other inputs are given as *csv*-files.

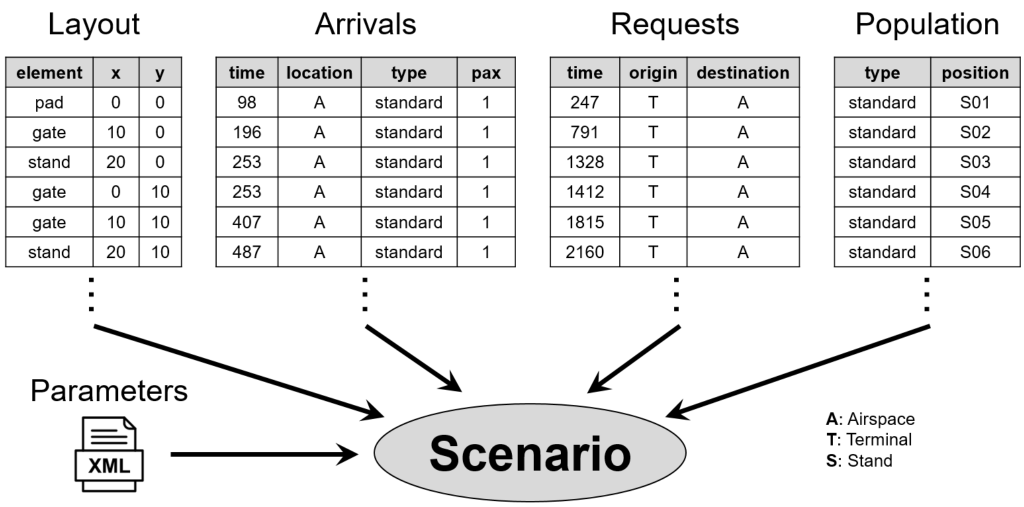


Figure A.3 Required inputs for simulation of one scenario (updated from [11]).

All five input files must be present to run a simulation. Moreover, the following variables need to be set in the “main.py”-file: start and end time of the simulation; type of plans, layout and booking system (see further details in Appendix A.3); and the mode of saving events. The mode of saving events, if set to *True*, will store results internally and save them to a file at the end; if set to *False*, it will print them out immediately. The latter is much slower, but allows for real-time monitoring of the simulation. Other options that could be changed are the time and length unit and the time-step of the simulation, but it is recommended to use the default settings. When all the inputs and settings are in place, the “main.py” file can be executed.

A.2.3 Simulation Results

If the simulation was successful, it will store an “events.csv” file in the “results” folder – this is the main output of the simulation. Each line of the file is one “event” and contains information about the involved agents and elements, the state changes, executed actions and a time stamp. All post-simulation analyses are based in this events-file and an example is illustrated in Figure A.4. The simulation will also produce certain files to document the auto-generation of lanes for open layouts (for more information see Appendix A.3.2), the assignment of IDs to agents (not yet present in v1.1) and the remaining population at the end of simulation. After the simulation the framework offers a range of analysis scripts as described in Sections 3.2.4 and Appendix A.4.2.

Events

time	agent	action	element	state
14	V01	init	S01	-
14			G01	free
14			S01	occupied
53	P01	arrived	T	
71	V01	entered	L01	
201	P01			waiting
205	V02+P02	left	A	

⋮

A: Airspace
T: Terminal
S: Stand
G: Gate
L: Lane

Figure A.4 Content of simulation results: events *csv*-file.

A.3 Simulation Extensions

There will be three extensions present in version 2.0 of the software framework related to (A) plans, (B) layout and (C) booking; A and B are completed in v1.1, C is under developement. The framework and activation of extensions is described in Appendix A.2 and is summarized in Section 3.2.2. The model for extension B (layout) was first published in publication #2 [2] and the two options of "open" and "defined" layouts are illustrated in Figure A.5. The model and implementation of extension A (plans) is documented by Cheng in [4]. In a one-time process a list of normal distributions, one for each parameter, was created. The process included the scripts "create_factors.py" and "aggregate_factors.py" and expresses each resulting normal distribution through the expected value σ and standard deviation μ. The parameter value specification is given in Table A.1 and the extension was put to work in a simulation study as described in [3] and summarized in Section 3.2.5.

Table A.1 Stochastic parameter values of vertiport model expressed through a normal distribution with expected value and standard deviation (extracted from [4]).

ID	Parameter	Unit	Expected value μ	Standard deviation σ
B1/B6	Terminal to/from gate	s	71.4	20.2
B2	Enter gate	s	71.4	20.2
B3	Boarding	s	39.1	22.6
B4	De-boarding	s	10.0	5.80
B5	Leave gate	s	71.4	20.2
T2	Passive taxiing	m/s	1.17	0.25
T1/T3	(De-)mounting passive taxiing device	s	37.7	36.7
T4	Active taxiing	m/s	3.01	1.55
T6	Hover taxiing	m/s	6.90	1.60
T5/D1	Start engine	s	5.61	1.57
T7/A3	Stop engine	s	5.63	1.58
A1	Enter airspace	s	7.63	1.53
A2	Final hover	s	7.72	1.14
D2	Initial hover	s	5.36	1.52
D3	Leave airspace	s	5.42	0.77
A4/D4	"Cool-down" after landing/take-off	s	25.4	19.4
E3	Charging speed	kW	255	148
E2	Battery capacity	kWh	94.7	35.6
E1	Energy loss	%	3.18	1.31

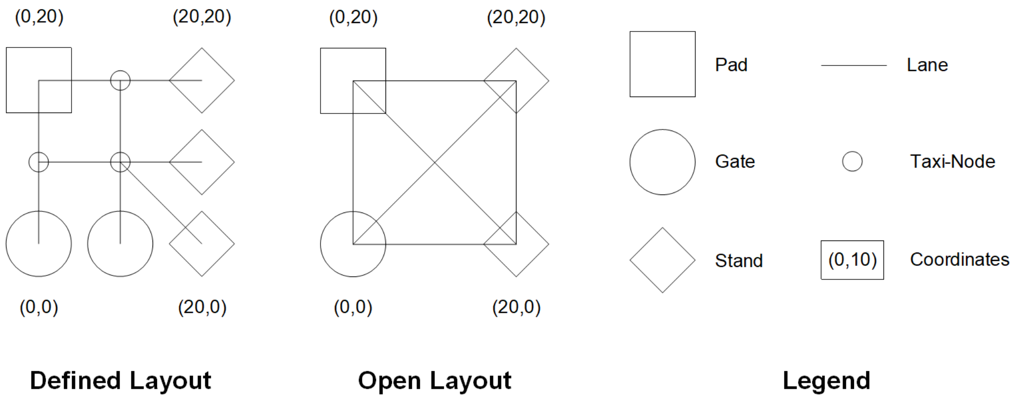


Figure A.5 Depiction of vertiport layout options as shown in publication #2 [2].

A.3.1 Extension A: Plans

Extension A offers the ability to select either a deterministic (“generic”) or stochastic (“defined”) definition of plans. In the deterministic way, each agent is treated equally and takes on identical characteristics as defined in “parameters.xml”. This way of simulation was used most often for this thesis. In the stochastic way, each agent is assigned individually varying characteristics. The characteristics are generated base on normal distributions through the script “population_generator.py”. The expected value σ and standard deviation μ of all parameters are shown in Table A.1. For the current version of the framework the aggregated parameters from Section 3.2.1 as shown in Table 3.11 are used. In Figure A.6 the different formats of input files for arrivals, requests and population are illustrated. In order to run a stochastic simulation the respective input files need to be copied into the “input” folder and the type of plans has to be set to “defined” in the “main.py” file.

generic

Arrivals

time	location	type	pax
98	A	standard	1

Requests

time	origin	destination
98	T	A

Population

type	position
standard	S01

defined

Arrivals

time	origin	taxi_speed	approach	departure	pax
98	A	2.04	49.3	18.9	1

Requests

time	origin	destination	terminal_gate	de_boarding
98	T	A	89.8	106.7

Population

taxi_speed	departure	origin
2.04	18.9	S01

A: Airspace
T: Terminal
S: Stand

Figure A.6 Vertiport plans options: deterministic ("generic") or stochastic ("defined").

A.3.2 Extension B: Layout

Extension B offers two types of layouts, namely a layout without designated taxiways (“open”) and a layout with designated taxiways (“defined”). Only the former was used for simulations in this thesis. For the layout without taxiways each element is automatically linked by a lane with each other element through a beeline connection. In this way, lanes cross and vehicles could collide in the real world, which is neglected in this simulation approach. The layout with defined taxiways requires a detailed definition of each taxiway through taxi-nodes and lanes. Each element and lane is assigned to one taxiway and each taxiway can only hold one vehicle at a time. Through this, it is guaranteed that collision in the real world is prevented. In Figure A.7 the different formats of the input-file “layout.csv” are illustrated. In order to run a simulation with designated taxiways the file for the layout needs to be copied into the “input” folder and the type of layout has to be set to “defined” in the “main.py” file.

open

element	x	y
pad	0	0
gate	10	0
stand	20	0
gate	0	10
gate	10	10
stand	20	10
⋮		

defined

element	x	y	ID
pad	0	0	H1
gate	10	0	G1
stand	20	0	S1
taxi	0	10	T1
lane	H1	T1	W1
lane	G1	S1	W2
⋮			

H: Pad
G: Gate
S: Stand
T: Taxi-Node
W: Taxiway

Figure A.7 Vertiport layout options: open or defined.

A.3.3 Extension C: Booking

Extension C will offer three types of booking systems. The first system ("no") turns the booking system off, which means that elements will only be booked for vehicles right before they move towards that element (e.g. a gate is booked as a vehicle starts taxiing from a pad to the respective gate). The second system ("all") books all elements a vehicle will need in the course of its current destination (e.g. if a vehicle arrives in the airspace a pad for approach and a gate for de-boarding are booked immediately). The thirds system ("hybrid") allows for booking in defined cases in order to keep the operations flexible while preventing deadlocks in times of high demand. For example, if a vehicle arrives in the airspace and multiple gates are free, no gate will be booked in advance; but if only one gate is free, it will be booked immediately to ensure the vehicle will be able to clear its pad right after touchdown. The third system was typically used for the simulations in this thesis. In order to run a simulation with a certain booking system respective variable needs to be set in the "main.py" script.

A.4 Analysis and Visualization Capabilities of the Framework

The ABMS framework provides, next to the simulation itself, a range of data analysis und visualization capabilities. These can be divided into three groups as mentioned in Section 3.2.4:

1. Pre-simulation demand-related analysis and visualization
2. Post-simulation scenario-related analysis and visualization
3. Para-simulation study-related analysis and visualization

The scripts providing these capabilities are written in *Python 3.8* analogue to the ABMS itself as described in Section 3.2.2. The difference is the following: the simulation is written in an object-oriented manner and the analysis and visualization scripts in a procedural manner. In fact, this was a major reason to choose the programming language *Python* as it allows for both ways of programming (other than e.g. *Java*, the programming language of *MATSim* [126], where only object-oriented programming is possible).

A.4.1 Demand Analysis

Demand-related analysis and visualization happens before the simulation and aims to aggregate the characteristics of a demand profile into just a few parameters. The demand generation and analysis capabilities are described in Section 3.2.3: displaying demand as rolling hour, imbalances in arrivals and departures, passenger and vehicle stock caused by imbalances over time and probability density functions from which concrete demand profiles can be randomly sampled. The name of the script is "visualize_demand.py" and it allows for batch analysis of demand profiles. Two output formats can be chosen: a *csv*-file with the aggregated data (see an example in Table 3.13) and/or a *png*-file with the visualization. One other visualization options that is not shown in Section 3.2.3 is bins (instead of rolling hour) with an hour- or custom-bin-base; an example is displayed in Figure A.8.

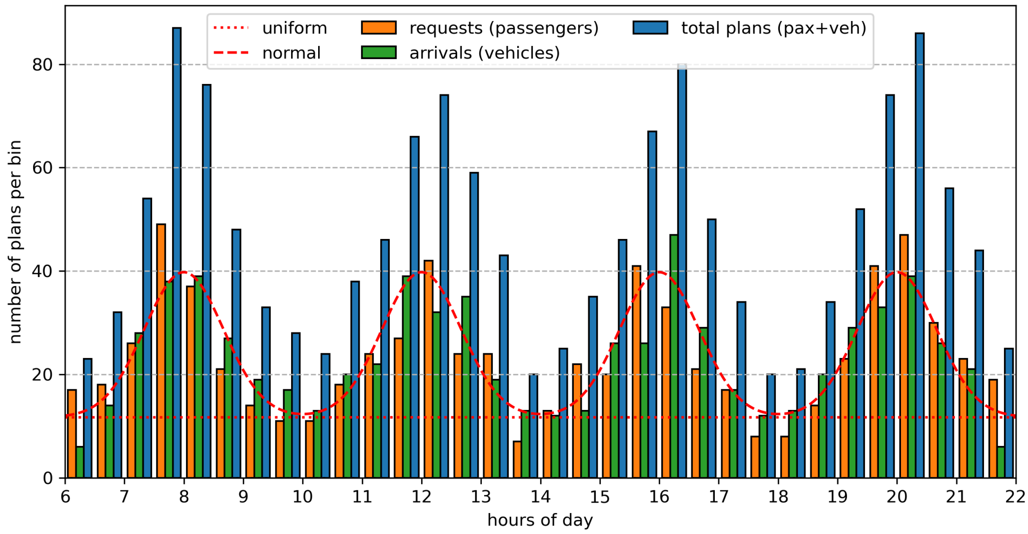


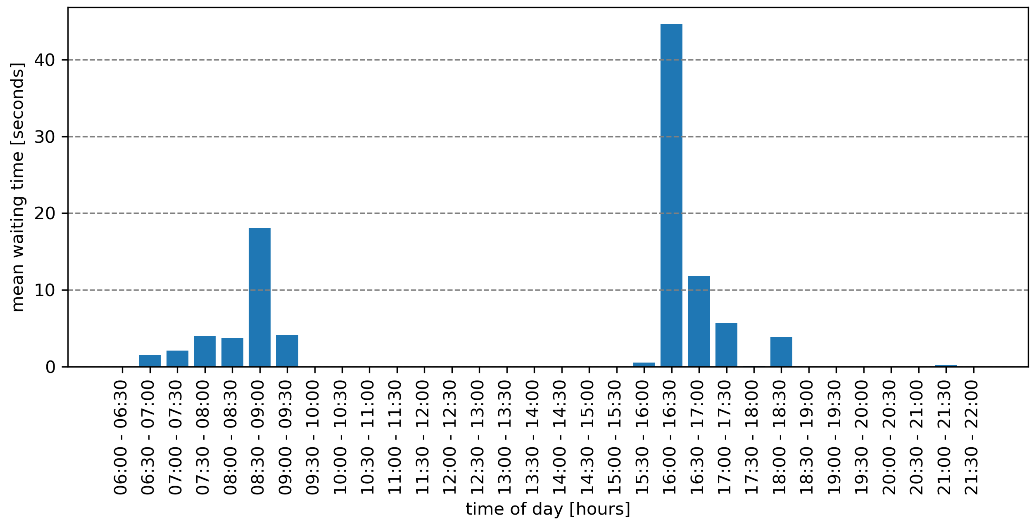
Figure A.8 Example of bin-based demand visualization in contrast to rolling-hour.

A.4.2 Scenario Analysis

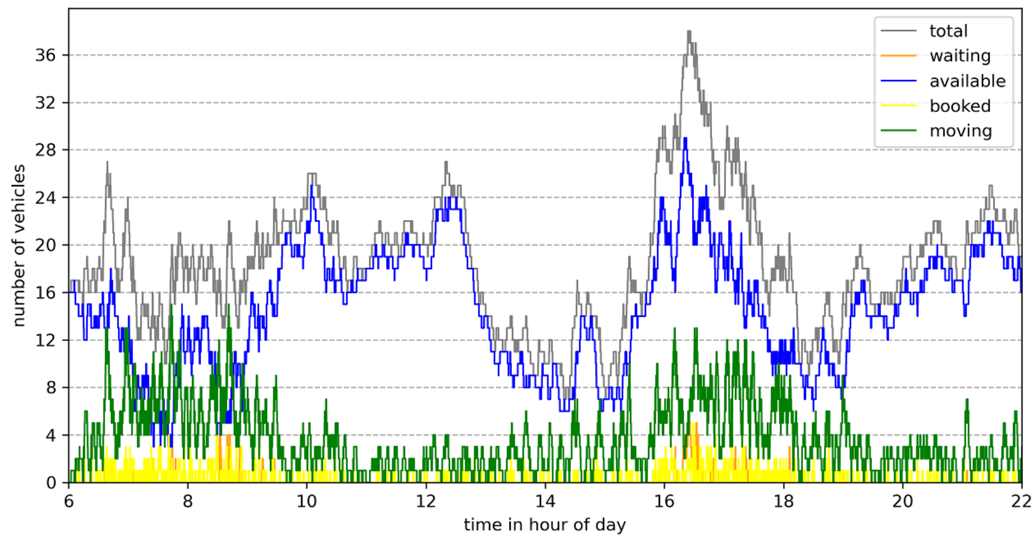
Scenario-related analysis and visualization happens after the simulation and it aims at showing the operational performance of a single scenario. The scenario analysis capabilities are described in Section 3.2.4: time-aggregated layout-based visualizations, space-aggregated time-based visualizations, agent-aggregated bin-based visualizations and hybrids between these formats. The framework provides many combinations, wherefore this section will only provide further examples (see Figure A.9) and not treat all possibilities exhaustively. Figure A.9a shows the waiting time of passengers in 30-minute-bins depending on the time of arrival (compare to Figures 3.11c and 3.11d). Figure A.9b shows the absolute number of vehicles in a state-resolved manner without averaging (compare to Figure 3.11b with at 15-minute running-average). Figure A.9c shows the share of occupied gates in a 15-minute bin-averaged manner (compare to Figures 3.11a and 3.11d). The different averaging methods (running, bin and none) are discussed in [11]. All scenario visualizations (scripts “visualize_layout.py”, “visualize_schedule.py” and “visualize_occpuancy.py”) depend on arranging data contained in the events file (scripts “read_schedule.py” and “read_occupancy.py”).

A.4.3 Study Analysis

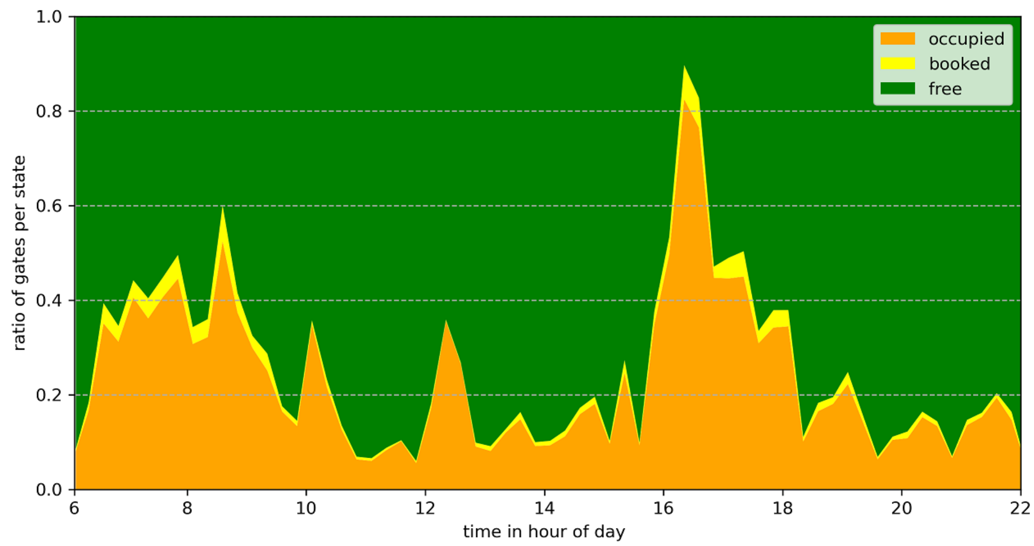
Study-related analysis and visualization happens after a batch of simulations is finished and aims at showing generalized information through mapping differing results onto the variations in scenarios. The analysis depends on aggregated values (e.g. average passenger waiting time), which are extracted from scenarios through the script “read_percentiles.py”. The data is then filtered and extracted through the scripts “custom_filter.py” and “custom_data.py”, respectively, and manually copied into the visualization script “custom_plot.py”. The main results are described in Section 3.2.5 and plots that were created through this process are for example the design heuristic in Figure 5.3, single parameter variations in Figure 3.12 or design driver evaluation in Figure 3.15. Publication #2 [2], publication #3 [12] and [11] contain further examples of study-related visualizations. There is a wide range of specialized plots that can be visualized through providing the respective data points and selecting plot characteristics through a list of keywords. This process is illustrated in Figure A.10, where the waiting times and percentiles of different segments of passengers are shown. For this plot, the keywords “pct”, “time”, “median” and “var” were chosen. A full list of possible keywords is given in Table A.2; here it should be mentioned that not all keywords are combinable with all others.



(a) Passenger waiting time in bins over course of day.



(b) Vehicle states without averaging in time-resolved manner.



(c) Gate states as ratios with 15-minute-bin-averaging and over course of day.

Figure A.9 Examplary visualizations of post-simulation scenario-related analysis.

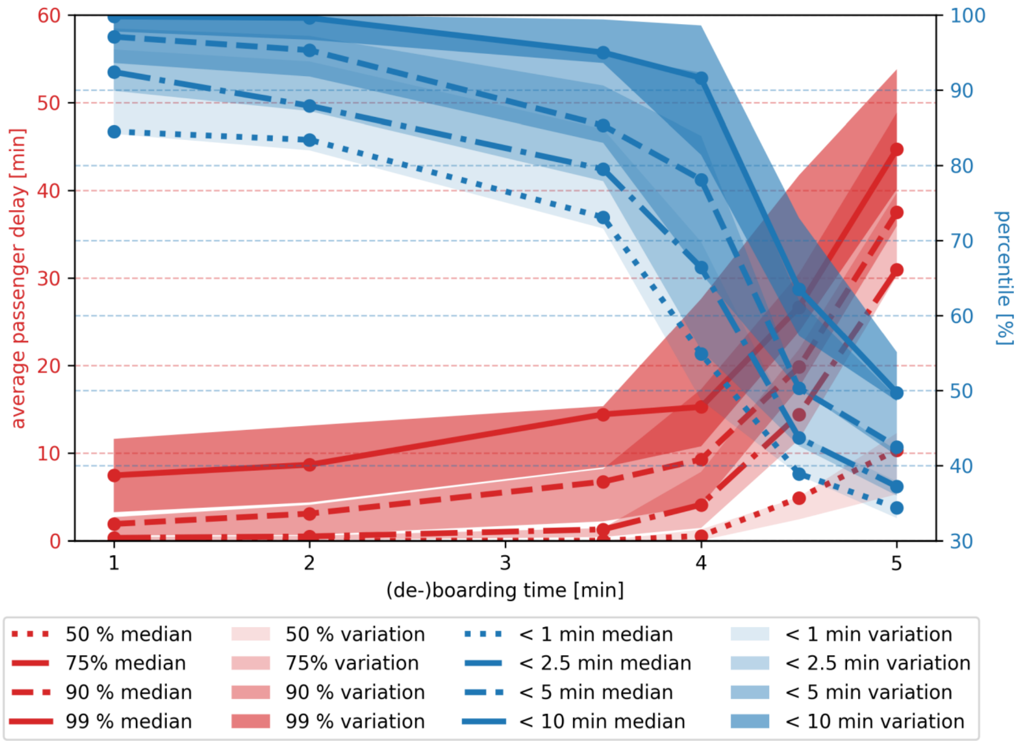


Figure A.10 Example for para-simulation study-related visualization: impact of boarding time on average delay for various segments of passenger.

Table A.2 Visualization options for study-related analysis.

Keyword group	Keywords
Data	pct, time, avg, fit
Select	min, max, median, var, mean, single, multi, norm, intersect, ceil
Fit	points, lin, poly2, poly3, exp, surface1, surface2
Type	3D, box, region, matrix

A.5 List of Rules

In this section a list of all rules contained in the *Rule_Machine* (see Appendix A.1) is given (in v1.1 the rules are still located in the *Controller.run()*-function, but are in the process of being moved). How the rules fit into the ABMS framework is described in Section A.2. The list of rules is split into three sections: rules related to arrivals (see Figure A.11a and A.11b), rules related to requests (see Figure A.11c) and rules related to waiting agents (see Figure A.11d). The rule numbers are included as comments in the software code to simplify navigation.

Rule No.	agent type	agent state	pax on board	position type	position state	destination type	destination state	Description
R01	vehicle			airspace		airspace		vehicle enters the system from the airspace
R01.1						pad	free	a pad is free
R01.1.1			yes					vehicle has passenger on board
R01.1.1.1						gate	free	multiple gates are free: vehicle starts approach, pad is set to occupied
R01.1.1.2							free	one gate is free: vehicle starts approach, pad is set to occupied, gate is set to booked
R01.1.1.X							occupied	no gate is free: vehicle goes into holding loop
R01.1.2			no					vehicle has no passenger on board
R01.1.2.1						stand	free	a stand is free: vehicle starts approach, pad is set to occupied
R01.1.2.2						gate	free	no stand is free, multiple gates are free: vehicle starts approach, pad is set to occupied
R01.1.2.3							free	one gate is free: vehicle starts approach, pad is set to occupied, gate is set to booked
R01.1.2.X							occupied	no gate or stand is free: vehicle goes into holding loop
R01.X						pad	occupied	no pad is free: vehicle goes into holding loop in airspace
R02	vehicle			airspace		pad	booked	vehicle finishes approach from airspace onto pad
R02.1				pad		gate		vehicle has destination pre-assigned
R02.1.1						lane	free	lane is free: vehicle starts taxiing
R02.1.X							occupied	lane is occupied: vehicle state is set to waiting at pad
R02.2			yes					vehicle arrived at pad with passenger on board
R02.2.1						gate	free	a gate is free: gate is booked
R02.2.1.1						lane	free	lane is free: vehicle starts taxiing towards gate
R02.2.1.X							occupied	lane is occupied: vehicle state is set to waiting at pad
R02.2.X						gate	occupied	no gate is free: vehicle state is set to waiting at pad
R02.3			no					vehicle arrived at pad with no passenger on board
R02.3.1	passenger	waiting		terminal				a passenger is waiting at terminal
R02.3.1.1	vehicle	moving		pad		gate	free	a gate is free: gate is booked, passenger walks to gate, vehicle destination set to gate
R02.3.1.1.1						lane	free	lane towards gate is free: vehicle starts taxiing
R02.3.1.1.X							occupied	lane towards gate is occupied: vehicle state is set to waiting at pad
R02.3.1.2						stand	free	no gate is free: stand is booked, destination set to gate
R02.3.1.2.1						lane	free	lane towards stand is free: vehicle starts taxiing
R02.3.1.2.X							occupied	lane towards stand is occupied: vehicle state is set to waiting at pad
R02.3.1.X						stand	occupied	no gate or stand is free: vehicle state is set to waiting at pad
R02.3.2	passenger	moving		terminal				no passenger waiting at terminal
R02.3.2.1	vehicle	waiting		pad		stand	free	stand is free for parking vehicle; dispatch vehicle to stand
R02.3.2.1.1						lane	free	lane towards stand is free: vehicle starts taxiing
R02.3.2.1.X							occupied	lane towards stand is occupied: vehicle state is set to waiting at pad
R02.3.2.2						gate	free	no stand is free: gate is booked, destination is set to gate
R02.3.2.2.1						lane	free	lane towards gate is free: vehicle starts taxiing
R02.3.2.2.X							occupied	lane towards gate is occupied: vehicle state is set to waiting at pad
R02.3.2.X						gate	occupied	no gate or stand is free: vehicle state is set to waiting at pad
R03	vehicle	moving		pad		airspace		vehicle finishes departure from pad into airspace
R04	vehicle	moving		lane		pad		vehicle is taxiing onto pad; vehicle starts departure into airspace
R05	vehicle			pad				vehicle is at pad and wants to taxi to other elements on airfield
R05.1	vehicle					lane	free	lane is free: vehicle starts taxiing
R05.X	vehicle						occupied	lane is occupied: vehicle state is set to waiting at pad

(a) Rules related to arrivals (part 1).

Figure A.11 List of rules for ABMS framework.

R06	vehicle			lane		gate	booked	vehicle is taxiing onto gate
R06.1			yes					vehicle has passenger on board: start de-boarding process
R06.2			no					vehicle has no passenger on board
R06.2.1	passenger	waiting		gate				a passenger is waiting at gate: start boarding process
R06.2.2		moving		terminal		gate		passenger is moving from terminal to gate: set vehicle state to booked
R06.2.3		waiting						a passenger is waiting in terminal: start walking towards gate, vehicle state set to booked
R06.2.X								no passenger waiting at terminal: vehicle state set to available
R08	vehicle			gate				vehicle is at gate and wants to taxi to other elements on airfield
R08.1	vehicle					lane	free	lane is free; vehicle starts taxiing
R08.X	vehicle					lane	occupied	lane is occupied; vehicle waits at gate
R09	vehicle			lane		stand	booked	vehicle enters stand
R09.1	passenger	waiting		terminal				dispatch vehicle to pick up passenger at gate
R09.2	vehicle	moving		stand				vehicle is set to available at stand
R10	vehicle			stand				vehicle is at stand and wants to taxi to other elements on airfield
R10.1	vehicle					lane	free	lane is free; vehicle starts taxiing
R10.X	vehicle					lane	occupied	lane is occupied; vehicle waits at stand
R11	passenger	moving		terminal		airspace		passenger finishes walking from terminal to gate
R11.1	vehicle	booked		gate				vehicle ist at gate and is booked for passenger; passenger starts boarding; vehicle set to moving
R11.X	passenger					gate	free	vehcile has not arrived at gate yet; passenger set to waiting
R12	passenger			gate		vehicle		passenger finishes boarding process; position is set to vehicle
R12.1	passenger					pad	free	pad is free; pad is set to booked; vehicle starts taxiing
R12.X	passenger					pad	occupied	no pad is free; vehicle and passenger are set to waiting
R13	passenger			vehicle		gate		passenger finishes deboarding process; position is set to gate; passenger starts walking to terminal
R13.1	passenger	waiting		terminal				other passenger is waiting at terminal; passenger starts walking to gate; vehicle set to booked
R13.2	vehicle					stand	free	stand is free for parking vehicle; dispatch vehicle to stand; stand is set to booked
R13.3	vehicle					stand	occupied	no stand is free; vehicle stays at gate and is set to available
R14	passenger			gate		terminal		passenger finished departure from gate into terminal

(b) Rules related to arrivals (part 2).

Rule No.	agent type	agent state	pax on board	position type	position state	destination type	destination state	Description
R30	passenger	waiting		terminal				passenger comes from outside the environment and arrives at the terminal
R30.1	vehicle	available		gate				vehicle is available at gate; passenger walks towards gate; vehicle is set to booked
R30.2	passenger					gate	free	
R30.2.1	vehicle	available		stand				find available vehicle; dispatch vehicle to free gate; passenger starts walking towards gate; gate set to booked
R30.2.X	vehicle	moving						no vehicle available; passenger set to waiting at terminal

(c) Rules related to requests.

Figure A.11 List of rules for ABMS framework (cont.).

Rule No.	agent type	agent state	pax on board	position type	position state	destination type	destination state	Description
R20	vehicle	waiting		airspace				vehicle is in holding loop in airspace waiting to land
R20.1						pad	free	pad becomes free
R20.1.1			yes					vehicle has passenger on board
R20.1.1.1						gate	free	multiple gates are free: vehicle starts approach, pad is set to occupied
R20.1.1.2							free	one gate is free: vehicle starts approach, pad is set to occupied, gate is set to booked
R20.1.1.X							occupied	no gate is free: vehicle remains in holding loop
R20.1.2			no					vehicle has no passenger on board
R20.1.2.1						stand	free	a stand is free: vehicle starts approach, pad is set to occupied
R20.1.2.2						gate	free	no stand is free, multiple gates are free: vehicle starts approach, pad is set to occupied
R20.1.2.3							free	one gate is free: vehicle starts approach, pad is set to occupied, gate is set to booked
R20.1.2.X							occupied	no gate or stand is free: vehicle remains in holding loop
R20.X						pad	occupied	no pad is free: vehicle stays in holding loop in airspace
R21	vehicle	waiting		pad				vehicle is waiting at pad
R21.1	vehicle		yes					vehicle has passenger on board
R21.1.1						gate	free	a gate is free: gate is booked
R21.1.1.1						lane	free	lane towards gate is free: vehicle starts taxiing, destination set to gate
R21.1.1.X							occupied	lane towards gate is occupied: vehicle stays at pad
R21.1.X						gate	occupied	no gate is free: vehicle stays at pad
R21.2			no					vehicle has no passenger on board
R21.2.1	passenger	waiting		terminal				a passenger is waiting at terminal
R21.2.1.1	vehicle	waiting		pad		gate	free	a gate is free: gate is booked, passenger walks to gate, vehicle destination set to gate
R21.2.1.1.1						lane	free	lane towards gate is free: vehicle starts taxiing
R21.2.1.1.X							occupied	lane towards gate is occupied: vehicle stays at pad
R21.2.1.2						stand	free	no gate is free: stand is booked, destination set to gate
R21.2.1.2.1						lane	free	lane towards gate is free: vehicle starts taxiing
R21.2.1.2.X							occupied	lane towards gate is occupied: vehicle stays at pad
R21.2.1.X						stand	occupied	no gate or stand is free: vehicle stays at pad
R21.2.2	passenger	moving		terminal				no passenger waiting at terminal
R21.2.2.1	vehicle	waiting		pad		stand	free	stand is free for parking vehicle; dispatch vehicle to stand
R21.2.2.1.1						lane	free	lane towards stand is free: vehicle starts taxiing
R21.2.2.1.X							occupied	lane towards stand is occupied: vehicle stays at pad
R21.2.2.2						gate	free	no stand is free: gate is booked, destination is set to gate
R21.2.2.2.1						lane	free	lane towards gate is free: vehicle starts taxiing
R21.2.2.2.X							occupied	lane towards gate is occupied: vehicle stays at pad
R21.2.2.X						gate	occupied	no gate or stand is free; vehicle continues waiting at pad
R22	vehicle	waiting	yes	gate				vehicle is waiting at gate with passenger on board
R22.1						pad	free	pad becomes free
R22.1.1						lane	free	lane towards pad is free: vehicle starts taxiing
R22.1.X							occupied	lane towards pad is occupied: vehicle stays at gate
R22.X						pad	occupied	no pad is free; vehicle with passenger stays at gate
R23	vehicle	available		gate				empty vehicle was not able to find an empty stand and was stuck at gate
R23.1						stand	free	vehicle starts taxiing towards stand; stand set to booked
R23.X							occupied	no stand free; vehicle stays at gate in state available
R24	vehicle	waiting				lane		vehicle is waiting to enter lane
R24.1							free	lane becomes free: vehicle starts taxiing
R24.X							occupied	lane is occupied: vehicles stays at element

(d) Rules related to waiting agents.

Figure A.11 List of rules for ABMS framework (cont.).

B Miscellaneous

B.1 Promising Locations and Suitable Sites for Vertiports

As mentioned in Section 3.1.1 two definitions for vertiport locations are given: a “promising location” as a general area with potential for UAM services (with a maximum radius of a few hundred meters); and a “suitable site” as the physical surface for a vertiport (e.g. a rooftop or vacant land). At *Bauhaus Luftfahrt* an expert workshop was held in 2021 that resulted in a list of relevant aspects as presented below. The aspects were grouped into “strongest positive effects” (Figure B.1a), “geast easily avoidable negative impacts” (Figure B.1b) and “Greatest uncertainty of impact” (Figure B.1c). Each group in Figure B.1 is sorted according to decreasing relevance and every individual aspect is assigned to one of the following five fields: airspace, building, community, transport or other. More information on the setup and results of the expert workshop were published in [9].

Strongest positive effects	**Related field**
Proximity to final destination	Transport
Advancements in UTM / U-Space regulations	Airspace
Access to shared mobility services	Transport
Number of alternative transportation options	Transport
New integrated and flexible planning concepts	Building
Redevelopment of old transport and mobility hubs	Building
Proximity to transportation hubs	Transport
Pop-up concepts and new forms of planning	Building
Being able to connect to mobility hubs	Transport
High density of business commuters	Community

(a) Strongest positive effects.

Least easily avoidable negative impacts	**Related field**
Regulation and certification	Other
Unclear demand of UAM	Community
Flight routing criteria	Airspace
Historic building and heritage protection	Building
Less expensive public transportation modes	Transport
Repurposing of existing buildings considering fire code etc.	Building
Availability of space	Building
Privacy concerns	Community
Special sites like hospitals, kindergarten, schools	Community
Nature reserve	Other
Proximity to transportation hubs and competition with existing modes	Transport
Constraints on passenger flow	Building
Impossibility of direct connection to transportation hubs	Transport
Surrounding buildings obstructing approach and departure path	Airspace
Load limits of roofs	Building
Noise pollution	Community

(b) Least easily avoidable negative impacts.

Figure B.1 Detailed aspects from expert workshop to identify promising vertiport locations [9].

Greatest uncertainty of impact	Related field
Political directions and climate policies	Community
Regulation and certification	Other
Advancements in UTM / U-Space regulations	Airspace
Unclear demand of UAM	Community
Flight routing criteria	Airspace
Urban / city's strategy	Community
Unclear advantage of eVTOLs over conventional helicopters	Other
Surrounding buildings obstructing approach and departure path	Airspace
Pop-up concepts and new forms of planning	Building
Fire codes	Building
Sound protection	Building
Reliable network connection	Other
Proximity to transportation hubs	Transport
Democratization of air mobility	Community
Redevelopment of old transport and mobility hubs	Building
Urban development plan	Community
Link to logistic	Transport
Data and data availability (e.g. GPS)	Airspace
New integrated and flexible planning concepts	Building
Automated planning tools	Building
Connection to mobility hubs	Transport
Less expensive public transportation modes	Transport
Impossibility of direct connection to transportation hubs	Transport

(c) Greatest uncertainty of impact.

Figure B.1 Detailed aspects from expert workshop to identify promising vertiport locations [9] (cont.).

These lists of aspects were used in a vertiport study in Northern Germany to identify promising vertiport locations. The study is described in [9] and the workflow and results are visualized in Figure B.2. Next to the aspects uncovered during the expert workshop, the following aspects for suitable vertiport sites were found in a literature review:

- **Highway cloverleaves** (first mentioned by [109]); the proximity to other transport modes and already existing noise level are put forth as reasons.
- **Top of high-rise buildings**, because they are often located in business districts [100, 108] and often have existing helipads [109].
- **Airports** [108, 54]; empty spaces close to the passenger terminal are ideal for airport shuttle services.
- **Floating barges on rivers** [54, 94].
- **Temporal re-purposing of existing spaces**, such as empty parking lots, temporally unused venues or open spaces on (technology) campuses [23].
- **Rooftop of parking garages** [23].
- **Train stations** [108].
- **Vacant land**.

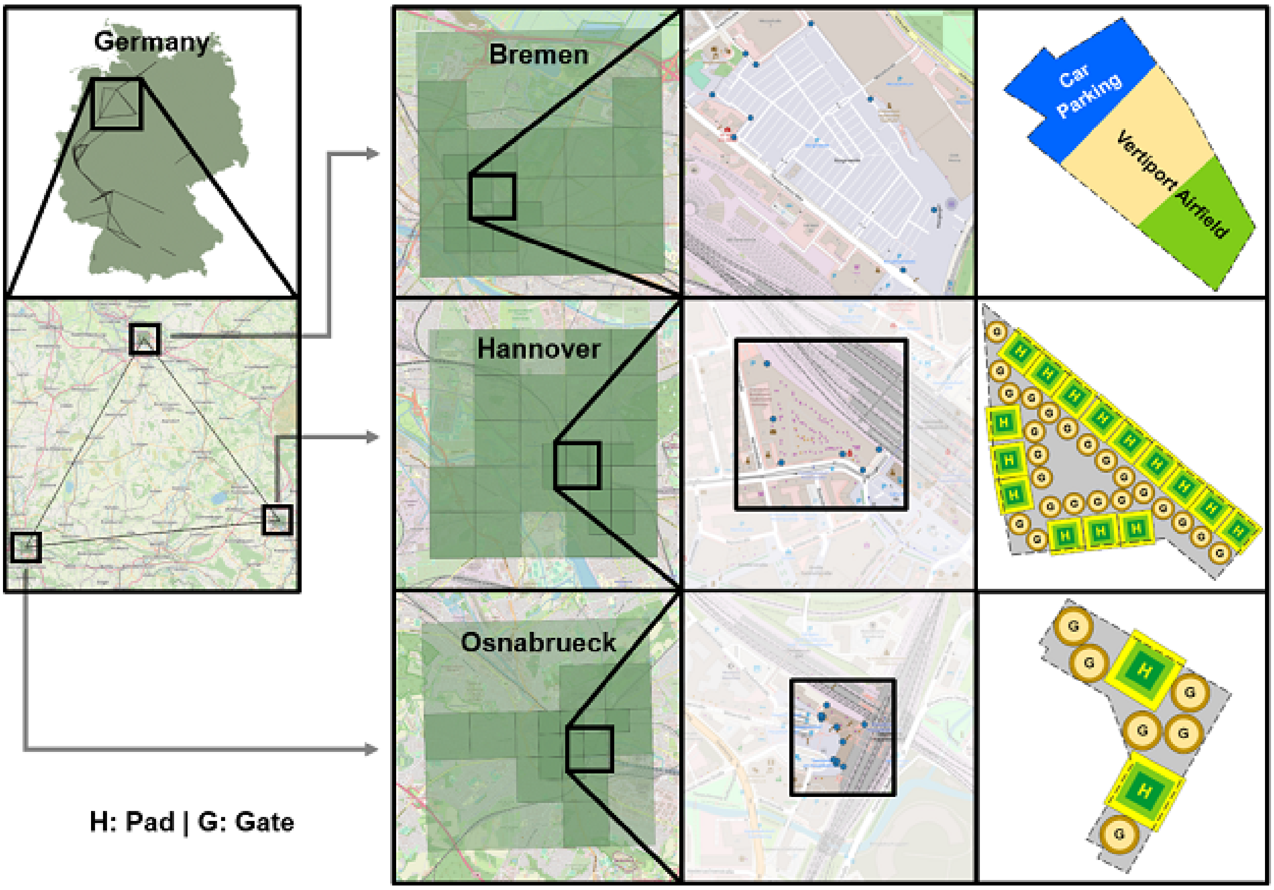


Figure B.2 Vertiport study in Northern Germany: promising locations, suitable sites and vertiport layouts [9].

B.2 Tabulation of Vertiport Throughput

In this section vertiport throughput capacities are tabulated. The following tables are results from the MIP-based vertiport design method as described in Section 3.1.3 and are another way, next to the rules-of-thumb (see Table 3.8), to estimate possible throughput on a given area without needing access to the vertiport design method itself. The tabulation is given for two vehicle sizes, a small one resembling typical multi-copters with $30\,ft$ maximum dimension (Figure B.3) and a large one resembling typical fixed-wing eVTOLs with $50\,ft$ maximum dimension (Figure B.4).

In the tables, the inputs are a variation of areas and turnaround times at the gates. From this the results are the number of pads and gates, the ideal topology and the possible vehicle throughput. The remaining assumptions are as follows:

- 1 minute approach and departure time
- square-shaped areas
- ground-taxiing with $2.15\,m/s$ taxiing speed
- pad dimensions according to [87] and gate/taxiway dimensions according to [86]
- definition of hourly vehicle "throughput" according to Figure 3.5

Area [km²]	10 min turnaround				20 min turnaround				30 min turnaround				40 min turnaround				50 min turnaround				60 min turnaround				Area [km²]
	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	
0,01	4	16	pier	94	4	16	pier	47	2	20	linear	38	2	22	linear	32	2	22	linear	24	2	22	linear	20	0,01
0,02	4	20	pier	104	4	32	linear	86	4	36	linear	70	4	36	linear	52	4	36	linear	42	4	36	linear	34	0,02
0,03	4	20	pier	104	4	36	pier	104	4	40	pier	79	4	48	linear	70	4	48	linear	56	4	48	linear	46	0,03
0,04	8	36	satellite	185	8	44	satellite	127	4	48	pier	95	4	52	linear	74	4	56	linear	64	4	56	linear	54	0,04
0,05	8	36	satellite	185	6	48	pier	132	6	60	pier	119	6	78	pier	109	6	84	pier	100	6	84	pier	83	0,05
0,06	8	36	satellite	185	6	48	pier	132	6	60	pier	119	6	78	pier	109	6	90	pier	103	6	96	pier	95	0,06
0,07	12	56	satellite	279	12	72	satellite	209	12	72	satellite	140	6	78	pier	109	6	90	pier	103	6	102	pier	98	0,07
0,08	12	56	satellite	279	12	72	satellite	209	8	80	pier	158	8	104	pier	146	8	120	pier	138	8	136	pier	131	0,08
0,09	12	56	satellite	279	12	72	satellite	209	8	80	pier	158	8	104	pier	146	8	120	pier	138	8	136	pier	131	0,09
0,10	12	56	satellite	279	12	72	satellite	209	8	80	pier	158	8	104	pier	146	8	120	pier	138	8	136	pier	131	0,10
0,11	12	56	satellite	279	12	72	satellite	209	8	80	pier	158	8	104	pier	146	8	120	pier	138	8	136	pier	131	0,11
0,12	16	76	satellite	373	16	100	satellite	291	16	100	satellite	195	16	100	satellite	147	8	120	pier	138	8	136	pier	131	0,12
0,13	16	76	satellite	373	16	100	satellite	291	10	100	pier	198	10	130	pier	182	10	150	pier	172	10	170	pier	163	0,13
0,14	16	76	satellite	373	16	100	satellite	291	10	100	pier	198	10	130	pier	182	10	150	pier	172	10	170	pier	163	0,14
0,15	16	76	satellite	373	16	100	satellite	291	10	100	pier	198	10	130	pier	182	10	150	pier	172	10	170	pier	163	0,15
0,16	16	76	satellite	373	16	100	satellite	291	10	100	pier	198	10	130	pier	182	10	150	pier	172	10	170	pier	163	0,16
0,17	16	76	satellite	373	16	100	satellite	291	10	100	pier	198	10	130	pier	182	10	150	pier	172	10	170	pier	163	0,17
0,18	20	96	satellite	467	20	128	satellite	373	20	128	satellite	250	20	128	satellite	188	10	150	pier	172	10	170	pier	163	0,18
0,19	32	128	pier	752	24	168	pier	498	20	180	pier	357	16	192	pier	286	14	210	pier	241	14	210	pier	209	0,19
0,20	34	136	pier	799	28	168	pier	498	20	200	pier	397	20	200	pier	298	16	208	pier	248	14	224	pier	223	0,20
0,21	36	144	pier	846	26	182	pier	540	20	200	pier	397	18	216	pier	322	16	224	pier	267	14	238	pier	229	0,21
0,22	38	152	pier	894	28	196	pier	582	22	220	pier	437	22	220	pier	328	18	234	pier	279	16	240	pier	239	0,22
0,23	40	160	pier	941	28	196	pier	582	22	220	pier	437	20	240	pier	358	18	252	pier	301	16	256	pier	255	0,23
0,24	42	168	pier	988	30	210	pier	623	24	240	pier	476	22	242	pier	361	18	252	pier	301	16	272	pier	262	0,24
0,25	44	176	pier	1035	32	224	pier	665	24	240	pier	476	20	260	pier	365	20	260	pier	310	18	270	pier	269	0,25
0,26	46	184	pier	1082	32	224	pier	665	26	260	pier	516	24	264	pier	394	20	280	pier	334	18	288	pier	287	0,26
0,27	48	192	pier	1129	34	238	pier	706	26	260	pier	516	22	286	pier	401	20	300	pier	345	20	300	pier	298	0,27
0,28	48	192	pier	1129	36	252	pier	748	28	280	pier	556	24	288	pier	429	20	300	pier	345	20	300	pier	298	0,28
0,29	50	200	pier	1176	34	272	pier	750	28	280	pier	556	24	312	pier	438	24	312	pier	372	20	320	pier	318	0,29
0,30	52	208	pier	1223	38	266	pier	790	30	300	pier	596	26	312	pier	465	22	330	pier	380	22	330	pier	328	0,30
0,31	54	216	pier	1270	40	280	pier	831	30	300	pier	596	26	312	pier	465	24	336	pier	401	24	336	pier	334	0,31
0,32	56	224	pier	1317	40	280	pier	831	32	320	pier	635	28	336	pier	501	26	338	pier	403	22	352	pier	350	0,32
0,33	58	232	pier	1364	42	294	pier	873	36	324	pier	643	28	336	pier	501	24	360	pier	414	22	374	pier	360	0,33
0,34	60	240	pier	1411	40	320	pier	883	34	340	pier	675	28	364	pier	511	28	364	pier	435	28	364	pier	362	0,34
0,35	62	248	pier	1458	44	308	pier	914	38	342	pier	679	30	360	pier	537	28	364	pier	435	24	384	pier	382	0,35
0,36	64	256	pier	1505	46	322	pier	956	36	360	pier	715	36	360	pier	537	28	392	pier	468	24	408	pier	393	0,36
0,37	64	256	pier	1505	46	322	pier	956	40	360	pier	715	32	384	pier	573	28	392	pier	468	26	416	pier	414	0,37
0,38	66	264	pier	1552	48	336	pier	997	38	380	pier	754	32	384	pier	573	28	420	pier	483	28	420	pier	418	0,38
0,39	68	272	pier	1599	50	350	pier	1039	38	380	pier	754	34	408	pier	608	30	420	pier	501	26	442	pier	425	0,39
0,40	70	280	pier	1646	50	350	pier	1039	40	400	pier	794	34	408	pier	608	30	420	pier	501	28	448	pier	446	0,40
0,41	72	288	pier	1693	52	364	pier	1081	40	400	pier	794	36	432	pier	644	32	448	pier	535	30	450	pier	448	0,41
0,42	74	296	pier	1741	54	378	pier	1122	42	420	pier	834	36	432	pier	644	32	448	pier	535	28	476	pier	458	0,42
0,43	76	304	pier	1788	54	378	pier	1122	42	420	pier	834	40	440	pier	656	32	448	pier	535	30	480	pier	478	0,43
0,44	78	312	pier	1835	56	392	pier	1164	44	440	pier	874	38	456	pier	680	34	476	pier	568	32	480	pier	478	0,44
0,45	80	320	pier	1882	58	406	pier	1205	44	440	pier	874	42	462	pier	689	34	476	pier	568	30	510	pier	491	0,45
0,46	80	320	pier	1882	58	406	pier	1205	46	460	pier	913	40	480	pier	716	36	504	pier	602	32	512	pier	510	0,46
0,47	82	328	pier	1929	60	420	pier	1247	46	460	pier	913	44	484	pier	722	36	504	pier	602	32	512	pier	510	0,47
0,48	84	336	pier	1976	62	434	pier	1289	48	480	pier	953	42	504	pier	752	42	504	pier	602	32	544	pier	524	0,48
0,49	86	344	pier	2023	62	434	pier	1289	48	480	pier	953	42	504	pier	752	38	532	pier	635	34	544	pier	542	0,49
0,50	88	352	pier	2070	64	448	pier	1330	50	500	pier	993	46	506	pier	755	38	532	pier	635	34	544	pier	542	0,50
0,51	90	360	pier	2117	64	448	pier	1330	50	500	pier	993	44	528	pier	788	42	546	pier	652	34	578	pier	557	0,51
0,52	92	368	pier	2164	66	462	pier	1372	52	520	pier	1033	48	528	pier	788	40	560	pier	669	36	576	pier	574	0,52
0,53	94	376	pier	2211	68	476	pier	1413	58	522	pier	1037	46	552	pier	823	40	560	pier	669	36	576	pier	574	0,53
0,54	96	384	pier	2258	68	476	pier	1413	54	540	pier	1072	46	552	pier	823	42	588	pier	702	38	608	pier	605	0,54
0,55	96	384	pier	2258	70	490	pier	1455	60	540	pier	1072	48	576	pier	859	42	588	pier	702	38	608	pier	605	0,55
0,56	98	392	pier	2305	72	504	pier	1496	56	560	pier	1112	48	576	pier	859	46	598	pier	714	38	608	pier	605	0,56
0,57	100	400	pier	2352	72	504	pier	1496	56	560	pier	1112	50	600	pier	895	44	616	pier	736	40	640	pier	637	0,57
0,58	102	408	pier	2399	74	518	pier	1538	58	580	pier	1152	50	600	pier	895	48	624	pier	745	40	640	pier	637	0,58
0,59	104	416	pier	2446	76	532	pier	1580	58	580	pier	1152	50	600	pier	895	46	644	pier	769	46	644	pier	641	0,59
0,60	106	424	pier	2493	76	532	pier	1580	60	600	pier	1192	52	624	pier	931	46	644	pier	769	42	672	pier	669	0,60
0,61	108	432	pier	2540	78	546	pier	1621	60	600	pier	1192	52	624	pier	931	50	650	pier	776	42	672	pier	669	0,61
0,62	110	440	pier	2588	80	560	pier	1663	62	620	pier	1231	54	648	pier	967	48	672	pier	803	48	672	pier	669	0,62
0,63	112	448	pier	2635	80	560	pier	1663	64	640	pier	1271	54	648	pier	967	52	676	pier	807	44	704	pier	701	0,63
0,64	112	448	pier	2635	82	574	pier	1704	64	640	pier	1271	56	672	pier	1002	50	700	pier	836	44	704	pier	701	0,64
0,65	114	456	pier	2682	84	588	pier	1746	66	660	pier	1311	56	672	pier	1002	50	700	pier	836	48	720	pier	717	0,65
0,66	116	464	pier	2729	84	588	pier	1746	66	660	pier	1311	58	696	pier	1038	54	702	pier	839	46	736	pier	733	0,66
0,67	118	472	pier	2776	86	602	pier	1788	68	680	pier	1350	58	696	pier	1038	52	728	pier	870	46	736	pier	733	0,67
0,68	120	480	pier	2823	86	602	pier	1788	68	680	pier	1350	58	696	pier	1038	56	728	pier	870	50	750	pier	747	0,68
0,69	122	488	pier	2870	88	616	pier	1829	70	700	pier	1390	60	720	pier	1074	54	756	pier	903	48	768	pier	765	0,69
0,70	124	496	pier	2917	90	630	pier	1871	70	700	pier	1390	60	720	pier	1074	54	756	pier	903	48	768	pier	765	0,70
0,71	126	504	pier	2964	90	630	pier	1871	72	720	pier	1430	62	744	pier	1110	54	756	pier	903	50	800	pier	797	0,71
0,72	128	512	pier	3011	92	644	pier	1912	72	720	pier	1430	62	744	pier	1110	56	784	pier	937	50	800	pier	797	0,72
0,73	128	512	pier	3011	94	658	pier	1954	74	740	pier	1470	64	768	pier	1146	56	784	pier	937	54	810	pier	807	0,73
0,74	130	520	pier	3058	94	658	pier	1954	74	740	pier	1470	64	768	pier	1146	56	784	pier	937	52	832	pier	829	0,74
0,75	132	528	pier	3105	96	672	pier	1995	76	760	pier	1509	70	770	pier	1149	58	812	pier	970	52	832	pier	829	0,75
0,76	134	536	pier	3152	98	686	pier	2037	76	760	pier	1509	66	792	pier	1182	58	812	pier	970	56	840	pier	837	0,76
0,77	136	544	pier	3199	98	686	pier	2037	78	780	pier	1549	72	792	pier	1182	60	840	pier	1003	54	864	pier	861	0,77
0,78	138	552	pier	3246	100	700	pier	2079	78	780	pier	1549	68	816	pier	1217	60	840	pier	1003	54	864	pier	861	0,78
0,79	140	560	pier	3293	102	714	pier	2120	80	800	pier	1589	68	816	pier	1217	60	840	pier	1003	58	870	pier	867	0,79
0,80	142	568	pier	3340	102	714	pier	2120	80	800	pier	1589	70	840	pier	1253	62	868	pier	1037	56	896	pier	893	0,80
0,81	144	576	pier	3387	104	728	pier	2162	82	820	pier	1629	70	840	pier	1253	62	868	pier	1037	60	900	pier	896	0,81
0,82	146	584	pier	3435	106	742	pier	2203	82	820	pier	1629	72	864	pier	1289	64	896	pier	1070	60	900	pier	896	0,82
0,83	146	584	pier	3435	106	742	pier	2203	84	840	pier	1668	72	864	pier	1289	64	896	pier	1070	58	928	pier	924	0,83
0,84	148	592	pier	3482	108	756	pier	2245	84	840	pier	1668	72	864	pier	1289	62	930	pier	1071	62	930	pier	926	0,84
0,85	150	600	pier	3529	108	756	pier	2245	86	860	pier	1708	74	888	pier	1325	66	924	pier	1104	62	930	pier	926	0,85
0,86	152	608	pier	3576	110	770	pier	2287	86	860	pier	1708	74	888	pier	1325	66	924	pier	1104	60	960	pier	956	0,86
0,87	154	616	pier	3623	112	784	pier	2328	88	880	pier	1748	76	912	pier	1361	68	952	pier	1137	64	960	pier	956	0,87
0,88	156	624	pier	3670	112	784	pier	2328	88	880	pier	1748	76	912	pier	1361	68	952	pier	1137	62	992	pier	988	0,88
0,89	158	632	pier	3717	114	798	pier	2370	90	900	pier	1788	78	936	pier	1396	66	990	pier	1140	62	992	pier	988	0,89
0,90	160	640	pier	3764	116	812	pier	2411	90	900	pier	1788	78	936	pier	1396	70	980	pier	1171	62	992	pier	988	0,90
0,91	162	648	pier	3811	116	812	pier	2411	92	920	pier	1827	80	960	pier	1432	70	980	pier	1171	64	1024	pier	1020	0,91
0,92	162	648	pier	3811	118	826	pier	2453	92	920	pier	1827	80	960	pier	1432	72	1008	pier	1204	64	1024	pier	1020	0,92
0,93	164	656	pier	3858	120	840	pier	2494	94	940	pier	1867	80	960	pier	1432	72	1008	pier	1204	64	1024	pier	1020	0,93
0,94	166	664	pier	3905	120	840	pier	2494	94	940	pier	1867	82	984	pier	1468	72	1008	pier	1204	66	1056	pier	1052	0,94
0,95	168	672	pier	3952	122	854	pier	2536	96	960	pier	1907	82	984	pier	1468	74	1036	pier	1238	66	1056	pier	1052	0,95
0,96	170	680	pier	3999	124	868	pier	2578	96	960	pier	1907	84	1008	pier	1504	74	1036	pier	1238	66	1056	pier	1052	0,96
0,97	172	688	pier	4046	124	868	pier	2578	98	980	pier	1946	84	1008	pier	1504	80	1040	pier	1243	68	1088	pier	1084	0,97
0,98	174	696	pier	4093	126	882	pier	2619	98	980	pier	1946	86	1032	pier	1540	76	1064	pier	1271	68	1088	pier	1084	0,98
0,99	176	704	pier	4140	128	896	pier	2661	100	1000	pier	1986	86	1032	pier	1540	82	1066	pier	1274	68	1088	pier	1084	0,99
1,00	178	712	pier	4187	128	896	pier	2661	100	1000	pier	1986	86	1032	pier	1540	78	1092	pier	1305	70	1120	pier	1116	1,00
Area [km²]	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	Area [km²]
	10 min turnaround				20 min turnaround				30 min turnaround				40 min turnaround				50 min turnaround				60 min turnaround				

Figure B.3 Tabulation of hourly vehicle throughput for eVTOLs with 30 ft maximum dimension.

Area [km²]	10 min turnaround				20 min turnaround				30 min turnaround				40 min turnaround				50 min turnaround				60 min turnaround				Area [km²]
	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	
0,01	1	4	linear	22	1	7	satellite	20	1	9	linear	17	1	9	linear	13	1	9	linear	10	1	9	linear	8	0,01
0,02	4	16	linear	88	4	20	satellite	57	4	20	satellite	38	4	20	satellite	29	4	20	satellite	23	4	20	satellite	19	0,02
0,03	4	20	pier	96	4	28	linear	78	4	28	linear	54	4	28	linear	40	4	28	linear	32	4	28	linear	26	0,03
0,04	4	20	pier	96	4	28	linear	78	4	32	linear	60	4	32	linear	46	4	32	linear	36	4	32	linear	30	0,04
0,05	8	32	satellite	166	8	48	satellite	137	8	52	satellite	100	8	52	satellite	75	8	52	satellite	60	8	52	satellite	50	0,05
0,06	8	32	satellite	166	8	48	satellite	137	8	52	satellite	100	8	52	satellite	75	8	52	satellite	60	8	52	satellite	50	0,06
0,07	8	32	satellite	166	8	48	satellite	137	8	52	satellite	100	6	60	pier	89	6	60	pier	71	6	60	pier	59	0,07
0,08	8	32	satellite	166	8	48	satellite	137	8	52	satellite	100	6	60	pier	89	6	66	pier	78	6	66	pier	65	0,08
0,09	8	32	satellite	166	8	48	satellite	137	8	52	satellite	100	6	60	pier	89	6	72	pier	84	6	72	pier	71	0,09
0,10	12	48	satellite	249	12	76	satellite	217	12	84	satellite	162	12	84	satellite	122	12	84	satellite	98	12	84	satellite	82	0,10
0,11	12	48	satellite	249	12	76	satellite	217	12	84	satellite	162	12	84	satellite	122	12	84	satellite	98	12	84	satellite	82	0,11
0,12	12	48	satellite	249	12	76	satellite	217	12	84	satellite	162	12	84	satellite	122	8	96	pier	112	8	112	pier	105	0,12
0,13	12	48	satellite	249	12	76	satellite	217	12	84	satellite	162	12	84	satellite	122	8	96	pier	112	8	112	pier	105	0,13
0,14	12	48	satellite	249	12	76	satellite	217	12	84	satellite	162	12	84	satellite	122	8	96	pier	112	8	112	pier	105	0,14
0,15	12	48	satellite	249	12	76	satellite	217	12	84	satellite	162	12	84	satellite	122	8	96	pier	112	8	112	pier	105	0,15
0,16	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	16	116	satellite	136	16	116	satellite	113	0,16
0,17	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	16	116	satellite	136	16	116	satellite	113	0,17
0,18	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	16	116	satellite	136	16	116	satellite	113	0,18
0,19	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	10	120	pier	140	10	140	pier	131	0,19
0,20	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	10	120	pier	140	10	140	pier	131	0,20
0,21	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	10	120	pier	140	10	140	pier	131	0,21
0,22	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	10	120	pier	140	10	140	pier	131	0,22
0,23	16	64	satellite	332	16	104	satellite	298	16	116	satellite	224	16	116	satellite	169	10	120	pier	140	10	140	pier	131	0,23
0,24	20	80	satellite	415	20	132	satellite	378	20	148	satellite	286	20	148	satellite	216	20	148	satellite	173	20	148	satellite	145	0,24
0,25	20	80	satellite	415	20	132	satellite	378	20	148	satellite	286	20	148	satellite	216	20	148	satellite	173	20	148	satellite	145	0,25
0,26	20	80	satellite	415	20	132	satellite	378	20	148	satellite	286	20	148	satellite	216	20	148	satellite	173	20	148	satellite	145	0,26
0,27	26	78	pier	453	20	132	satellite	378	20	148	satellite	286	20	148	satellite	216	20	148	satellite	173	20	148	satellite	145	0,27
0,28	28	84	pier	488	20	132	satellite	378	20	148	satellite	286	20	148	satellite	216	20	148	satellite	173	12	168	pier	157	0,28
0,29	28	84	pier	488	20	132	satellite	378	20	148	satellite	286	20	148	satellite	216	20	148	satellite	173	12	168	pier	157	0,29
0,30	30	90	pier	523	20	132	satellite	378	20	148	satellite	286	20	148	satellite	216	14	154	pier	183	12	168	pier	157	0,30
0,31	30	90	pier	523	22	132	pier	385	20	148	satellite	286	20	148	satellite	216	14	154	pier	183	12	168	pier	157	0,31
0,32	32	96	pier	558	22	132	pier	385	20	148	satellite	286	16	160	pier	238	14	168	pier	196	14	168	pier	167	0,32
0,33	32	96	pier	558	22	132	pier	385	20	148	satellite	286	18	162	pier	241	14	168	pier	196	14	168	pier	167	0,33
0,34	34	102	pier	593	24	160	satellite	459	24	180	satellite	348	24	180	satellite	263	24	180	satellite	211	14	182	pier	181	0,34
0,35	34	102	pier	593	24	160	satellite	459	24	180	satellite	348	24	180	satellite	263	24	180	satellite	211	14	182	pier	181	0,35
0,36	36	108	pier	627	24	160	satellite	459	24	180	satellite	348	18	180	pier	267	16	192	pier	224	16	192	pier	190	0,36
0,37	36	108	pier	627	24	160	satellite	459	24	180	satellite	348	20	180	pier	267	16	192	pier	224	16	192	pier	190	0,37
0,38	38	114	pier	662	24	160	satellite	459	24	180	satellite	348	20	180	pier	267	18	198	pier	236	16	208	pier	206	0,38
0,39	38	114	pier	662	24	160	satellite	459	24	180	satellite	348	20	180	pier	267	18	198	pier	236	16	208	pier	206	0,39
0,40	40	120	pier	697	28	168	pier	490	24	180	satellite	348	20	200	pier	297	20	200	pier	238	16	208	pier	206	0,40
0,41	40	120	pier	697	28	168	pier	490	24	192	pier	379	20	200	pier	297	18	216	pier	252	18	216	pier	214	0,41
0,42	42	126	pier	732	28	168	pier	490	24	192	pier	379	20	200	pier	297	20	220	pier	262	20	220	pier	218	0,42
0,43	42	126	pier	732	30	180	pier	525	24	192	pier	379	20	200	pier	297	20	220	pier	262	18	234	pier	232	0,43
0,44	44	132	pier	767	30	180	pier	525	26	208	pier	411	22	220	pier	327	22	220	pier	262	18	234	pier	232	0,44
0,45	44	132	pier	767	32	192	pier	560	26	208	pier	411	22	220	pier	327	20	240	pier	280	20	240	pier	238	0,45
0,46	46	138	pier	802	32	192	pier	560	26	208	pier	411	22	220	pier	327	20	240	pier	280	20	240	pier	238	0,46
0,47	46	138	pier	802	32	192	pier	560	30	210	pier	415	22	220	pier	327	22	242	pier	288	22	242	pier	240	0,47
0,48	48	144	pier	837	34	204	pier	595	28	224	pier	443	24	240	pier	357	22	242	pier	288	20	260	pier	258	0,48
0,49	48	144	pier	837	34	204	pier	595	28	224	pier	443	24	240	pier	357	22	242	pier	288	20	260	pier	258	0,49
0,50	50	150	pier	872	34	204	pier	595	32	224	pier	443	24	240	pier	357	22	264	pier	308	22	264	pier	262	0,50
0,51	50	150	pier	872	36	216	pier	630	30	240	pier	474	30	240	pier	357	24	264	pier	314	20	280	pier	263	0,51
0,52	52	156	pier	907	36	216	pier	630	30	240	pier	474	26	260	pier	386	24	264	pier	314	20	280	pier	263	0,52
0,53	52	156	pier	907	36	216	pier	630	30	240	pier	474	26	260	pier	386	24	264	pier	314	22	286	pier	284	0,53
0,54	54	162	pier	941	38	228	pier	665	30	240	pier	474	26	260	pier	386	24	288	pier	336	24	288	pier	286	0,54
0,55	54	162	pier	941	38	228	pier	665	32	256	pier	506	28	280	pier	416	26	286	pier	341	24	288	pier	286	0,55
0,56	56	168	pier	976	38	228	pier	665	32	256	pier	506	28	280	pier	416	26	286	pier	341	22	308	pier	289	0,56
0,57	56	168	pier	976	40	240	pier	700	32	256	pier	506	28	280	pier	416	26	286	pier	341	24	312	pier	310	0,57
0,58	58	174	pier	1011	40	240	pier	700	34	272	pier	538	28	280	pier	416	26	286	pier	341	24	312	pier	310	0,58
0,59	58	174	pier	1011	42	252	pier	735	34	272	pier	538	30	300	pier	446	28	308	pier	367	26	312	pier	310	0,59
0,60	60	180	pier	1046	42	252	pier	735	34	272	pier	538	30	300	pier	446	28	308	pier	367	26	312	pier	310	0,60
0,61	60	180	pier	1046	42	252	pier	735	36	288	pier	569	30	300	pier	446	28	308	pier	367	24	336	pier	315	0,61
0,62	62	186	pier	1081	44	264	pier	770	36	288	pier	569	30	300	pier	446	28	308	pier	367	26	338	pier	336	0,62
0,63	62	186	pier	1081	44	264	pier	770	36	288	pier	569	32	320	pier	476	30	330	pier	393	26	338	pier	336	0,63
0,64	64	192	pier	1116	44	264	pier	770	36	288	pier	569	32	320	pier	476	30	330	pier	393	26	338	pier	336	0,64
0,65	64	192	pier	1116	46	276	pier	805	38	304	pier	601	32	320	pier	476	30	330	pier	393	26	338	pier	336	0,65
0,66	66	198	pier	1151	46	276	pier	805	38	304	pier	601	36	324	pier	482	30	330	pier	393	26	364	pier	342	0,66
0,67	66	198	pier	1151	46	276	pier	805	38	304	pier	601	34	340	pier	505	34	340	pier	405	28	364	pier	362	0,67
0,68	68	204	pier	1186	48	288	pier	840	40	320	pier	633	34	340	pier	505	30	360	pier	420	28	364	pier	362	0,68
0,69	68	204	pier	1186	48	288	pier	840	40	320	pier	633	34	340	pier	505	30	360	pier	420	28	364	pier	362	0,69
0,70	70	210	pier	1221	48	288	pier	840	40	320	pier	633	38	342	pier	508	30	360	pier	420	28	364	pier	362	0,70
0,71	70	210	pier	1221	50	300	pier	875	40	320	pier	633	36	360	pier	535	36	360	pier	429	28	392	pier	368	0,71
0,72	72	216	pier	1255	50	300	pier	875	42	336	pier	664	36	360	pier	535	32	384	pier	448	30	390	pier	387	0,72
0,73	72	216	pier	1255	50	300	pier	875	42	336	pier	664	36	360	pier	535	32	384	pier	448	30	390	pier	387	0,73
0,74	74	222	pier	1290	52	312	pier	910	42	336	pier	664	40	360	pier	535	32	384	pier	448	30	390	pier	387	0,74
0,75	74	222	pier	1290	52	312	pier	910	44	352	pier	696	38	380	pier	565	38	380	pier	453	30	390	pier	387	0,75
0,76	76	228	pier	1325	54	324	pier	945	44	352	pier	696	38	380	pier	565	34	408	pier	477	32	416	pier	413	0,76
0,77	76	228	pier	1325	54	324	pier	945	44	352	pier	696	38	380	pier	565	34	408	pier	477	32	416	pier	413	0,77
0,78	78	234	pier	1360	54	324	pier	945	46	368	pier	728	38	380	pier	565	34	408	pier	477	32	416	pier	413	0,78
0,79	78	234	pier	1360	56	336	pier	980	46	368	pier	728	40	400	pier	595	34	408	pier	477	32	416	pier	413	0,79
0,80	80	240	pier	1395	56	336	pier	980	46	368	pier	728	40	400	pier	595	38	418	pier	498	38	418	pier	415	0,80
0,81	80	240	pier	1395	56	336	pier	980	46	368	pier	728	40	400	pier	595	36	432	pier	505	34	442	pier	439	0,81
0,82	82	246	pier	1430	58	348	pier	1015	48	384	pier	759	40	400	pier	595	36	432	pier	505	34	442	pier	439	0,82
0,83	82	246	pier	1430	58	348	pier	1015	48	384	pier	759	42	420	pier	625	36	432	pier	505	34	442	pier	439	0,83
0,84	84	252	pier	1465	58	348	pier	1015	48	384	pier	759	42	420	pier	625	40	440	pier	524	34	442	pier	439	0,84
0,85	84	252	pier	1465	60	360	pier	1050	50	400	pier	791	42	420	pier	625	38	456	pier	533	38	456	pier	453	0,85
0,86	86	258	pier	1500	60	360	pier	1050	50	400	pier	791	42	420	pier	625	38	456	pier	533	36	468	pier	465	0,86
0,87	86	258	pier	1500	60	360	pier	1050	50	400	pier	791	44	440	pier	654	38	456	pier	533	36	468	pier	465	0,87
0,88	88	264	pier	1535	62	372	pier	1085	52	416	pier	823	44	440	pier	654	38	456	pier	533	36	468	pier	465	0,88
0,89	88	264	pier	1535	62	372	pier	1085	52	416	pier	823	44	440	pier	654	42	462	pier	550	36	468	pier	465	0,89
0,90	90	270	pier	1569	64	384	pier	1120	52	416	pier	823	44	440	pier	654	40	480	pier	561	40	480	pier	477	0,90
0,91	90	270	pier	1569	64	384	pier	1120	52	416	pier	823	46	460	pier	684	40	480	pier	561	38	494	pier	491	0,91
0,92	92	276	pier	1604	64	384	pier	1120	54	432	pier	854	46	460	pier	684	40	480	pier	561	38	494	pier	491	0,92
0,93	92	276	pier	1604	66	396	pier	1155	54	432	pier	854	46	460	pier	684	44	484	pier	577	38	494	pier	491	0,93
0,94	94	282	pier	1639	66	396	pier	1155	54	432	pier	854	46	460	pier	684	42	504	pier	589	42	504	pier	501	0,94
0,95	94	282	pier	1639	66	396	pier	1155	56	448	pier	886	48	480	pier	714	42	504	pier	589	40	520	pier	517	0,95
0,96	96	288	pier	1674	68	408	pier	1190	56	448	pier	886	48	480	pier	714	42	504	pier	589	40	520	pier	517	0,96
0,97	96	288	pier	1674	68	408	pier	1190	56	448	pier	886	48	480	pier	714	46	506	pier	603	40	520	pier	517	0,97
0,98	98	294	pier	1709	68	408	pier	1190	56	448	pier	886	48	480	pier	714	46	506	pier	603	40	520	pier	517	0,98
0,99	98	294	pier	1709	70	420	pier	1225	58	464	pier	918	50	500	pier	744	44	528	pier	617	44	528	pier	525	0,99
1,00	100	300	pier	1744	70	420	pier	1225	58	464	pier	918	50	500	pier	744	44	528	pier	617	42	546	pier	543	1,00
Area [km²]	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	pads	gates	topology	throughput	Area [km²]
	10 min turnaround				20 min turnaround				30 min turnaround				40 min turnaround				50 min turnaround				60 min turnaround				

Figure B.4 Tabulation of hourly vehicle throughput for eVTOLs with 50 ft maximum dimension.

B.3 Vertiport Layout Tool

For this thesis two methods were implemented, MIP-based vertiport design (see Section 3.1.3) and ABMS-based vertiport operations (see Section 3.2.1), which function self-sufficiently. In order to link the results of these two methods, in particular to feed vertiport layouts designed from the former method into the latter method for simulation, a graphical user interface (GUI) was developed. The interface is implemented in the programming language *Visual Basic* and uses *Microsoft Publisher* as environment. The GUI loads the results of the MIP tool, in particular the number of pads and gates and the shape of the area, into a *Microsoft Publisher* document and sizes everything to scale. In a manual step, the layout of the vertiport can be arranged by drag-and-drop of elements. Next the positions of the elements are extracted and saved in a *csv*-file, which then in turn can be used as input for the ABMS framework. The process is illustrated in Figure B.5.

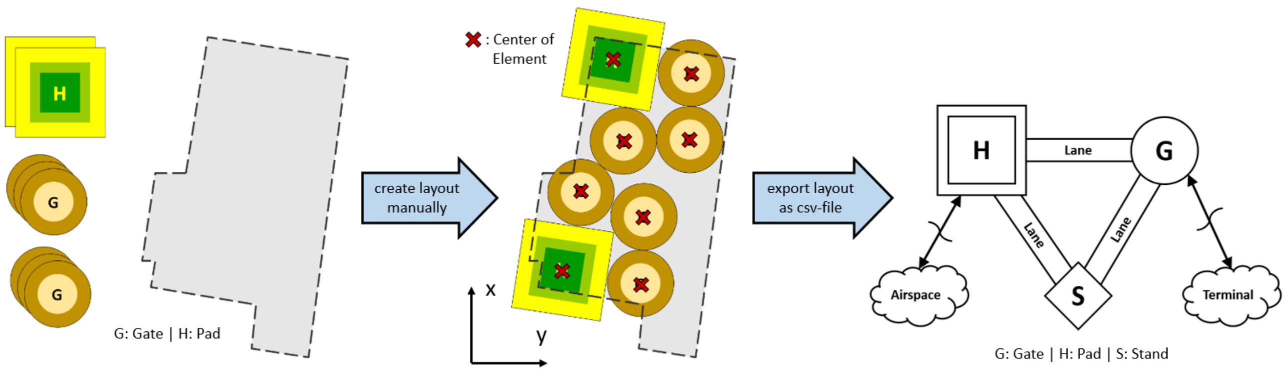


Figure B.5 GUI as interface between MIP (vertiport design) and ABMS (vertiport operations simulation).

The GUI also provides a quick and easy way of visualizing vertiport layouts (see also Section 3.1.2). There are various points throughout the presented research where the GUI was used for visualizations, for example in the Northern Germany use case shown in Figure B.2 or in [9, 113, 110, 111].

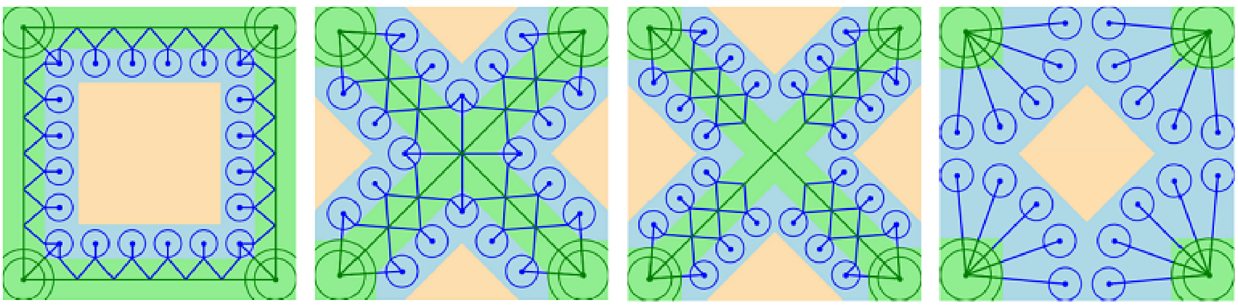
B.4 Vertiport Design Renderings

Vertiports do not exist today, but there are numerous concepts and renderings. Section 3.1.2 discusses four different vertiport airfield topologies and makes references to where these occur in the scientific literature. In this section, renderings (no real pictures) of technical vertiport layouts (Figure B.6), individual vertiports (Figure B.7) and vertiport families (Figure B.8) will be shown. The list of references is a selection of illustrative examples and meant to give an idea of current concepts.

B.4.1 Renderings of Technical Vertiport Layouts

(a) Single-pad, linear and pier topologies by *Volocopter* [116].

(b) Linear and pier topologies by *Lilium* [123].



(c) Satellite and pier topologies by NASA [121].

Figure B.6 Illustrations of technical vertiport layouts.

B.4.2 Individual Vertiport Designs

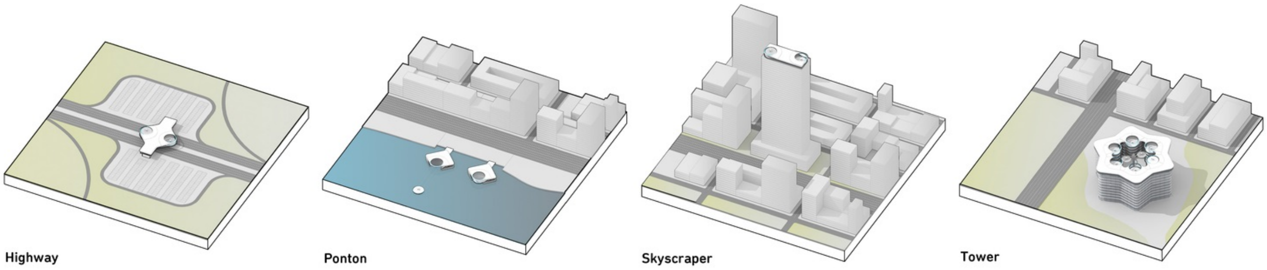
(a) Voloport [116].

(b) *Lilium* regional airport [21].

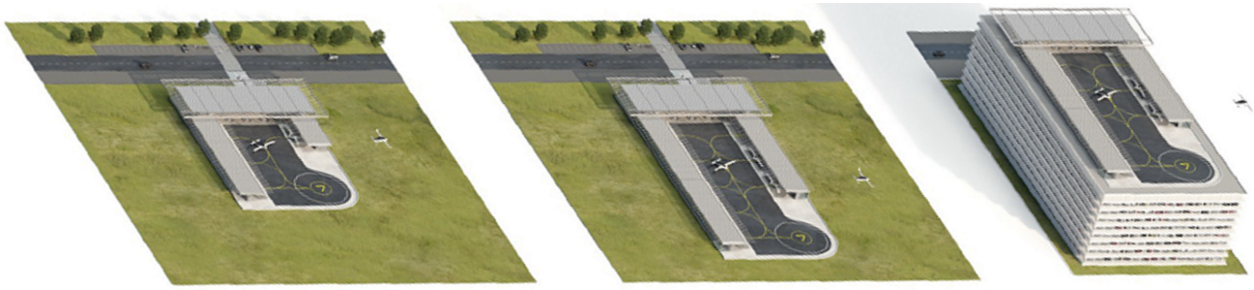
(c) *Uber* bee hive [130].

Figure B.7 Renderings of individual vertiport designs.

B.4.3 Vertiport Families

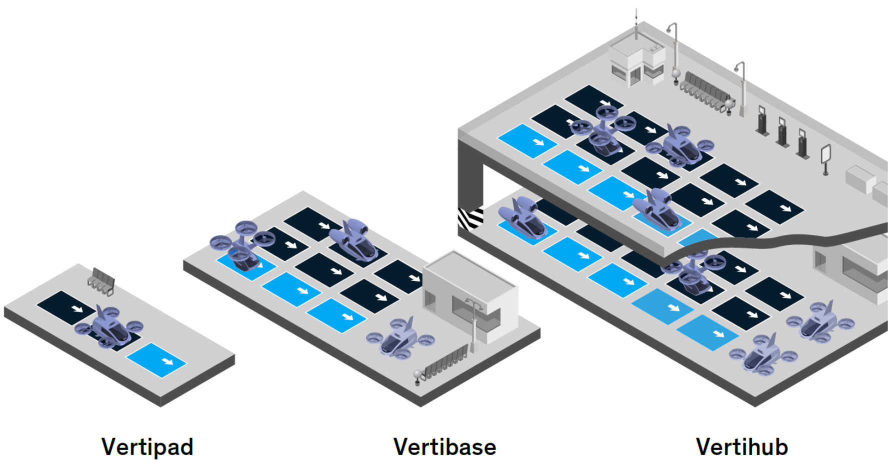


(a) *Volocopter* [116].



(b) *Lilium* [123].

(c) *Deloitte* [114].



(d) *McKinsey* [41].

Figure B.8 Illustrations and renderings of vertiport families.

B.5 Considerations on Vertiport Demand

Magnitude of the and shape of the demand profile are both essential factors in planning efficient vertiport operations. The estimation of demand magnitude can be reduced to a few key factors that are described in Section B.5.1. Central to the demand estimation is the question of mode choice: "under what conditions will a traveler switch his mode of transport to UAM?" (see Section B.5.2). Yet, knowing the magnitude is not enough, even though many studies do not go further in their level of detail; knowledge of the (time-resolved) demand profile is necessary. The presented research shows the need to analyze dynamically changing demand, in particular peaks and imbalances of arrivals and departures (see Section 3.2.5 and [3, 11]). This insight suggests that most vertiport studies are deficient in fidelity – increasing the detail of analysis around dynamic vertiport airfield operations is therefore a major contribution of this thesis.

B.5.1 Demand Estimation

[55] finds 542 cities worldwide with high estimated demand for UAM based on gross domestic product (GDP) and population. [109] identify San Francisco as a promising city because of many mega-commuters (90+ minute commute), high income and high cost of living. [131] review factors affecting demand estimation listed in literature: GDP, population and GDP per capita; travel distance and travel time; employment rate, income, airfare and buying power index; frequency of service, size of aircraft and load factor. [42] identify rapidly growing cities where infrastructure development is not keeping up with the growth rate as fertile ground for UAM services. [132] highlight ground traffic as a main factor for potential mode share. [133] use income, working hours, perceived cost and travel time for modeling demand. [134] model demand based on income, single-person vehicles and long commute distances on the ground. And, lastly, the perhaps most popular way to estimate demand is using value of time [19, 56, 57, 44]. This concept compares income with travel time savings (a combination of travel distance, speed and alternative modes of transport) and thereby estimates the possible trip cost, or airfare. Four factors will be put forth that summarize the review above in a simple list:

1. **Wealth** (as a representation of income, cost of living and available leisure time)
2. **Population** (in absolute and relative terms, the latter as population density)
3. **Nature of trip** (including distance, terrain and available/obstructing infrastructure)
4. **Transport alternatives** (foremost the travel time and cost, but also safety, comfort, level of automation, etc.)

B.5.2 Mode Choice Modeling

UAM "effectively represents a new mode of travel" [135] and the research community can therefore use experience from other modes of (air) travel only in a limited degree. From the literature on mode choice modeling in the context of UAM particularily the work of Garrow [135, 136, 137] and Fu [138, 139] will be highlighted in the following paragraph. There a various ways of modeling transport starting with the classical four step modeling[1] as used by [134]. Another popular approach is using agent-based simulation: *Bauhaus Luftfahrt* did high-fidelity modeling of travel behavior through their Microscopic Transportation Orchestrator (MITO) for the Munich metropolitan area with a 10 % representative sample of ca. 15 million daily trips [45, 141]. A less common approach is the pain-gain acceptance test put forth by [142] where the "gain" has to be significantly higher than the "pain" to result in acceptance and willingness to pay for UAM services.

Garrow first mentioned a survey to develop a UAM mode choice model in 2017 [135] and presented the questions and survey layout in 2018 [43]. The survey results were published in 2019 encompassing 1,400 participants in the U.S. with more than $75,000 annual household income and more than 30-minute

[1] The parts of four-step transport modeling are trip generation, trip distribution, mode choice and route assignment. A detailed introduction can for example be found in the standard work by Ortuzar and Willumsen [140].

commutes [136]. The survey was carefully executed with special attention to eliminating biases. The interpretation of the survey results were finally published in 2020 [137], but the concrete mode choice model is still underway.

Fu executed a stated-preference survey in Munich/Germany with 248 participants [139]. The ambiguity between stated and revealed preference are highlighted together with a review of related literature on UAM mode choice modeling [138]. From the survey results, a multi-nominal-logit model was built.

B.5.3 Dynamic Demand Profiles

Demand is typically modeled through a bi-modal profile to represent the common pre- and post-work rush hours. Depending on the city, there are two peaks of traffic roughly around 8 am in the morning and 5 pm in the afternoon. Accordingly, UAM studies considering commuting cases are modeled in a bi-modal fashion based on random samples derived from a probability distribution [41, 40, 143, 144, 129]. While a probability density function is a good first step, it will not account for the particularities of any given city. The demand profile generation and analysis module (see Section 3.2.3) of the ABMS framework has the ability to do one of three things: (1) generate demand (random samples from a probability density function), (2) process real-life demand or (3) a hybrid of both (i.e. when concrete demand is given in aggregated time bins and not with individual time stamps).

Next to peaks in demand, it was possible to identify imbalances between arrivals and departures as a main driver of efficiency [12, 11]. This part of demand modeling is virtually absent in current vertiport analyses. Difficulties arise when either all staged vehicles are gone and arriving passengers first have to wait for vehicles to be relocated; or when all staging stands are filled up and incoming vehicles have no opportunity to land and clear the pads and therefore approach has to be delayed. The phenomenon of accumulated imbalance between arrivals and departures is defined in this thesis as "vehicle stock" (when there is surplus of incoming vehicles) or "passenger stock" (when there is a lack of staged vehicles caused by a surplus of passenger requests). While not addressed in the current UAM literature these phenomena, including the need for vehicle relocation, has been studied extensively in one-way station-based car sharing [145, 146, 147, 148, 149, 150, 151].

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