34th Congress of the International Council of the Aeronautical Sciences
ICAS Florence CONGRESS September 9-13 2024 ITALY

COMPARING THE CAPACITY OF DIFFERENT VERTIPORT TOPOLOGIES USING DISCRETE EVENT SIMULATION

Eva Wille[1]

[1] RWTH Aachen University, Institute of Transport Science

Abstract

On the adoption of Urban Air Mobility (UAM), the development of UAM infrastructure for vertical takeoff and landing operations, commonly referred to as vertiports, constitutes a significant hurdle. Vertiport operations and the effect of vertiport design on the achievable vertiport capacity need to be understood in order to develop efficient vertiport designs. This study presents a discrete event simulation framework to assess the throughput capacity and practical capacity of vertiports by comparing different topologies, i. e. the physical arrangement of the airside components of the vertiport. The results indicate that the vertiport topology has a significant effect on the achievable capacity, in terms of both throughput capacity and practical capacity. It is also shown that the ratio of practical capacity to throughput capacity varies with infrastructural parameters.

Keywords: vertiport operations, vertiport capacity, discrete-event simulation, urban air mobility

1. Introduction

Urban Air Mobility (UAM) is considered as an enabler to “faster, cleaner and extended connectivity” [1] by using aircraft that are capable of electric Vertical TakeOff and Landing (eVTOLs). Current UAM research focuses on vehicle technologies, operations, and acceptance, among others [2–4]. However, one of the main hurdles to the adoption of UAM may also be the lack of an adequate UAM infrastructure [1, 5], commonly referred to as vertiports. As eVTOLs shall primarily operate in densely populated urban areas, the available space to build new vertiports will be strongly limited. UAM planners and operators will need to develop an efficient and well-designed infrastructure. Thus, the design and capacity assessment of vertiports represents a significant research area, in addition to other vertiport-related topics such as airspace integration and location selection [6]. The existing UAM literature emphasizes the need for a deeper understanding of vertiports and their operations to establish the development of an effective and economical vertiport infrastructure [3, 7].

This work presents a discrete event simulation (DES) framework to investigate the vertiport airside capacity for different vertiport sizes and layouts, also referred to as vertiport topologies. Previous parts of this work have been published in [8]. The vertiport simulation framework is conceptualized and developed in the software Anylogic. The simulation framework provides outputs such as throughput, delay, and utilization rates. We retrieve the throughput and practical capacity for the three vertiport topologies satellite, linear, and pier. The practical capacity is evaluated for different levels of acceptable average delay. The results are used to provide recommendations regarding vertiport design, which may be valuable to vertiport planners and future operators.

Section 2 introduces the vertiport as UAM infrastructure and provides a literature review on vertiport operations modeling and capacity assessment. It concludes by formulating the literature gap and the contribution of this paper. The development of the model and the conduction of the simulation are described in Section 3. In section 4, the results in terms of capacity measures and infrastructure utilization are presented and discussed. The final section highlights the main findings of the study and provides an outlook to further research needs.

2. Background on Vertiport Operations and Capacity Assessment

2.1 Vertiport Definitions and Components

A vertiport is defined by the European Union Aviation Safety Agency (EASA) as “an area of land, water, or structure that is used or intended to be used for the landing, take-off, and movement of VTOL-capable aircraft” [9]. In the literature, some other terms such as ‘vertipads’, ‘vertibases’, ‘vertidromes’, etc. can also be found. However, a systematic literature review on UAM-related keywords referring to the ground infrastructure has revealed that the term ‘vertiport’ is the most prominent one [6].

In 2022, both the EASA and the Federal Aviation Administration (FAA) published prototype (or interim) specifications for the design of vertiports [9, 10]. A vertiport consists of at least one ‘final-approach and take-off area’ (FATO), which is “a defined, load-bearing area over which the aircraft completes the final phase of the approach, to a hover or a landing, and from which the aircraft initiates takeoff.” [10] The FATO is surrounded by an obstacle-clear ‘safety area’. A ‘touchdown and lift-off area’ (TLOF) is “an area where a VTOL-capable aircraft may touch down or lift off” [9]. A ‘VTOL-capable aircraft stand’, hereinafter referred to as ‘stand’, is “a defined area that is intended to accommodate a VTOL-capable aircraft for loading or unloading passengers, mail, or cargo, fuelling/charging, parking, or maintenance, and, for the TLOF, where air taxiing operations are contemplated, the TLOF” [9]. A ‘VTOL-capable aircraft taxiway’, hereinafter referred to as ‘taxiway’, means “a defined path on a vertiport that is intended for the ground movement of VTOL-capable aircraft and that may be combined with an air taxi-route to permit both ground and air taxiing” [9].

The previously mentioned components can be summarized as the essential components of the vertiport airside. We define the ‘topology’ of a vertiport as the physical arrangement of these components. Other components of the vertiport, such as hangars, complementing stands for long-time parking, or passenger facilities, are not considered in the vertiport topology.

2.2 Capacity Measures

Capacity assessment has a long history in airport management and research. The primary literature on airport planning and design [11–13] distinguishes between two primary capacity measures: ‘maximum throughput capacity’ and ‘practical capacity’. Maximum throughput capacity, also referred to as ultimate capacity or saturation capacity, is defined as “the maximum number of operations that a service facility can accommodate over a defined period of time” [11]. A continuous demand for service is required to realize this capacity. As Ref. [12] points out, “[t]hroughput capacity is truly the theoretical definition of capacity.” Opposed to this capacity measure, practical capacity is defined as “the number of aircraft operations during a specified interval of time corresponding to a tolerable level of average delay” [11]. The idea of practical capacity was introduced by the FAA as the practical hourly capacity (PHCAP), which refers to an average delay per movement of four minutes [13]. However, there is a general lack of agreement on the specification of the acceptable level of average delay. Airport procedures, policies, and constraints differ from each other, leading to individual requirements regarding acceptable delay and punctuality. Figure 1 illustrates the definition of throughput capacity and practical capacity.

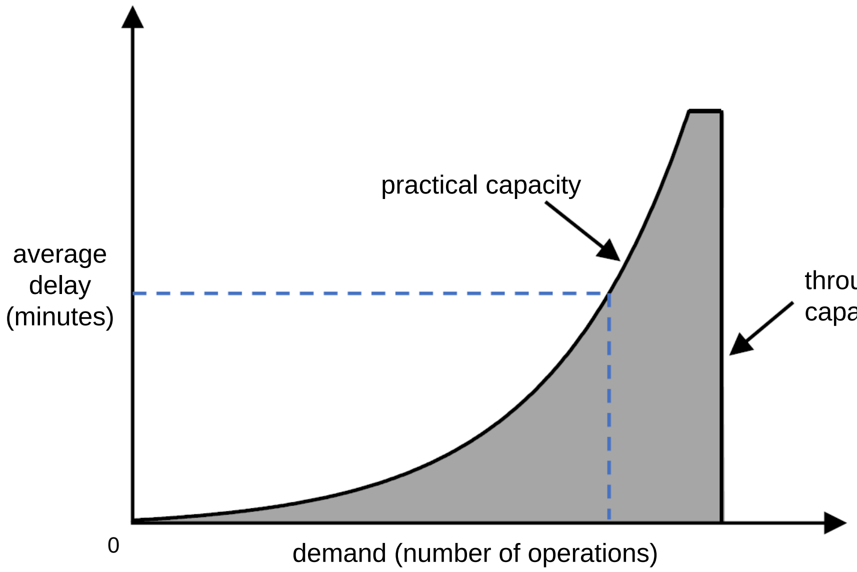


Figure 1 – Delay as a function of capacity and demand. Based on [11].

2.3 State-of-the-Art of Vertiport Operations Modeling and Capacity Assessment

Vertiport operations modeling and capacity assessment has gained interest in research within the last five years. Ref. [14] provided an essential milestone to vertiport research by identifying four different vertiport topologies: 'linear', 'satellite', 'pier', and 'remote apron'. The first three of these topologies are depicted in Figure 2. An Integer Programming (IP) formulation was used to estimate the throughput capacity of the vertiports and to create corresponding capacity envelopes. The authors investigated the effect of the vertiport topology and operational parameters. The results indicated that the ratio of TLOFs to stands is a key design factor for maximizing the vertiport capacity.

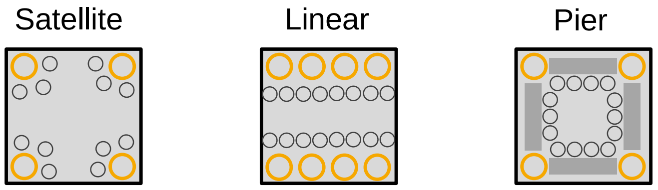


Figure 2 – Examples of the satellite, linear and pier topology with four or more TLOFs.

A theoretical model of vertiport throughput capacity was introduced in Ref. [15]. The model helped to identify either surface-limited or TLOF-limited operating conditions at the vertiport. It was used to provide a comparison to the results of a simulation model. In the theoretical model, the vertiport layout was defined by the number of TLOFs and stands; taxiways or topologies were not considered, and the surface time was aggregated into one single parameter. The number of TLOFs and stands was varied from 1-6 and 4-38, respectively.

The theoretical model from Ref. [15] was adapted in Ref. [16]. The surface process was divided into taxiing and turnaround. The purpose of the model was again to assess vertiport throughput (or theoretical) capacity. The author introduced three new topologies named 'perimeter', 'central', and 'disconnected', which resemble the linear, pier, and satellite topology. The topologies were designed for a square surface footprint with 4 TLOFs and 2-8 stands each. Besides throughput, the surface area utilization was also considered for the evaluation of the topologies. The author evaluated and compared the topologies regarding their operational efficiency, including considerations of wind constraints. The importance of expanding the evaluation by considering surface congestion was emphasized in the discussion of the paper.

A DES model was developed in Ref. [17] to assess the vertiport throughput capacity for a case study in the San Francisco Financial District. The vertiport was designed for a pier topology with 1-4 TLOFs and 8-9 stands each. The efficiency of the designs was evaluated by infrastructure utilization. Other outputs were queue lengths for departure and arrival tasks. A sensitivity analysis showed that the vertiport capacity was sensitive against changes in service times at TLOFs, service times at stands, and time between repositioning request and its completion.

Ref. [18] presented a “Vertidrome Airside Level of Service Concept” (VALos) to evaluate vertiport airside operations. The VALos included three stakeholder-oriented criteria in terms of acceptable delay. They applied the VALoS criteria to a “Linear Independent Expandable Drive Through” (LIEDT) topology [19] and used a DES model to determine the corresponding delays for two different demand distributions and two different flight schedule characteristics. The LIEDT topology consisted of two independently operating arrival and departure TLOFs and 3-4 complementing stands in between.

In Ref. [20], an agent-based modeling and simulation (ABMS) framework was used to understand the effects on vertiport operations and derive a design heuristic. The vertiport model was developed for the case of a satellite topology. The authors identified the following design drivers: peaks in demand, imbalance between arrivals and departures, pad operations and gate operations. Practical capacity was analyzed by comparing the average passenger delay with an acceptable delay level of 2-4 minutes. In the included parameter study, the number of TLOFs was ranged from 2-5, while the number of stands was ranged from 6-12. Other varied parameters were the duration of approach/departure and boarding/de-boarding, and the level of demand. The results were aggregated to a vertiport design heuristic.

An assessment of vertiport throughput capacity was conducted for the case of Gimpo airport in Ref. [21]. The authors developed different vertiport designs for a specific surface footprint at the airport, applying the satellite, linear, and pier topologies. The throughput capacity was evaluated in terms of movements and passengers by a MATLAB program. The results were presented as capacity envelopes, based on Ref. [14]. Additionally, the utilization of TLOFs and stands was analyzed.

In Ref. [22], an IP was developed which was able to find the optimal vertiport design in terms of throughput capacity and the net profit of the vertiport operator. Different to other literature, the authors only distinguished between ‘connected’ (i. e. satellite) and ‘disconnected’ vertiport topologies. The developed IP was only applicable for connected topologies. A case study was conducted for the Samseong vertiport in Seoul, Korea. The authors highlighted the need to consider the operations of the aircraft on the taxiway in future work.

A queuing model was developed in Ref. [23] to determine the throughput capacity and the practical capacity of vertiports. The practical capacity was assessed by applying acceptable levels of delay between 30-210 seconds. The vertiport was assumed to consist of two TLOFs and complementing stands in between. The vertiport processes were split into arrival, taxiing and turnaround, and departure. Three separate queueing models were developed for each of the vertiport subsystems. This approach did not provide the option to consider different vertiport topologies.

Ref. [24] presented a simulation model, which was implemented by using the “Pedestrian library“ tools of the Anylogic software. The authors referred to the central topology as introduced in Ref. [16] and derived two other topologies named ‘connected’ and ‘compact’. The topologies were designed for 4 TLOFs and 24, 28, and 32 stands. The authors introduced different operational modes called ‘independent’ and ‘segregated’. The evaluation comprises a comparison of the different topologies and operational modes by the simulation outputs throughput capacity, delay, and infrastructure utilization.

Table 1 – Literature overview on vertiport operations modeling.

Ref.	Research focus	Modeling approach	Output parameters	Vertiport topology	TLOFs	Stands
[14]	Capacity envelopes	IP	Throughput capacity, infrastructure utilization	Linear, Satellite, Pier, Remote	1-3	0-12
[15]	Throughput capacity and bottleneck	Analytical	Throughput capacity	-	1-6	4-38
[16]	Operational efficiency incl. wind constraints	Analytical	Throughput capacity, surface area	Perimeter, Central, Disconnected	4	8-32
[17]	Capacity for a case study of San Francisco Financial District	DES	Throughput, queue length, infrastructure utilization	Pier	1-3	8-34
[18]	VALos evaluation	DES	Delay	LIEDT	2	1, 3, 4
[20]	Design heuristic	ABMS	Delay and practical capacity	Satellite	2-5	6-12
[21]	Capacity envelopes for a case study of Gimpo airport	MATLAB program	Throughput capacity, infrastructure utilization	Linear, Satellite, Pier	2-4	6-20
[22]	Optimal vertiport design by maximizing throughput capacity and operators' net profit	IP	Optimal vertiport design and corresponding throughput capacity	Connected topologies	n/a	n/a
[23]	Determine throughput and practical capacity	Analytical queueing model	Throughput capacity, delay, practical capacity	-	2	2-20
[24]	Compare vertiport topologies and operational modes	Simulation (Anylogic Pedestrian Library)	theoretical capacity, eVTOL delay, infrastructure utilization, taxiway congestion	Central, Connected, Compact (based on Ref. [16])	4	24, 28, 32

As the literature review demonstrates, vertiport operations and simulation has only been researched very recently. All references from the literature review have been published from 2019 onwards. The investigated topologies were either identical or based on the four different topologies initially identified in Ref. [14]. The importance to consider specific vertiport topologies has been recognized in the majority of the studies. However, when multiple topologies were included, there was a lack of a comprehensive assessment of the practical capacity. This work addresses this research gap and provides a comparison of the three most researched topologies: linear, satellite, and pier. The topologies are compared by the measures of throughput capacity and practical capacity, which are determined by using a DES model of the vertiport airside operations.

3. Methodology

3.1 Vertiport Design and Selection of Operational Parameters

Vertiports were designed for the linear topology, satellite topology, and pier topology for a range of 1-4 TLOFs and 1-10 stands per TLOF. The TLOFs are placed at the edges of the vertiport to avoid eVTOLs overflying taxiways or stands. The dimensions of the infrastructure elements are based on the EASA design specifications [9]. The dimensioning requires the definition of the design parameter ‘D’, which is the diameter of the smallest circle enclosing the VTOL aircraft. Considering the eVTOL concepts that are currently under development, the dimension D is assumed to be 12 m.

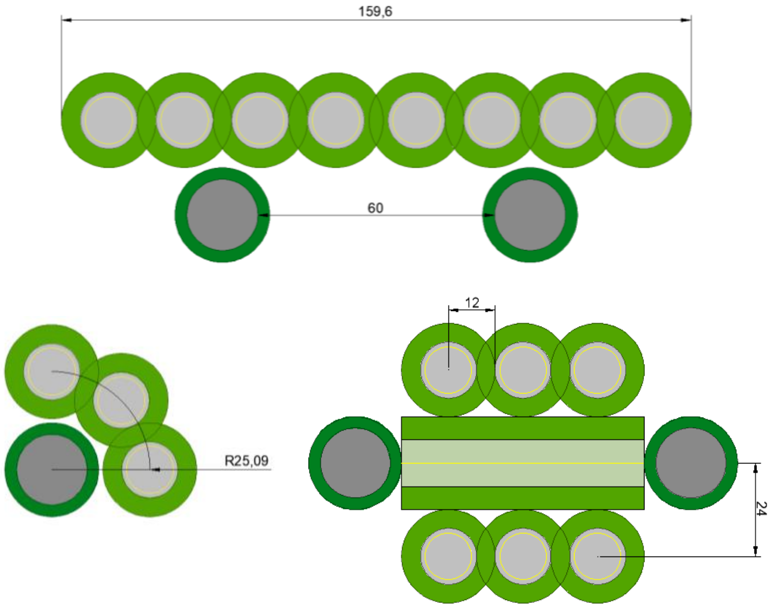


Figure 3 – Exemplary designs of the linear, satellite, and pier topology with D = 12 m.

To date, eVTOL process times such as for the final approach phase, the initial takeoff phase, or turnaround cannot be observed from real vertiport operations. Assumptions can be based on educated guesses made by experts, technical specifications announced by eVTOL manufacturers, or literature reviews. Table 2 provides an overview of the (baseline) parameter values applied in recent studies. For this study, the values for departure time, arrival time, turnaround time, and taxi speed are set to 60 s, 70 s, 500 s, and 1.8 m/s. Each taxi time is calculated based on the taxi speed and the actual taxiing distance between a specific TLOF and stand. Taxi distances depend on the number of stands at the vertiport and are determined during the simulation for each vertiport size and topology considered.

Table 2 – Literature review of vertiport process times.

Ref.	Departure time [s]	Arrival time [s]	Turnaround time [s]	Taxi speed [m/s]
[15]	60.0	60.0	-	-
[16]	60.0	60.0	480.00	1.22
[17]	60.0	90.0	600.00	-
[19]	66.0	75.0	600.00	2.60
[21]	60.0	60.0	300.00	-
[22]	90.0	90.0	600.00	-
[23]	30.0	45.0	386.95	1
[25]	-	90.0	-	-
[26]*	46.7	74.2	-	2.15
[26]*	60.0	60.0	-	2.20
[27]	-	-	-	1.34

* In Ref. [26], an expert- and literature-based parameter determination is conducted. In addition, a sensitivity analysis is included with a different set of baseline parameters.

3.2 Model Development

Prior to creating a computer-based simulation model, it is necessary to develop a conceptual model. The conceptual model for this study is shown in Figure 4. The start and the end of the flowchart are defined as eVTOLs are entering and leaving the airspace surrounding the TLOF. The eVTOLs are delayed in a holding queue until the vertiport is available for the next arrival. An eVTOL can only perform the final approach and landing process if the required resources of TLOF, stand and connecting taxiway are available. If these requirements are satisfied, the resources are immediately seized by the eVTOL. After landing, an eVTOL clears the TLOF, taxis to the assigned stand, and begins the turnaround. Before an eVTOL is released to taxi to the TLOF and takeoff, it is delayed until the next TLOF and the connecting taxiway are available.

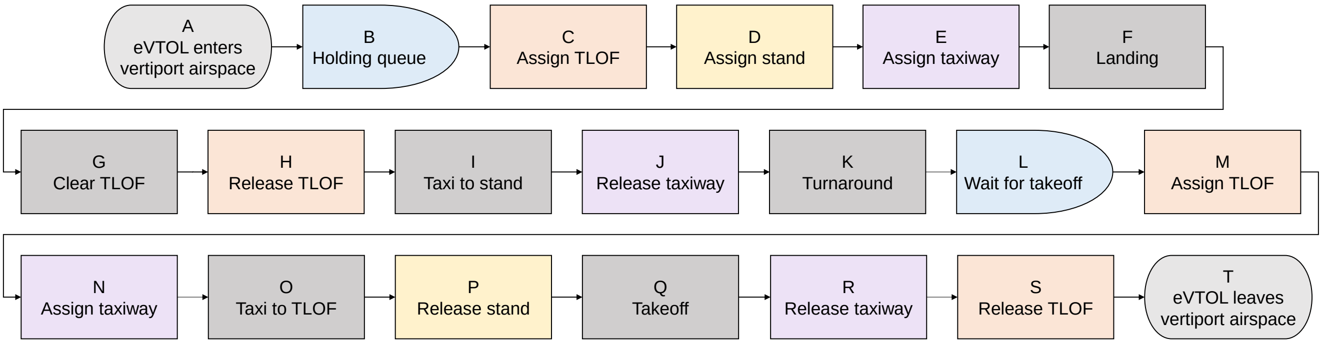


Figure 4 – Conceptual model of the vertiport operations. Grey elements represent processes; blue elements represent queues; elements of other colors represent the seize or release task of a resource.

When implementing the conceptual model into the DES model in Anylogic, one model is developed for each topology. This is necessary as the shared use of resources requires different rules for each topology. For example, the satellite topology does not comprise any taxiways that may be used by multiple eVTOLs at the same time. In the linear topology, a TLOF is complemented by two taxiway sections heading to each side of the TLOF; in the pier topology, one taxiway is used for all taxiing tasks from or to the allocated TLOF. The use of the taxiways is represented in the model by implementing the according taxiway resources.

Model verification and validation constitute fundamental steps in conducting a simulation study. Model verification is the “determination of whether the computer implementation of the conceptual model is correct” [28]. Model verification is performed using the following techniques: modular model development and successive debugging, conduction of a sensitivity study, and observation of visual animation.

Model validation is the “determination of whether the conceptual model can be substituted for the real system for the purposes of experimentation” [28]. The validation of a vertiport operations model constitutes a major challenge because there is no data from real operations that could be used for validation. Therefore, the results from the DES model are compared to the theoretical model introduced in Ref. [15]. Due to the nature of the theoretical model, the outputs can only be compared by means of throughput capacity. The comparison between the theoretical model and the DES model is beyond the scope of this study.

3.3 Simulation Plan and Model Output Evaluation

We aim to analyze and compare the different infrastructure scenarios in terms of throughput capacity, practical capacity, and utilization rates. An infrastructure scenario is defined by the vertiport topology, the number of TLOFs, and the number of stands.

To assess the vertiport throughput capacity and practical capacity, the average eVTOL delay is the key output parameter of the simulation framework. Every infrastructure scenario is simulated for varying demand levels, specified by the number of operations per hour. The number of operations per hour is gradually increased by 2 arrivals and 2 departures until the resulting waiting times are significantly longer than 10 minutes. The arrivals are distributed randomly, following a uniform distribution. An eVTOL departs as soon as it has completed its turnaround and the vertiport enables the next departure operation. To consider the stochastic effects of the arrival schedule, the simulation of a specific infrastructure scenario and demand level is performed for five different arrival schedules.

In this study, the throughput capacity and practical capacity are evaluated for the time window of one hour. As previously stated, the initially defined acceptable level of average delay for airports was established by the FAA at four minutes [13]. Given the limited energy reserves that battery-powered eVTOLs will be able to provide, it may be necessary to reduce the acceptable level of average delay for UAM operations. Therefore, we evaluate the practical capacity in this study for acceptable delay levels of 1, 2, 3, and 4 minutes. The throughput capacity of each infrastructure scenario is determined by the maximum recorded average delay from all simulation runs of each infrastructure scenario. To assess the practical capacity for the selected delay levels, an exponential fit is applied to the simulation results with an average delay between 0 and 10 minutes.

4. Results

4.1 Capacity Measures

Figure 5 shows how the throughput and practical capacities are retrieved for an exemplary infrastructure scenario. By applying this method to all infrastructure scenarios, we are able to plot the capacity as a function of the number of stands (see Figure 6). The partially irregular shape of the capacity curves can be attributed to the fact that each point of these curves depends on a fitted exponential function, as shown in Figure 3. It is assumed that these irregularities could be mitigated by simulating a higher number of simulation runs per infrastructure scenario.

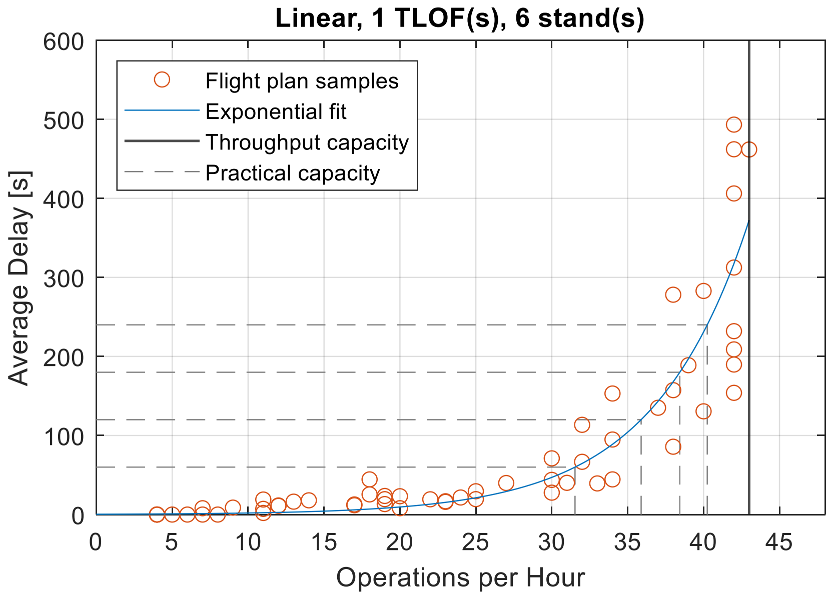
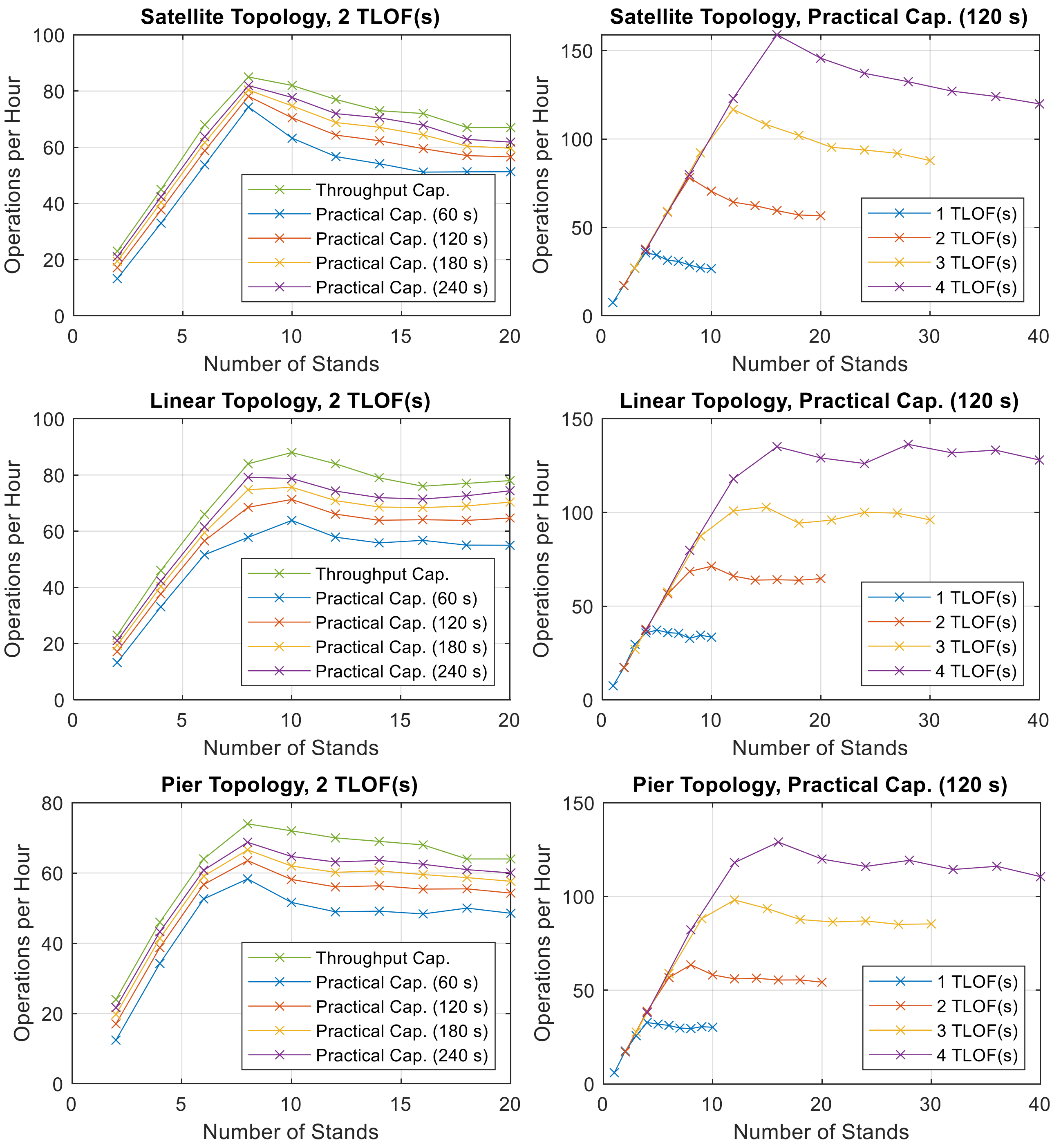


Figure 5 – Average eVTOL delay plotted against the number of operations per hour. The practical capacity is determined by an exponential function, which is fitted to the results of the simulation runs.

Figure 6 (b) shows that the maximum achievable vertiport capacity increases with the number of TLOFs for all topologies. The curves appear to have a similar shape for the different number of TLOFs. Figure 6 also illustrates that, for small numbers of stands, the addition of another stand increases the capacity. Once a specific number of stands has been added, the capacity does not increase further or even decreases. These two different sections of the capacity curve can be attributed to the TLOF-limited or surface-limited condition of the vertiport, as introduced by Ref. [15]. The decrease in capacity for large numbers of stands is most significant in the case of the satellite topology. This observation can be attributed to the geometric characteristic of the satellite topology: Adding more stands to the circumference around the TLOF requires longer taxi distances as the protection areas must remain clear. The increase in taxi distance reduces the capacity of the vertiport. All topologies achieve the highest capacity at 4 stands (in case of the linear topology also at 5 stands), given the assumed process times.



(a) Evolution of the different capacity measures.

(b) Effect of the number of TLOFs on the practical capacity.

Figure 6 – Exemplary capacity measures plotted against the number of stands.

Figure 7 shows the comparison of the three topologies with two TLOFs in terms of throughput capacity and practical capacity for an acceptable average delay of 120 seconds. The figure illustrates that the pier topology generally achieves the lowest capacity for both capacity measures. This difference is most significant for 4-7 stands per TLOF; it is not significant for 3 or fewer stands per TLOF. Similarly, for topologies with 1, 3, or 4 TLOFs, no significant difference of capacities can be observed for 3 or fewer stands per TLOF.

Figure 7 also shows that the satellite or the linear topology achieves the highest capacity, depending on the number of stands. For 4 or fewer stands per TLOF, the satellite topology performs better than the linear topology; the opposite is true for 5 or more stands per TLOF. In general, this trend is also observed for topologies with 1, 3, or 4 TLOFs.

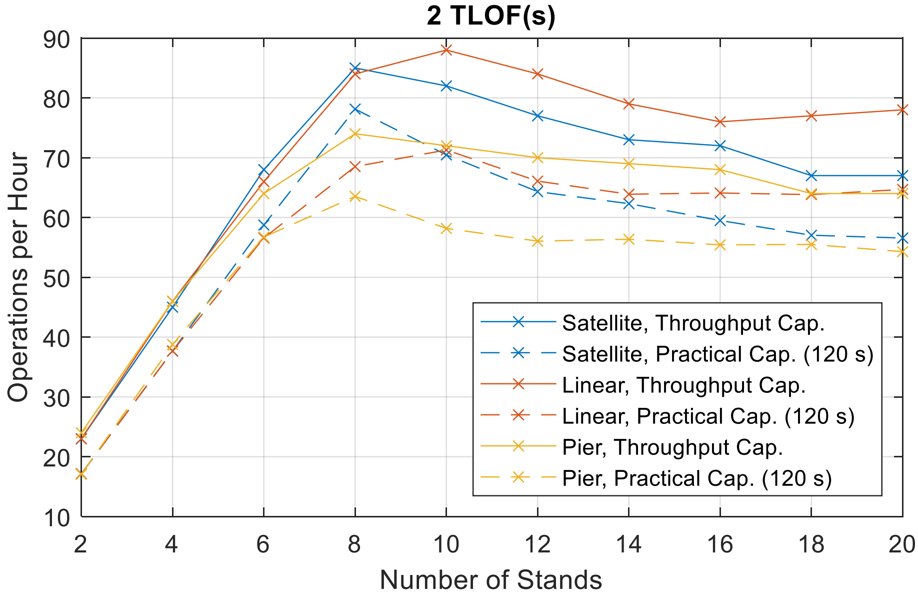


Figure 7 – Comparison of the three topologies for throughput capacity and practical capacity for an acceptable average delay of 120 seconds.

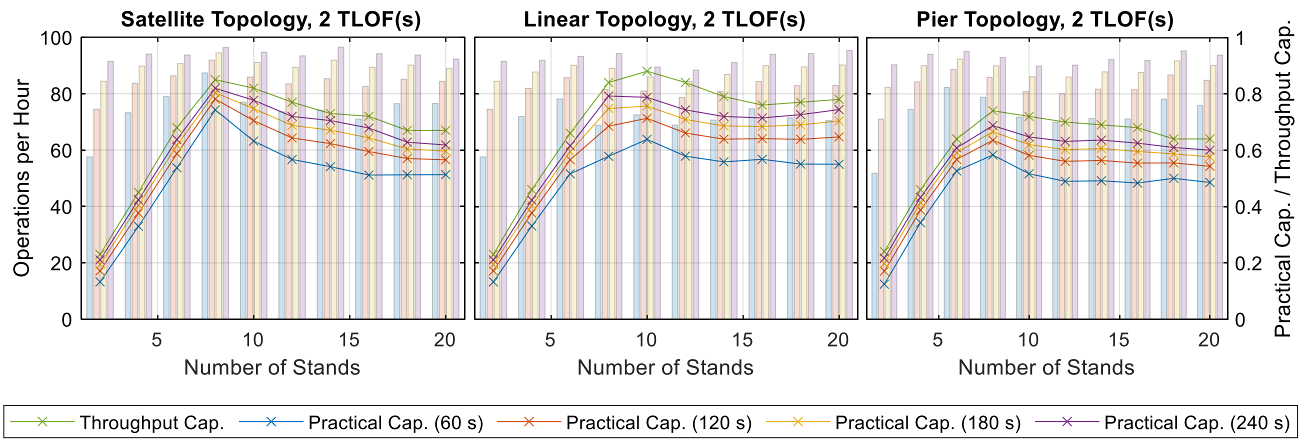


Figure 8 – Comparison of the three topologies for throughput capacity and all practical capacities. The bars indicate the ratio of practical capacity to throughput capacity for each acceptable level of average delay.

The comparison of the three topologies for all capacity measures and the ratio of the practical capacities to the throughput capacity is illustrated in Figure 8. The ratio between practical and throughput capacity shows a higher range and deviation for increasing values of acceptable average delay. For example, the ratio of the practical capacity at 1 minute acceptable average delay varies between 51% and 87%, while the ratio of the practical capacity at 4 minutes acceptable average delay varies between 88% and 96%. The range and deviation of the ratios is slightly smaller for the linear topology compared to the satellite and the pier topology.

4.2 Infrastructure Utilization

The illustration of the infrastructure utilization can be used to verify the trends that were observed from the capacity evolution. In Figure 9, the bar charts depict the average utilization of all TLOFs, stands, and taxiways, averaged for the five flight plan samples with a demand level of 34 arrivals per hour. Since the satellite topology comprises a separate taxiway for each stand, taxiway resources are not shared by multiple eVTOLs and the taxiway utilization is proportional to the stand utilization. Therefore, it is not displayed.

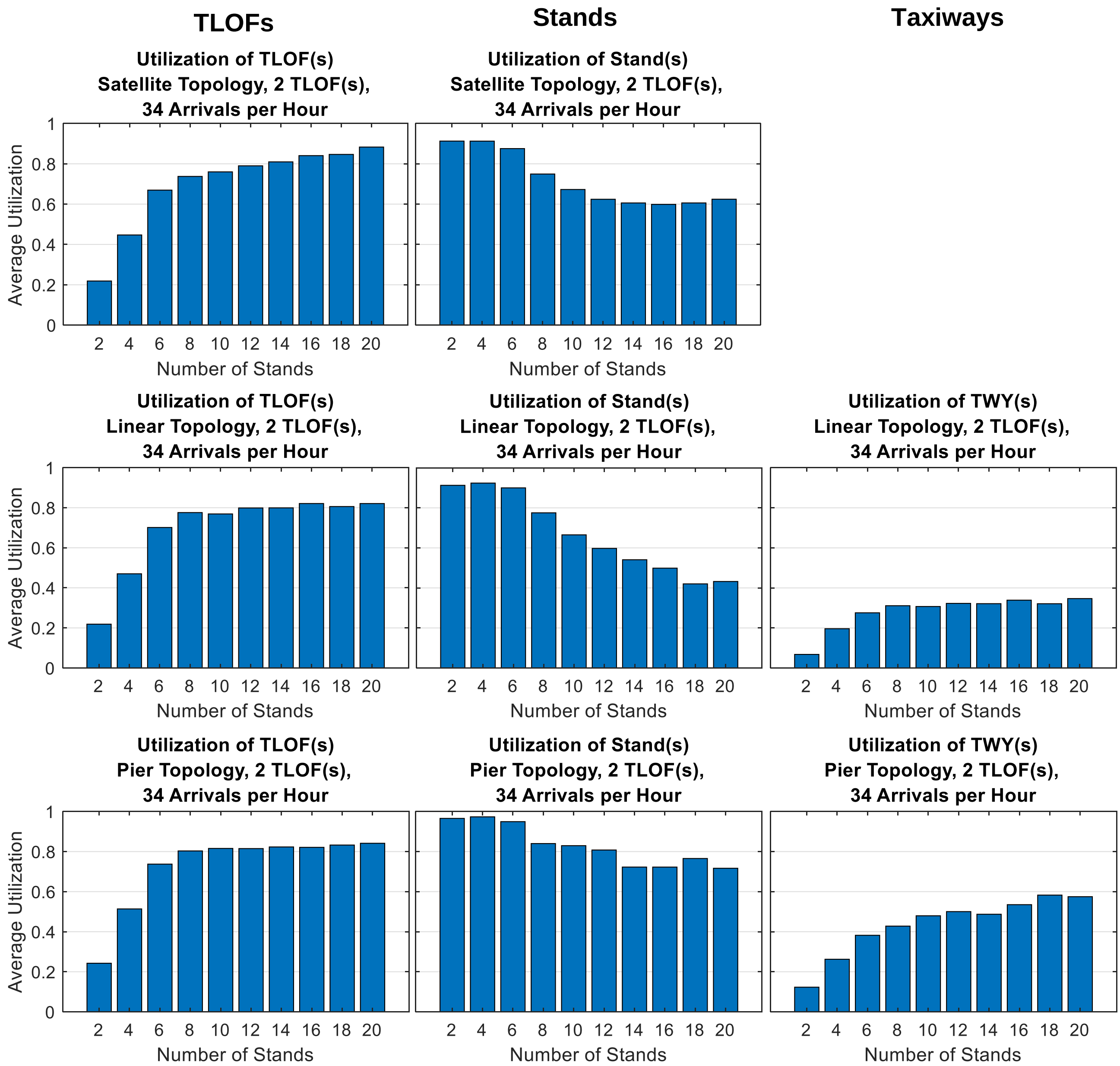


Figure 9 – Exemplary bar charts of the utilization of TLOFs, stands and taxiways for each topology at a demand level of 34 arrivals per hour.

For small numbers of stands (three or fewer), the stands are utilized to 90% or more, while the TLOFs and taxiways are utilized to up to 74%. For this case, it is anticipated that the vertiports are limited by stand capacity. With eight stands, the TLOF utilization reaches about 80% and increases only slightly when further stands are added. It is therefore concluded that the vertiports operate efficiently with eight stands.

As anticipated, the stand utilization tends to decline as the number of stands increases. However, a stagnation or slight increase in stand utilization can be observed for a large number of stands (16 or more). This observation may be explained by the taxiway utilization, which increases with an increasing number of stands. Comprising a larger number of stands, the vertiport can accommodate more eVTOLs in total. This may lead to higher waiting times for takeoff taxiing and extends the dwell time on the stands.

In general, it is concluded that a utilization of 90% or more indicates that the demand is reaching or exceeding the throughput capacity of the vertiport. A utilization of 100% is observed in none of the charts, although the given demand level in Figure 10 exceeds the throughput capacity of most infrastructure scenarios. This fact may result from some inevitable periods of resource inactivity, such as when an eVTOL has cleared the TLOF (i. e. the TLOF is not utilized) and taxis to a stand while the vertiport is fully occupied and a subsequent eVTOL is awaiting clearance for its takeoff taxiing.

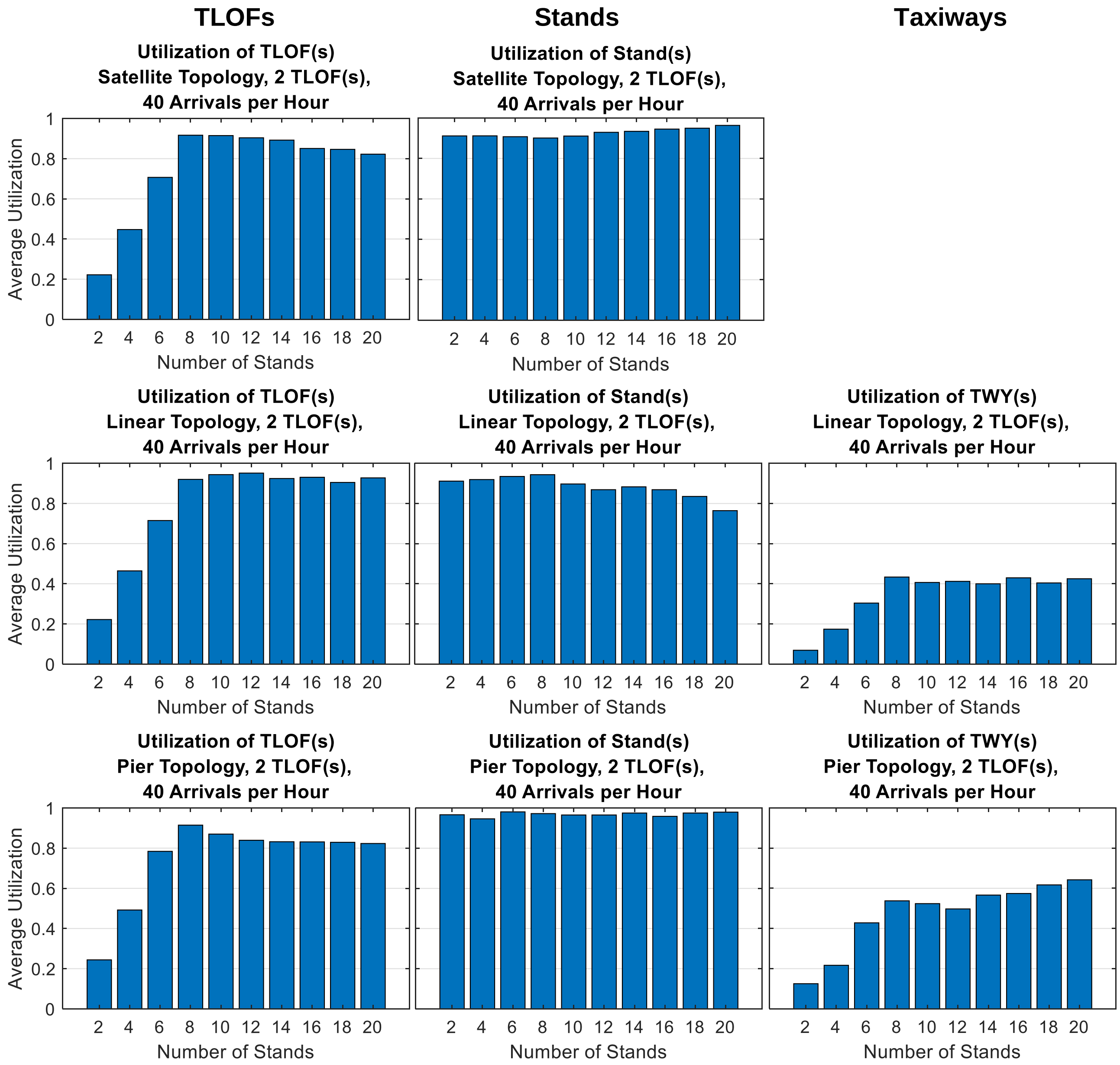


Figure 10 – Exemplary bar charts of the utilization of TLOFs, stands and taxiways for each topology at a demand level of 40 arrivals per hour.

5. Conclusion and Outlook

In this study, a DES simulation framework was developed to assess the throughput capacity and practical capacity of the different vertiport topologies satellite, linear, and pier. The DES model recorded the output parameters throughput, waiting time for landing and takeoff, and the utilization of TLOFs, stands, and taxiways, among others. The practical capacity was evaluated for acceptable level of average delays of 1, 2, 3, and 4 minutes.

Regarding the simulation model development, the satellite topology was easier to develop in terms of model implementation and verification than linear and satellite topology. This was due to the fact that simulation models with shared resources, such as taxiways, were more susceptible to incorrect implementation of processes and were therefore more time-consuming in the debugging process.

The simulation of the different topologies revealed that the topology leading to the highest capacity depends on infrastructural parameters such as the number of stands. Planning and designing vertiports by using only one topology may lead to the loss of achievable vertiport capacity.

However, if a TLOF was complemented with 3 or fewer stands, the topology had nearly no effect on the vertiport capacity (throughput and practical capacity) for the given operational parameters.

The ratio of practical capacity to throughput capacity was found to vary with different operational and infrastructural parameters. Especially for a small acceptable average delay, it may not be appropriate to estimate the practical capacity by multiplying the throughput capacity with a fixed ratio. Also, basing vertiport designs on the analysis and comparison of throughput capacity might not lead to the highest achievable practical capacities.

The relevant parameter to determine the practical capacity is the *average* delay per movement. However, this parameter may not be appropriate for UAM operations as eVTOLs are limited in their battery capacity and cannot provide a large amount of reserved energy. A more distinguished analysis of waiting times for arrival and departure is necessary to verify if the imposed delay can be handled in real operations. Also, the technical development of eVTOL batteries is ongoing and may require the adaptation of the acceptable level of delay.

In a next step, we will evaluate the effect of the process times on the vertiport throughput and practical capacity. Also, a case study will be conducted to apply the analyzed topologies on a specific exemplary surface footprint.

6. Contact Author Email Address

mailto: wille@via.rwth-aachen.de

Former publications by the author can be found under the name Eva Feldhoff.

7. Copyright Statement

References

[1] European Union Aviation Safety Agency (EASA), "Study on the societal acceptance of Urban Air Mobility in Europe," May. 2021.

[2] A. Straubinger, R. Rothfeld, M. Shamiyeh, K.-D. Büchter, J. Kaiser, and K. O. Plötner, "An overview of current research and developments in urban air mobility – Setting the scene for UAM introduction," *Journal of Air Transport Management*, vol. 87, 2020, doi: 10.1016/j.jairtraman.2020.101852.

[3] L. A. Garrow, B. J. German, and C. E. Leonard, "Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research," *Transportation Research Part C: Emerging Technologies*, vol. 132, 2021, doi: 10.1016/j.trc.2021.103377.

[4] J. Pons-Prats, T. Živojinović, and J. Kuljanin, "On the understanding of the current status of urban air mobility development and its future prospects: Commuting in a flying vehicle as a new paradigm," *Transportation Research Part E: Logistics and Transportation Review*, vol. 166, 2022, doi: 10.1016/j.tre.2022.102868.

[5] P. D. Vascik and R. J. Hansman, "Scaling Constraints for Urban Air Mobility Operations: Air Traffic Control, Ground Infrastructure, and Noise," in *2018 Aviation Technology, Integration, and Operations Conference*, Atlanta, Georgia, 2018, p. 413.

[6] K. Schweiger and L. Preis, "Urban Air Mobility: Systematic Review of Scientific Publications and Regulations for Vertiport Design and Operations," *Drones*, vol. 6, no. 7, pp. 1–55, 2022, doi: 10.3390/drones6070179.

[7] M. Brunelli, C. C. Ditta, and M. N. Postorino, "New infrastructures for Urban Air Mobility systems: A systematic review on vertiport location and capacity," *Journal of Air Transport Management*, vol. 112, 2023, doi: 10.1016/j.jairtraman.2023.102460.

[8] E. Feldhoff, G. Ronzani, and J. Reichmuth, "Comparing the Performance of Different Vertiport Topologies Using Discrete Event Simulation," in *XX SITRAER Proceedings*, 2023, pp. 533–542.

[9] European Union Aviation Safety Agency (EASA), "Prototype Technical Specifications for the Design of VFR Vertiports for Operation with Manned VTOL-Capable Aircraft Certified in the Enhanced Category (PTS-VPT-DSN)," 2022.

[10] Federal Aviation Administration (FAA), "Engineering Brief No. 105, Vertiport Design.," Sep. 2022.

Accessed: Jun. 11 2024. [Online]. Available: https://www.faa.gov/sites/faa.gov/files/eb-105-vertiports.pdf
[11] R. Horonjeff, F. McKelvey, W. Sproule, and S. Young, *Planning and Design of Airports, Fifth Edition,* 5th ed. New York, N.Y.: McGraw-Hill Education; McGraw Hill, 2010.
[12] S. B. Young and A. T. Wells, *Airport Planning & Management, Seventh Edition,* 7th ed. New York, N.Y.: McGraw-Hill Education; McGraw Hill, 2019. [Online]. Available: https://www.accessengineeringlibrary.com/content/book/9781260143324
[13] R. De Neufville and A. R. Odoni, *Airport systems: Planning, design, and management,* 2nd ed. New York: McGraw-Hill, 2013.
[14] P. D. Vascik and R. J. Hansman, "Development of Vertiport Capacity Envelopes and Analysis of Their Sensitivity to Topological and Operational Factors," in *AIAA Scitech 2019 Forum*, San Diego, California, 2019.
[15] N. M. Guerreiro, G. E. Hagen, J. M. Maddalon, and R. W. Butler, "Capacity and Throughput of Urban Air Mobility Vertiports with a First-Come, First-Served Vertiport Scheduling Algorithm," in *AIAA AVIATION 2020 FORUM*, VIRTUAL EVENT, 2020.
[16] S. Zelinski, "Operational Analysis of Vertiport Surface Topology," in *2020 AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, San Antonio, TX, USA, 2020, pp. 1–10.
[17] M. Rimjha and A. Trani, "Urban Air Mobility: Factors Affecting Vertiport Capacity," in *2021 Integrated Communications Navigation and Surveillance Conference (ICNS)*, Dulles, VA, USA, 2021, pp. 1–14.
[18] K. Schweiger, F. Knabe, and B. Korn, "Urban Air Mobility: Vertidrome Airside Level of Service Concept," in *AIAA AVIATION 2021 FORUM*, VIRTUAL EVENT, 2021.
[19] K. Schweiger, F. Knabe, and B. Korn, "An exemplary definition of a vertidrome's airside concept of operations," *Aerospace Science and Technology*, vol. 125, 2022, doi: 10.1016/j.ast.2021.107144.
[20] L. Preis and M. Hornung, "A Vertiport Design Heuristic to Ensure Efficient Ground Operations for Urban Air Mobility," *Applied Sciences*, vol. 12, no. 14, pp. 1–17, 2022, doi: 10.3390/app12147260.
[21] B. Ahn and H.-Y. Hwang, "Design Criteria and Accommodating Capacity Analysis of Vertiports for Urban Air Mobility and Its Application at Gimpo Airport in Korea," *Applied Sciences*, vol. 12, no. 12, p. 6077, 2022, doi: 10.3390/app12126077.
[22] B. T. Park and S. H. Kim, "Vertiport Design Optimization using Integer Programming," in *2022 IEEE/AIAA 41st Digital Avionics Systems Conference (DASC)*, Portsmouth, VA, USA, 2022, pp. 1–6.
[23] H. Zhang, Y. Fei, J. Li, B. Li, and H. Liu, "Method of Vertiport Capacity Assessment Based on Queuing Theory of Unmanned Aerial Vehicles," *Sustainability*, vol. 15, no. 1, pp. 1–23, 2023, doi: 10.3390/su15010709.
[24] H. Zhang, J. Li, Y. Fei, C. Deng, and J. Yi, "Capacity Assessment and Analysis of Vertiports Based on Simulation," *Sustainability*, vol. 15, no. 18, pp. 1–22, 2023, doi: 10.3390/su151813377.
[25] I. C. Kleinbekman, M. A. Mitici, and P. Wei, "eVTOL Arrival Sequencing and Scheduling for On-Demand Urban Air Mobility," in *37th DASC - Digital Avionics Systems Conference: London, England, UK, September 23-27, 2018 : 2018 conference proceedings*, London, 2018.
[26] L. Preis and M. Hornung, "Vertiport Operations Modeling, Agent-Based Simulation and Parameter Value Specification," *Electronics*, vol. 11, no. 7, 2022, doi: 10.3390/electronics11071071.
[27] Uber, "UberAir Vehicle Requirements and Missions," 2019.
[28] J. Banks, *Handbook of Simulation*: Wiley, 1998. [Online]. Available: https://onlinelibrary.wiley.com/doi/book/10.1002/9780470172445