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

Lukas Preis [1,2,*] and **Mirko Hornung** [1,2]

1   School of Engineering and Design, Technical University of Munich, Arcisstraße 21, 80333 München, Germany; mirko.hornung@bauhaus-luftfahrt.net
2   Bauhaus Luftfahrt, Willy-Messerschmitt-Straße 1, 82024 Taufkirchen, Germany
*   Correspondence: lukas.preis@tum.de

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

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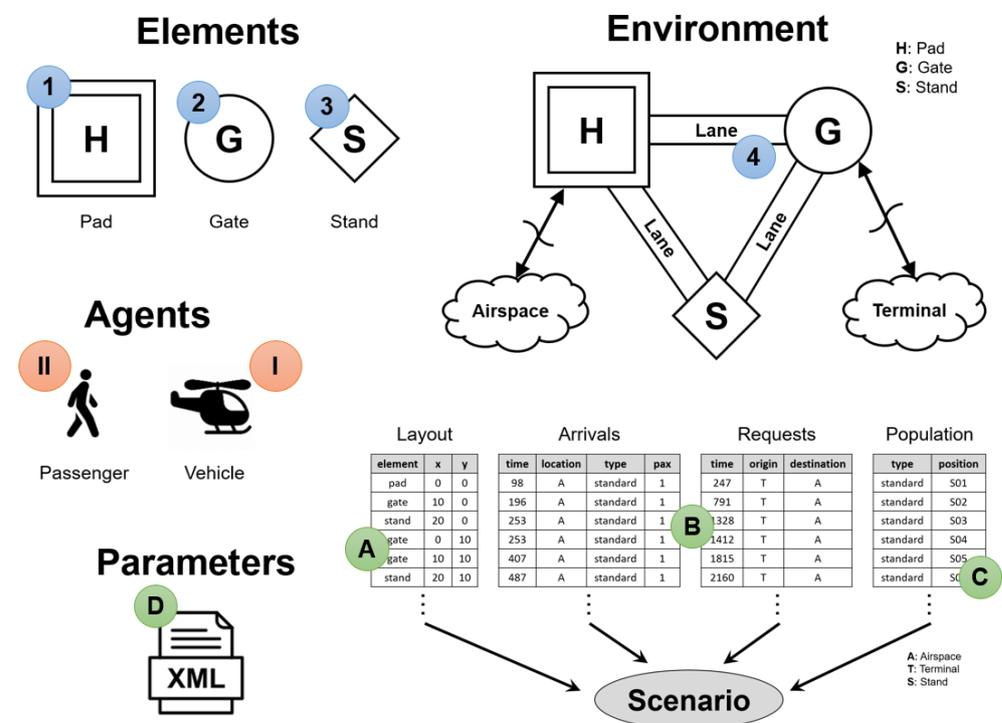
Figure 1. Depiction of elements, agents and environment of the agent-based simulation framework for vertiport operations; further including inputs needed for one simulation scenario.

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.
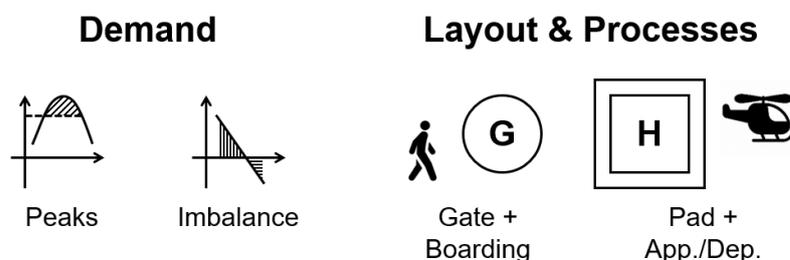
Figure 2. Depiction of design drivers for vertiport operations.

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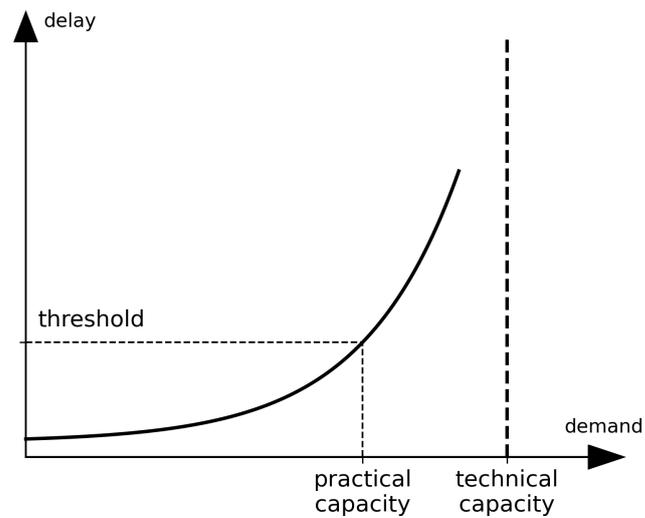
Figure 3. Concept of practical capacity, defined by a threshold of acceptable (average) delay.

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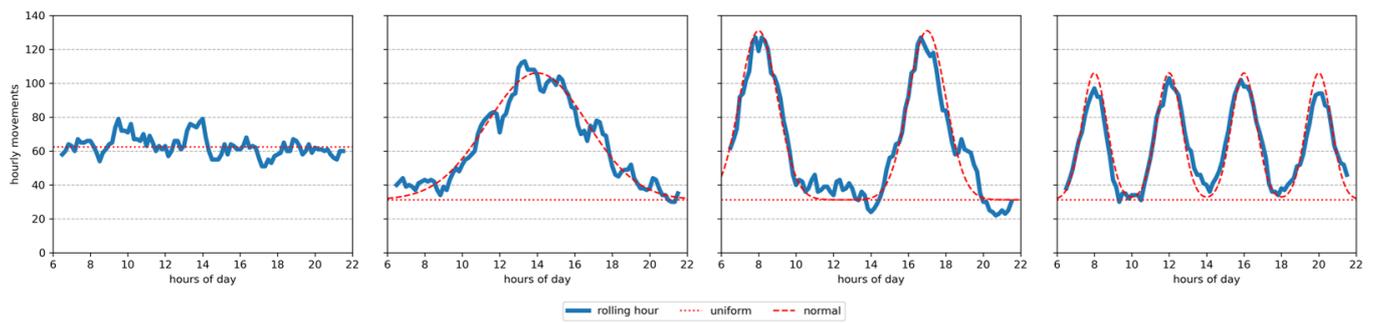
Figure 4. Examples of four shapes of randomly sampled demand profiles: uniform, single peak, bi-modal and four peaks (left to right).

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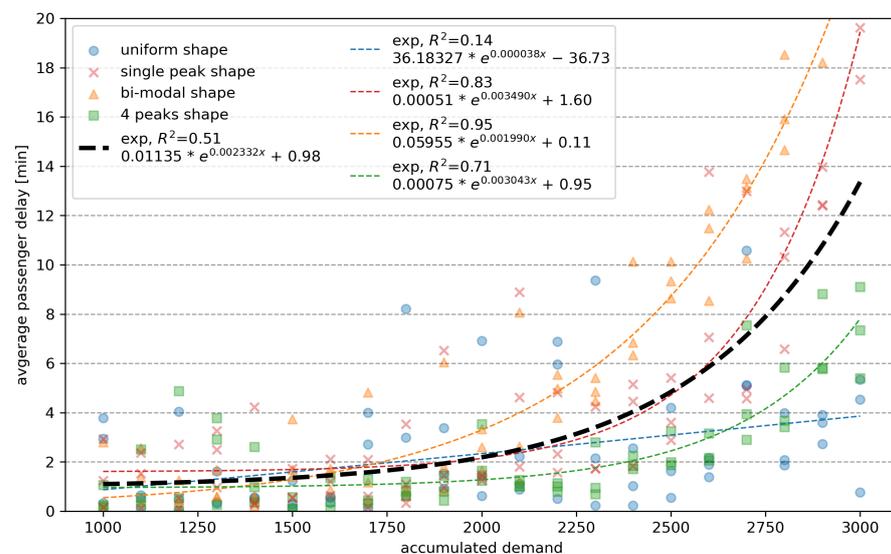
Figure 5. Analyzing the effect of accumulated daily demand on the average passenger delay.

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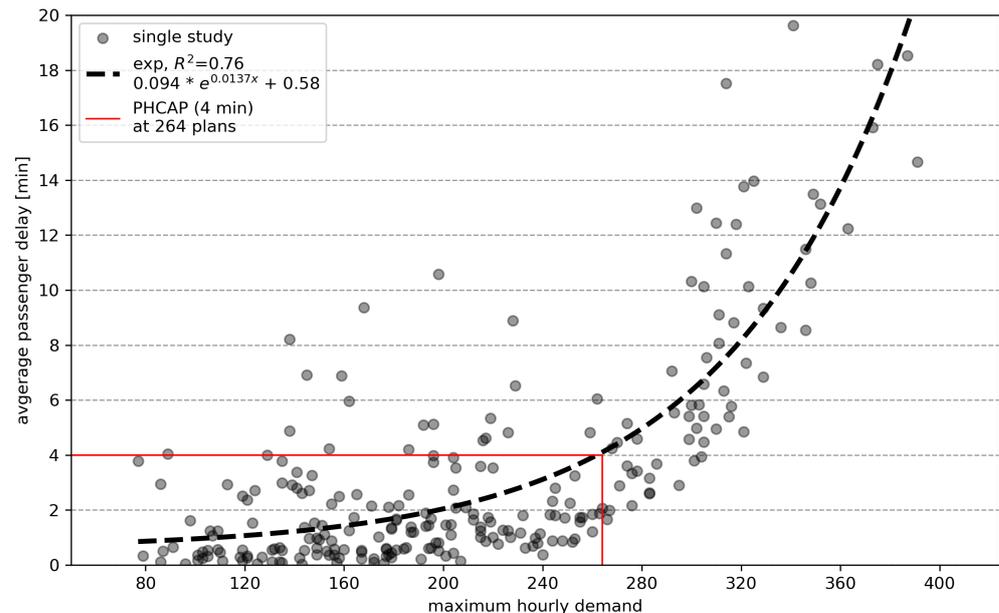
Figure 6. Analyzing the effect of peak-hour demand on the average passenger delay and identification of the practical hourly capacity PHCAP.

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 $PICAP = 33$.
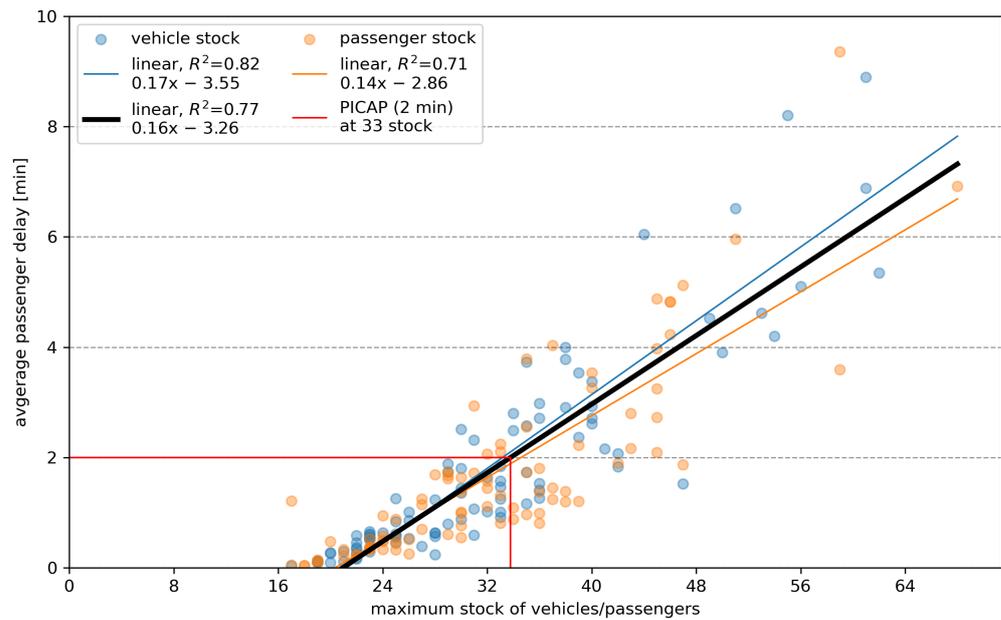
Figure 7. Analyzing the effect of vehicle/passenger stock on the average passenger delay and identification of the practical imbalance capacity PICAP.
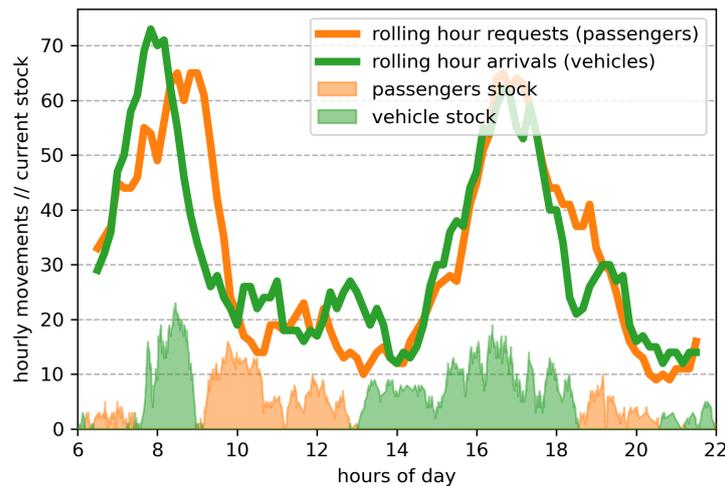
Figure 8. Illustration of vehicle and passenger stock resulting from imbalances in arrivals and departures.

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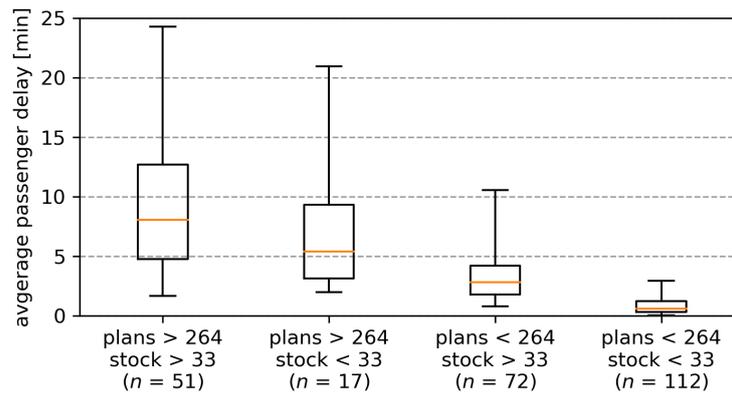
Figure 9. Four groups of scenarios based on their position related to the thresholds of PHCAP (plans = 264) and PICAP (stock = 33); the number *n* of scenarios falling into each category is listed in brackets.

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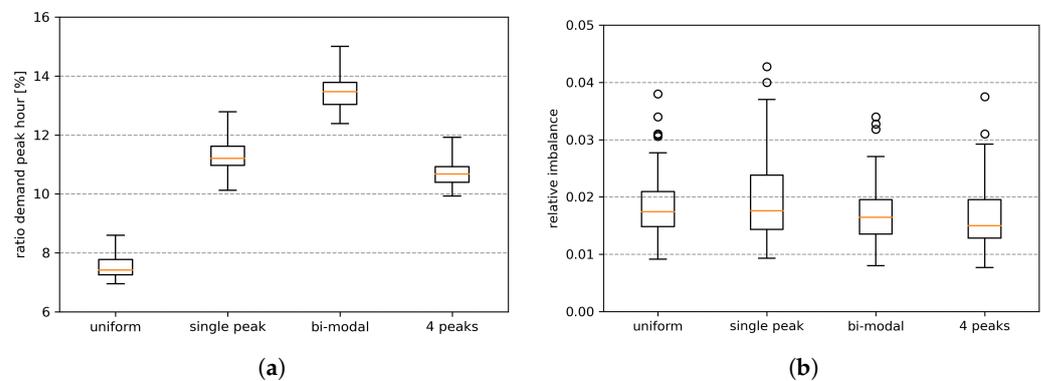
Figure 10. Reconstructing peak-hour demand and maximum stock based on knowledge of the accumulated daily demand and the shape of the demand profile. (**a**) Relation of peak hour demand to daily demand. (**b**) Relation of largest imbalance to daily demand.

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.
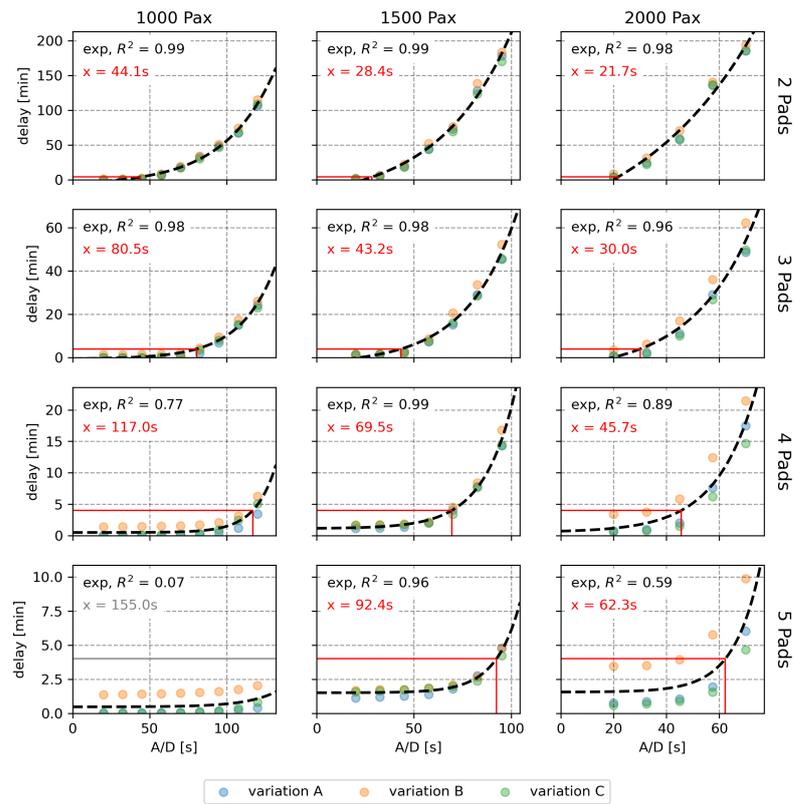
Figure 11. Simulation study under variation of demand, number of pads and approach and departure time (A/D).
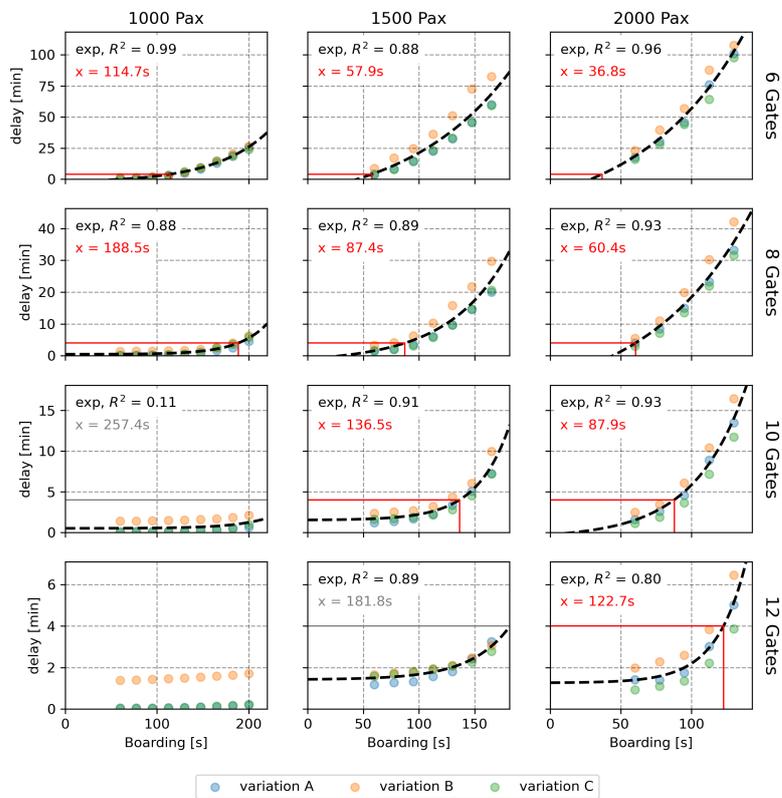
Figure 12. Simulation study under variation of demand, number of gates and boarding and de-boarding time.

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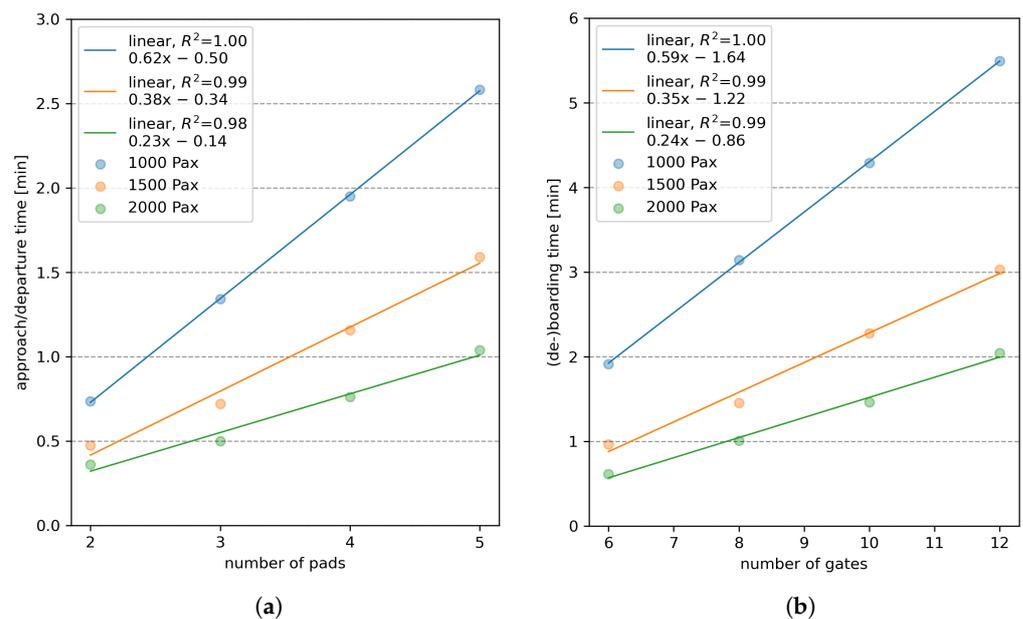
Figure 13. Graphical display of the interchangeability of demand capacity, number of elements and related processes. (**a**) Design heuristic for pad operations. (**b**) Design heuristic for gate operations.

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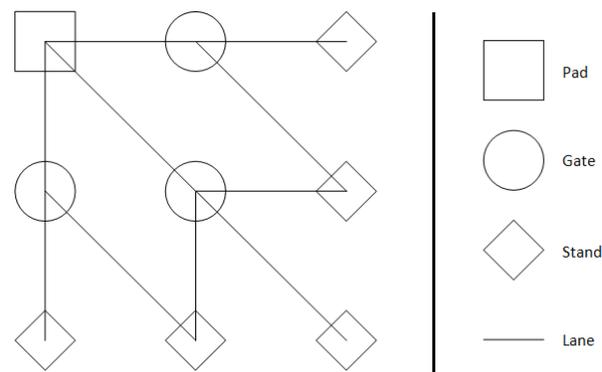
Figure A1. Schematic representation of one group of vertiport elements: 1 pad surrounded by 3 gates and 5 stands.

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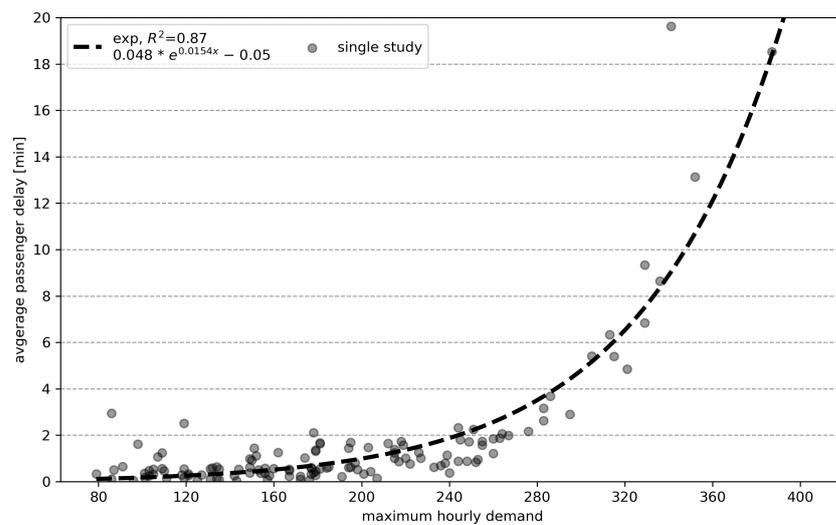
Figure A2. Refined analysis of the effect of peak-hour demand on the average passenger delay (excluding all scenarios surpassing the PICAP threshold).

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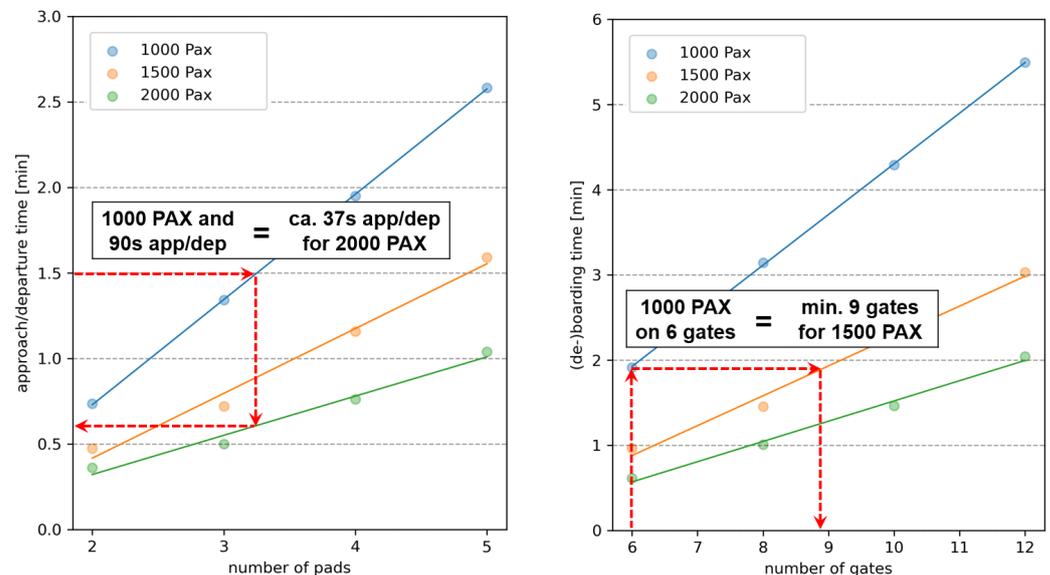
Figure A3. Application examples illustrating the use of the vertiport design heuristic.

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