Capacity and Throughput of Urban Air Mobility Vertiports with a First-Come, First-Served Vertiport Scheduling Algorithm

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In this paper, a first-come, first-served vertiport scheduling algorithm for Urban Air Mobility (UAM) was exercised to assess and compare the capacity and throughput of various vertiport configurations. The scheduler models each vertiport by the number of vertipads and parking spaces, and manages reservations on timelines for those vertiport resources, at a level of fidelity suitable for fast-time and system-level analyses of UAM concepts and other airspace studies. The paper defines the theoretical model that can be used to estimate the capacity of various vertiport configurations. The theoretical model provides an understanding of the conditions that can lead to either a parking space-limited or a vertipad-limited vertiport. Examples of potential throughput for some vertiport configurations are provided using both a queueing approach as well as a simulated UAM demand scenario. The study demonstrated that a first-come, first-served scheduling approach can have inefficiencies in the use of the vertiport resources. The inefficiencies can increase as the number of resources increases. Nonetheless, 80% or better peak throughput to capacity ratio was observed for most vertiport configurations.

Nomenclature

$\boldsymbol{C_{pads}}$ = vertipad capacity of a vertiport
$\boldsymbol{C_{port}}$ = overall vertiport capacity
$\boldsymbol{C_{port,max}}$ = maximum vertiport capacity; determined by minimum surface time
$\boldsymbol{C_{surf}}$ = surface capacity of a vertiport
$\boldsymbol{N_p}$ = number of vertipads at a vertiport
$\boldsymbol{N_s}$ = number of parking spaces at a vertiport
$\boldsymbol{t_{arr}}$ = vertipad time allocated to an arrival
$\boldsymbol{t_{dep}}$ = vertipad time allocated to a departure
$\boldsymbol{t_{surf}}$ = surface time at the vertiport between arrival and departure
$\boldsymbol{t_{surf,avg}}$ = assumed, estimated, or observed average surface time
$\boldsymbol{t_{surf,min}}$ = minimum surface time at a vertiport
$\boldsymbol{t_{win}}$ = time widows for capacity and throughput values; typically 15 minutes

I. Introduction

NASA's Air Traffic Management-Exploration (ATM-X) project[1,2] is studying the impact that new entrants may have on the National Airspace System. These new entrants include Urban Air Mobility (UAM) operations, or the carrying of goods and people in and around cities. Research studies currently underway are focused on understanding

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the impact to existing operations, refining existing or new concepts of operations, and identifying the air traffic and other services required to enable safe and efficient use of the National Airspace System for these new operations.

UAM represents a new type of air traffic operations. These operations will need to safely operate in a near-term environment (within 5-10 years) but also require a well-defined concept of operations for how the air traffic system can support the predicted level of demand[3-5] of a far-term (20-30 years) environment. One way that NASA is supporting both of these environments is through the development of services that enable a service-oriented architecture, similar to the approach used for the UAS Traffic Management[6] system. A service-oriented architecture provides advantages such as reliability, scalability, and simplified maintenance. These services may implement a variety of resource scheduling, planning, coordination, or other constraint resolution algorithms that support the required functions of a UAM air traffic eco-system.

In this study, one instantiation of a first-come, first-served (FCFS) algorithm for scheduling of vertiport resources is described and analyzed. FCFS is considered the simplest scheduling algorithm in that no complex decision making is performed (either the resource is available or not). More sophisticated algorithms tend to require more information or rely on detailed models of operation. The intent of this study is to inform decision makers regarding the need for more sophisticated scheduling algorithms. In this way, FCFS provides a baseline for performance and any more sophisticated algorithm could out-perform the baseline provided in this paper.

II. Background

The sharing of a single resource by multiple agents creates the need for scheduling, especially in high-demand situations. Whether the resource is a flight vehicle that must be used to execute multiple flights, or a vertipad that must be used for multiple takeoff or landing operations, there is a requirement that the resource can only satisfy one operation at any given time. In this paper, an algorithm for scheduling the limited resources of a vertiport is described. In addition, we describe a study that was conducted to examine the effects of this algorithm on UAM vertiport performance, in terms of capacity, throughout, and efficiency, with respect to the vertiport configuration and vertiport demand.

The term “vertiport” is commonly used to describe the takeoff and landing locations for UAM operations. Others also use the term heliport, helistop, or vertistop. In general, a vertiport consists of one or more designated takeoff and landing areas, or vertipads, and zero or more designated parking spaces. Parking spaces are areas that can be used for charging a vehicle and loading or unloading passengers, and that can only support one vehicle at any given time. At some vertiports, the site limitations may be few, allowing for the implementation of additional vertiport surface areas, such as ramps or staging areas that are distinct from the vertipads and parking spaces. However, in a constrained city environment this may be the exception and not the rule. Thus, in the simple vertiport model considered here, vertiports have vertipads and parking spaces, which are resources shared by vehicles executing assigned flights, and that require scheduling. Furthermore, we do not consider the scheduling of resources such as taxiways between the vertipads and the parking spaces in this model, and all surface time at a vertiport is allocated to a parking space.

Under the assumption that future vertiports could be designed using today’s standards for heliport design, the FAA provides advisory circular AC150/5390-2C[7], which sets forth the recommended guidelines for the design of a vertiport for a particular application and airspace. However, the size of a particular vertiport, in terms of vertipads and parking spaces, is largely driven by demand and site size limitations.

The capacity assessment for conventional airports is well understood. The analysis takes into account many factors[8,9], including the number of runways and gates. In an analysis related to vertiport capacity, Vascik and Hansman[10] used an integer programming approach to analyze the capacity of various vertiport configurations. This work explored capacity analysis through an approach that was focused on the detailed layouts of specific vertiports whereas the current study is focused on analyzing the capacity of a vertiport through a higher-level of abstraction that is suitable for fast-time analysis of the impacts to UAM airspace operations. In addition, the current work extends the capacity analysis by including assessment of potential throughput with a given demand scenario and a specific FCFS scheduling algorithm. In another vertiport capacity analysis[11], researchers used a queueing model and simulation model to estimate the throughput of vertiports that included vehicle and terminal airspace constraints but a scheduling algorithm was not the focus of that work.

Traditional scheduling algorithms for airspace resources typically include predicting or estimating the arrival of a flight at a given resource[12,13]. The vertiport scheduling algorithm discussed and analyzed in this paper uses a slightly different approach by relying on external functions to make those estimations and focusing only on the management of the shared resource. This scheduling approach has some potential benefits that are worth exploring in a service-oriented architecture. Namely, UAM operators may have more control over the scheduling of their operations, the scheduling can be achieved in a distributed or federated manner, and the estimates of arrival times at resources may be more accurate due to the reduced number of assumptions about aircraft performance and vehicle current state.

In this work, a prototype FCFS scheduling algorithm has been developed and has been characterized for its ability to serve a given UAM demand. The remainder of this section describes the details of the FCFS vertiport scheduling algorithm.

A. Vertiport Scheduler

The Vertiport Scheduler (VS) algorithm models a single vertiport given the configuration parameters of number of vertipads and number of parking spaces, with each vertiport containing one or more of each of these resources. The vertipads are the designated takeoff and landing areas, while the parking spaces are the areas designated for charging a vehicle, loading or unloading of passengers, and where vehicles remain idle between subsequent operations. Each of these resources (vertipads or parking spaces) is abstracted by a timeline. Reservations for operations on these timelines are represented by non-overlapping time blocks. Consequently, each resource can only support one operation at any given time. The VS algorithm manages the reservations and the timelines of a single vertiport by providing interfaces for querying the availability of the vertiport, and for making reservations on the vertiport's resources.

The current implementation of the VS is a FCFS, reservation-based algorithm. It does not try to optimize the resource usage of the vertiport. The algorithm allows reservations to be made on a vertiport's resources as long as they do not overlap with existing reservation time blocks on the resource timelines. The vertiport reservations are requested from the VS by external entities, such as UAM operators with their planning tools. As such, the VS does not perform trajectory prediction to estimate when an operation would require a reservation on the VS; those trajectory predictions are made by the external entities making the reservation request.

The VS represents a simplified model for a vertiport. The VS does not model the complexities of specific vertiport topologies, which can lead to different inter-connections between vertipads and parking spaces, with possibly different taxi times given any vertipad and parking space combination. In that sense, the VS is agnostic to vertiport layout, with the core assumption being that each vertipad has access to any parking space and vice versa. The higher-level complexities of taxi times or additional ground movement delay can be captured in the assumed surface time spent at a vertiport by any vehicle, which, in this model, is allocated to the parking space timeline reservation. This simple framework provides a suitable first-order methodology for analyzing vertiport resource usage. In order to capture the dependencies related to vertiport layout, a more sophisticated model should be used.

The VS does not currently support the special case of vertiports with no parking spaces and, as such, those type of vertiports are not considered in this analysis. These are vertiports where the vehicle must remain on the takeoff and landing vertipad during passenger loading and unloading, as well as vehicle charging or refueling, if necessary. Although these are interesting configurations, they may also be the exception and not the rule in a high demand UAM environment. Furthermore, the VS algorithm could be easily extended to support these vertiport configurations for future studies.

Vertiport Scheduler Reservations

In the VS, a reservation is associated with a specific vehicle with a unique identifier (typically referred to as a "tail number"). This association allows an arrival reservation, which is already linked to a parking space reservation, to also be linked to a departure reservation when a departure flight is scheduled for that vehicle. A linkage using a flight identifier would be more difficult to track because a vehicle's inbound flight identifier is typically not the same as a vehicle's outbound flight identifier.

Under most circumstances, a vehicle will have an arrival reservation (which includes a parking reservation) and a departure reservation at a vertiport. An arrival to a vertiport consists of a vertipad time block reservation, followed by an associated reservation on the timeline of a parking space for an infinite period of time to indicate an un-specified departure time. A departure from a vertiport consists of changing the parking space reservation end time from infinity to an appropriate time, followed by a departure time block reservation on a vertipad. Figure 1 provides an example of this typical set of reservations for a vertiport with a single vertipad and a single parking space. In the example, flight UF123, operated by vehicle UV999, has an arrival reservation from 00:01:00 until 00:02:00. This arrival is followed by the associated parking reservation for vehicle UV999 starting at time 00:02:00. The parking space reservation for UV999 is closed 6 minutes later, at 00:08:00, followed by a departure reservation from 00:08:00 until 00:09:00 for a flight with identifier UF345.

Each arrival and departure reservation also encodes an operational time. This operational time is representative of the nominal landing and takeoff times for the flight associated with the reservation and falls somewhere between the start and end of the vertipad reservation. This distinction between the reservation start time and the operational time allows for the VS to account for the time required to enter the airspace directly above and near the vertipad and land, as well as the time required to exit a vertipad area after landing. Similarly, for departure operations, this allows accounting of the time required to move onto a vertipad before takeoff, as well as the time required to clear an airspace region immediately above and near a vertipad after takeoff. These time parameters can be defined as part of a VS configuration.

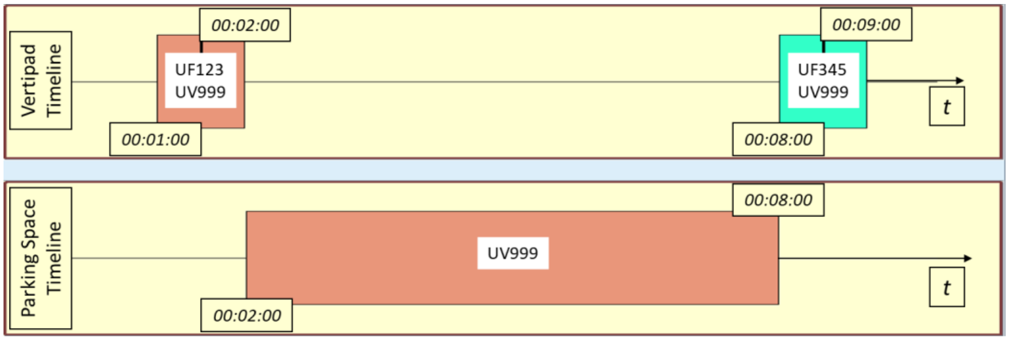

Figure 1. Example arrival, parking, and departure reservations on a single vertipad and single parking space vertiport.

Vertiport Scheduler Interfaces and Logic

The VS provides four primary interfaces to the vertiport resources: *nextAvailableArrival*, *nextAvailableDeparture*, *reserveArrival*, and *reserveDeparture*. The *nextAvailableArrival* and *nextAvailableDeparture* are querying interfaces that allow an external entity to evaluate the availability of the vertiport for an arrival operation or a departure operation, respectively, at or after a given time. In the FCFS scheduling approach, these interfaces use a first-available search method. Arrival reservations require a parking space to be available for an infinite amount of time after the arrival in order to support the vehicle remaining idly parked at the vertiport. This is due to the subsequent departure for a given vehicle not being known at the time the arrival reservation is made, which is true in the case of on-demand operations as well as in FCFS scheduling. The *reserveArrival* and *reserveDeparture* interfaces allow an external entity to make the appropriate reservations at a vertiport, typically after the associated availability queries have been performed.

The *nextAvailableArrival* query provides mechanisms to support the movement of vehicles in the event that a vertiport is full. When a vertiport has no parking spaces available for an arrival reservation at a given time, the VS can report information about vehicles that could be re-located to other vertiports in order to create availability. The identifiers for idly parked vehicles at time *t* are provided to the external application making the requests. This information can be used by the external entity to decide how to create vertiport availability. For example, an operator may identify another of their vehicles idly parked and may choose to move that vehicle to another vertiport via a clearing flight and associated departure reservation. Alternatively, an operator may elect to negotiate with a competing operator to make a clearing flight movement for a vehicle that does not belong to the requesting operator.

The VS provides other advanced interfaces not exercised in this work. For example, in the event that a desired arrival flight and departure flight at a vertiport using the same vehicle are known at the same time (a world other than on-demand), the VS provides an interface for scheduling an arrival and a departure simultaneously without the need to create a temporary parking reservation of infinite length.

III. Analysis Design

In this analysis, the objective was to compute the capacity of vertiport configurations under different assumptions and to compare those to the achievable throughput under a UAM demand scenario. The capacity of a vertiport with a given number of vertipads and parking spaces can be computed using a set of simplifying assumptions. Under some configurations, a vertiport is considered to be capacity-limited due to the number of vertipads. In other cases, a vertiport is capacity-limited due to the number of parking spaces. This study explores this dynamic vertipad and parking space tradeoff, highlights the limitations that arise with a FCFS scheduler, and identifies the impact of observed conditions that don't always match the simplifying assumptions of a theoretical model.

A. Definitions/Metrics

The following are a set of definitions for terms commonly used in this analysis:

Operation(s) – an operation is equivalent to a single reservation on a vertipad or a single reservation at a parking space. An arrival is considered a single vertipad operation because it creates a single reservation on a vertipad timeline at a vertiport. Similarly, a departure from a vertiport is considered a single vertipad operation. A vehicle that makes a reservation on a vertiport's parking space timeline is considered a single surface operation. Thus, the time window shown in Figure 1 depicts two vertipad operations and one surface operation.

Capacity – the estimated number of operations on a resource over a given time period, given some assumptions. The vertipad capacity is the estimated number of arrivals and departures over all vertipads at a vertiport, assuming unlimited parking spaces. The surface capacity is the estimated number of surface operations over all parking spaces at a vertiport, assuming unlimited vertipads. The overall vertiport capacity is the estimated number of arrivals and departures at a vertiport and is determined from the vertipad capacity or the surface capacity under the assumption that a single surface operation is equivalent to two vertipad operations.

Throughput – the observed number of operations on a resource over a given time period. In this analysis, throughput is only discussed at the vertiport level and, thus, represents the observed total number of arrivals and departures.

Vertipad Usage – the percentage of time used by vertipad reservations, from the total available time of all vertipads at a vertiport, over a given time window.

Space Usage – the percentage of time used by parking reservations, from the total available time of all parking spaces at a vertiport, over a given time window.

Space-Limited Vertiport – a vertiport where the limiting factor for capacity is the number of parking spaces (e.g., the vertipads are able to support higher capacity).

Vertipad-Limited Vertiport – a vertiport where the limiting factor for capacity is the number of vertipads (e.g., the parking spaces are able to support higher capacity).

B. Theoretical Model

Let the arrival time parameter ($\boldsymbol{t_{arr}}$) denote the amount of time reserved on a vertipad for an arrival operation. Similarly, let the departure time parameter ($\boldsymbol{t_{dep}}$) denote the amount of time reserved on a vertipad for a departure operation. Both of these parameters account for the time required to enter or exit the vertipad, as well as the time required to enter or exit the airspace immediately above the vertipad. In actual operations, these parameters may be dependent on many factors, including the performance characteristics of the vehicle, environmental conditions, vertiport layout, vertiport arrival and departure procedures, and many other factors. For the purposes of this analysis, the arrival and departure time parameter values were selected to be a single fixed value of 60 seconds each.

Let the surface time parameter ($\boldsymbol{t_{surf}}$) represent the total amount of time spent at a vertiport in a non-vertipad area. In general, this is the time between the end of an arrival reservation and the start of a departure reservation. As such, this includes the time to transfer the vehicle from the vertipad to a parking space after arrival (taxi in time), any time spent at the parking space (e.g., for passenger loading, un-loading, charging), and the time to transfer the vehicle from the space to the vertipad for departure (taxi out time). Note that, in the parametric VS model, the entire surface time is allocated to the parking space, whereas, higher fidelity models may provide mechanisms for tracking these additional details for surface time independently. Additionally, note that the surface time distribution will be different for different vertiports and is, in general, not known for this class of operations. Surface time is dependent on many factors, including vehicle fleet characteristics, fleet size for each operator, vertiport layout, vertiport surface operational procedures, and other factors. For theoretical modeling, this analysis uses a minimum surface time and average surface times. The minimum surface time ($\boldsymbol{t_{surf,min}}$) used in this analysis is 120 seconds and, notionally, represents an aircraft that arrives at the vertiport, taxis to the parking space, and is immediately scheduled for a departure, perhaps without the need to perform any passenger loading/un-loading or any other surface functions.

Let $\boldsymbol{N_s}$ denote the number of parking spaces available at a vertiport. The rate of surface operations at the vertiport can then be computed by dividing the number of parking spaces by the surface time parameter ($\frac{\boldsymbol{N_s}}{\boldsymbol{t_{surf}}}$). Then the surface capacity ($\boldsymbol{C_{surf}}$) of a given vertiport with $\boldsymbol{N_s}$ parking spaces and $\boldsymbol{t_{surf}}$ surface time, over a desired time window ($\boldsymbol{t_{win}}$), is given by equation (1):

$$\boldsymbol{C_{surf} = N_s \cdot \frac{t_{win}}{t_{surf}}} \tag{1}$$

Equation (1) is used to compute the theoretical surface capacity of a vertiport, assuming infinite vertipad capacity. Using the minimum value of surface time parameter in equation (1) yields the theoretical maximum surface capacity of the vertiport. Similarly, using an average surface time yields the average surface capacity of the vertiport.

The theoretical vertipad capacity of the vertiport can be computed in a similar way. Let $\boldsymbol{N_p}$ denote the number of vertipads at a vertiport. Assuming balanced arrival and departure operations at the vertiport, the rate of vertipad operations is computed by dividing two times the number of vertipads by the sum of the arrival and departure time parameters ($\boldsymbol{2 \cdot \frac{N_p}{t_{arr}+t_{dep}}}$). Then, the vertipad capacity ($\boldsymbol{C_{pads}}$) of a given vertiport with $\boldsymbol{N_p}$ vertipads, $\boldsymbol{t_{arr}}$ arrival time, $\boldsymbol{t_{dep}}$ departure time, over a desired time window ($\boldsymbol{t_{win}}$), is given by equation (2):

$$\boldsymbol{C_{pads} = 2 \cdot N_p \cdot \frac{t_{win}}{t_{arr} + t_{dep}}} \tag{2}$$

The factor of two represents the balanced operations assumption in the rate equation with the summation of the arrival and departure time parameters. The theoretical vertipad capacity also assumes independent operations to all vertipads, as well as infinite surface capacity at the vertiport.

In general, a vertiport's capacity will be limited by either the surface capacity or the vertipad capacity. Under the assumption that each surface operation is associated with two vertipad operations (an arrival and a departure), the overall vertiport capacity ($\boldsymbol{C_{port}}$) can be computed by equation (3):

$$\boldsymbol{C_{port} = min\left(2 \cdot C_{surf}\,, C_{pads}\right)} \tag{3}$$

Using equations (1)-(3), a vertiport under this model is considered to be surface capacity limited when the following inequality is true; otherwise the vertiport is considered to be vertipad capacity limited:

$$\boldsymbol{N_s < N_p \cdot \frac{t_{surf}}{t_{arr} + t_{dep}}} \tag{4}$$

Note that this relationship, and the tradeoff between surface capacity limited and vertipad capacity limited, is dependent on the assumed surface usage time and vertipad usage times. Nonetheless, equation (4) is useful for first-order assessment of feasible vertiport configurations, in terms of number of vertipads and number of parking spaces.

In this analysis, the theoretical model was used to compute the expected, or average, capacity for a variety of vertiport configurations. This model was also used to compare the expected capacity with the observed throughput of the simulation model described in section III.C.

C. Simulation Model

The simulation model used for this analysis leveraged the ATS-TIGAR toolkit and Mission Planner capability described in prior work[14,15]. The ATS-TIGAR toolkit supports analysis of a UAM scenario in terms of on-demand UAM trips between a network of vertiports over a given city. A UAM trip defines the number of passengers traveling between one vertiport and another, as well as the desired trip start time. The Mission Planner algorithm implements a pre-departure planning function that computes the flights required to support a given UAM trip, and their associated 4-dimensional trajectories, in the presence of UAM operator, vertiport, and airspace constraints. The simulation model implemented a VS model for each vertiport in the scenario and the Mission Planner algorithm leveraged the interface to those vertiports to evaluate and reserve arrival and departure operations at the vertiports associated with each trip.

This simulation model was chosen in order to exercise the FCFS VS model in the presence of a realistic UAM traffic scenario, and to analyze the throughput of the vertiports in this scenario network. As discussed before, one of the challenges to assessing the capacity of vertiports using this parametric model is that the distribution of surface time for UAM vehicles at a vertiport is not known. Using the simulation model described here, UAM trips were planned with an operator's limited fleet of vehicles. Because those vehicles were selected for various UAM trips, their movement through the network of vertiports naturally created a synthetic surface time distribution at each vertiport. In the model, each vehicle's surface time was composed of a taxi-in time after arrival (60 seconds), the passenger un-loading time if the arriving flight contained any passengers (60 seconds per passenger), any idle time at the vertiport between demanded UAM trips, the passenger loading time if the departing flight contained any passengers (60 seconds per passenger), and the taxi-out time before departure (60 seconds).

The surface time distribution for a set of vehicles at a vertiport is a function of many factors, including the fleet management model and the available vehicle fleet used in analysis. The fleet management function implemented in the mission planning algorithm used a first-available approach; the vehicle that could be made available at a trip's origin vertiport at the earliest time was chosen for a trip. In some situations, this vehicle was a vehicle already parked at the origin vertiport. In other cases, this was the vehicle whose ability to depart their current vertiport, travel to the origin vertiport, and find an available arrival slot at the origin vertiport, produced the earliest available time from the set of all vehicles in the operator's fleet. This is an example of a repositioning flight or trip. The fleet management model also created clearing flights or trips, where the destination vertiport for a demanded UAM trip was full (all parking spaces were reserved), and a vehicle movement was created to make room at that vertiport for the incoming flight. Naturally, the fleet management model had an impact on how long each vehicle remained idly parked at a vertiport between trips, thereby impacting the overall surface time distribution.

The simulation model did not implement airspace constraints for this analysis. Typically, the mission planning algorithm implements pre-departure conflict detection and resolution between planned trajectories as well as airspace avoidance regions or other airspace constraints for trajectory planning. In this analysis, all airspace constraints were disabled, leaving the vehicle fleet and the vertiport resources as the only constraints for UAM mission planning remaining in the model. The simulation model allowed for the analysis of the observable throughput at a set of vertiports, where the vehicle fleet and vertiport constraints created a synthetic surface time distribution at each of the vertiports.

D. Queueing Model

The VS was exercised in a queueing model approach in order to assess the VS algorithm's throughput in the absence of some of the simulated model's functions, such as fleet management. In this approach, a large queue of demand was used to fill the VS at the next available time for a 24-hour period. Each demand element in the queue consisted of an arrival operation, followed by a surface operation, then by a departure operation. The surface time for the surface operation was sampled randomly from a distribution. Because the surface time distribution is unknown for UAM operations, a simple uniform distribution with specified minimum and average surface times was used. The queueing model provides an estimate of the throughput for a given vertiport configuration under this assumed uniform surface time distribution. In one example, the resulting surface time distribution from the simulation model at one vertiport was used in the queueing model in order to compare the queueing model throughput to the simulation model throughput.

E. UAM Demand Scenario

A UAM scenario input to the simulation model was defined by a set of desired trips, the vertiport system, the vehicle fleet, and other scenario parameters. Each trip included an origin vertiport, a destination vertiport, the number of passengers, and the desired trip start time. The vertiport system defined the location of each vertiport and their basic configuration, including the number of vertipads and the number of parking spaces. The vehicle fleet was defined by the type and quantity of each vehicle, their performance characteristics, their passenger capacity, and the initial allocation of the vehicles to the available vertiports.

A single UAM demand scenario was run in the simulation model for this analysis. The scenario was developed by Virginia Tech for NASA using a mode choice model for commuter trips that included automobile, public transit, and UAM as competing modes of transportation[16]. This mode choice model was applied to a pool of commuter trips obtained from historical surveys of traveler data for the Dallas/Fort Worth area to determine the number of trips that could be attracted by the UAM mode under a set of cost, time, and other assumptions. An iterative, demand-driven approach was used to select suitable vertiport locations within the Dallas/Fort Worth area given a desired number of vertiports. Finally, the size of each vertiport in the network was determined using the resulting UAM demand and the projected number of operations at each vertiport, prior to any clearing or repositioning flights.

The selected demand scenario was designed to meet the NASA UAM sub-project's level of 100's of simultaneous airborne flights. The scenario contained a total of 25,472 multi-passenger trips, with an estimated peak number of simultaneous airborne flights of 595 (prior to any clearing or repositioning flights), over a 24-hour period. Figure 2 shows the unimpeded time distribution of the multi-passenger trips over the 24-hour period, highlighting the morning and afternoon commuter demand peaks, and the distribution of the number of passengers for the multi-passenger trips. The passenger trips were distributed to two UAM operators at a 75%/25% split to create a large operator and a small operator in the same airspace. Similarly, the fleet of vehicles (1,190 vehicles) was allocated using a 75%/25% split between the two operators. Note that the simulation model's demand and fleet management functions insert clearing and repositioning flights, which resulted in a total of 51,632 flights over the 24-hour period, with the peak simultaneous number of airborne flights reaching 668. Each trip was scheduled only once in this simulation model run and, as such, the model does not account for a passenger canceling a trip or an operator speculatively claiming slots at desirable times or locations.

There was a total of 102 vertiports, with the highest projected demand vertiport (DF4) having 6 vertipads and 38 parking spaces. Figure 3 shows the number of vertipads for each vertiport in the scenario. Similarly, Figure 4 shows the number of parking spaces for each vertiport. Four storage vertiports with unlimited surface capacity were added to the demand scenario to help facilitate clearing and repositioning flights when nearby vertiports were full or busy. The geographic location of all vertiports for the UAM scenario can be seen in Figure 14 in the Appendix.

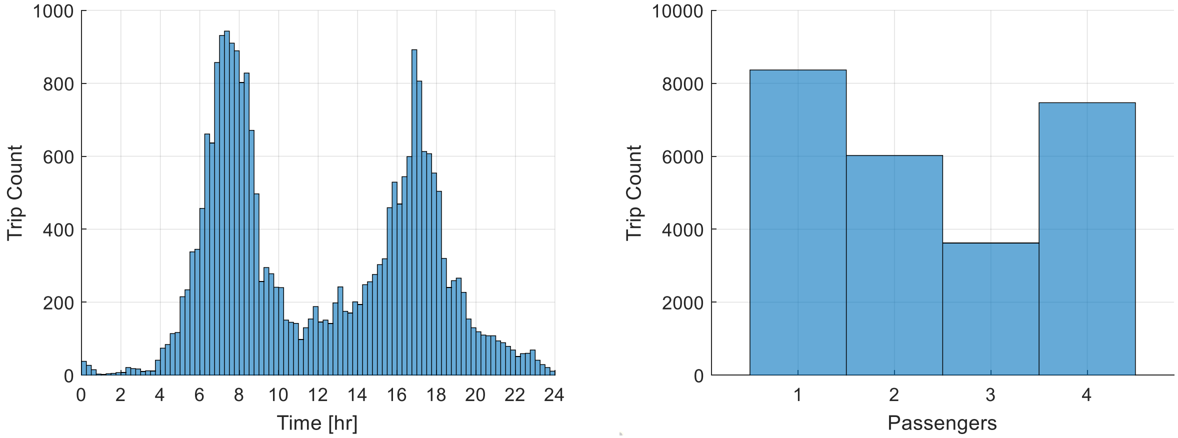

Figure 2. Multi-passenger trip distribution in 15-minute bins over the 24-hour period of the demand scenario (left) and distribution of multi-passenger trips by number of passengers (right).

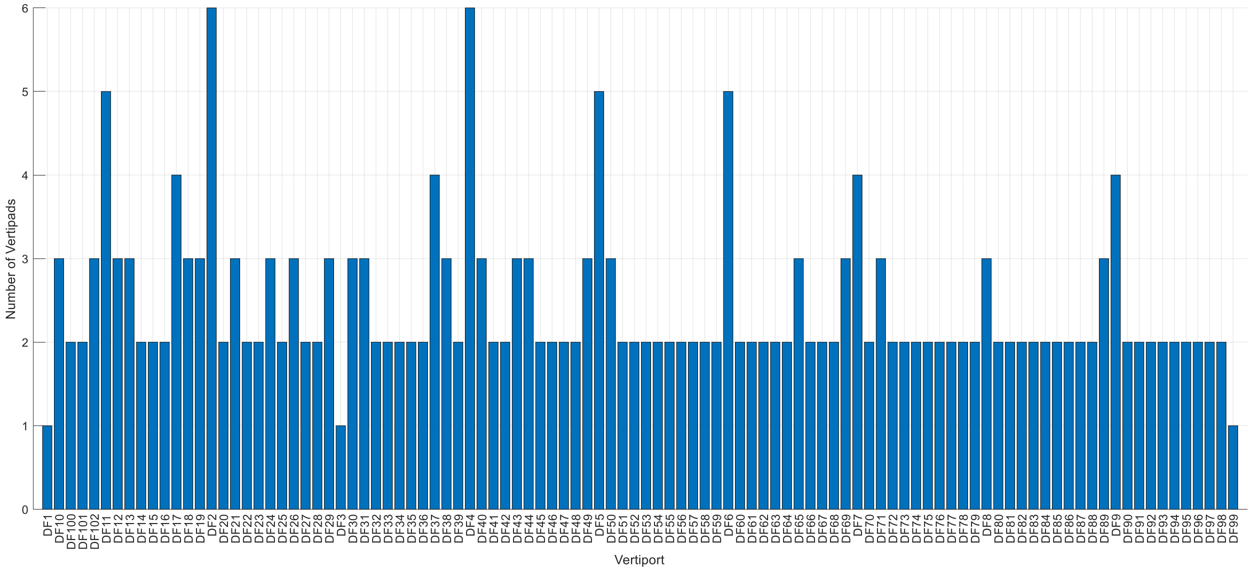

Figure 3. Number of vertipads for each vertiport in the UAM demand scenario.

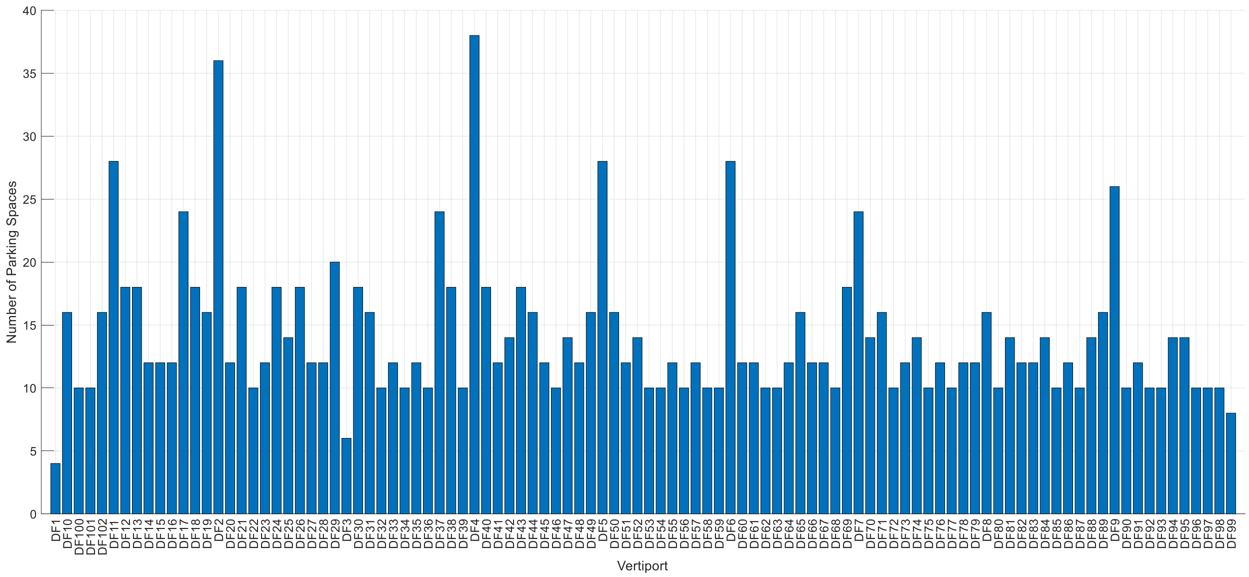

Figure 4. Number of parking spaces for each vertiport in the UAM demand scenario.

F. Assumptions/Parameter Values

Table 1 lists the parameter values and other assumptions used for this VS analysis.

Table 1. Parameters and assumptions used in this analysis.

Parameter	Value
t_{arr}	60 [s]
t_{dep}	60 [s]
$t_{surf,min}$	120 [s]; represents taxi in plus taxi out times
$t_{surf,avg}$	Dependent variable; 15 [min] used for comparison and discussion in some examples
N_p	Varies by vertiport (min: 1, max: 6)
N_s	Varies by vertiport (min: 4, max: 38)
t_{win}	15 [min]
Number of Vertiports	102
Number of Vehicles	1,190
Passenger Loading Time (per Passenger)	60 [s]
Passenger Unloading Time (per Passenger)	60 [s]
Vehicle Charge Time	0 [s]
Vehicle Model	Generic VTOL model with cruise speed of 130 [kts]

IV. Results

In this section, capacity estimates from the theoretical model are computed and discussed. Then, the results of queueing model throughput are compared to the simulation model throughput and discussed.

A. Theoretical Capacities

The theoretical capacity equations indicate that, to achieve a desired capacity, as the average surface time for surface operations at a vertiport increases, the number of required parking spaces must also increase. Similarly, as the arrival and/or departure time slot sizes increase, the number of vertipads also increases, for a given capacity. The equations also provide a means for estimating the number of parking spaces required to configure a vertiport such that it is not surface capacity limited.

Figure 5 shows the minimum number of parking spaces required for a vertiport to not be surface capacity limited under different surface time assumptions. For example, for a vertiport with 6 vertipads, and with a minimum surface time of two minutes ($t_{surf,min}$), only 6 parking spaces are required to avoid the surface capacity limitation. However, when the surface time increases to 15 minutes, 7.5 times that many parking spaces (45) would be required for the same vertiport to not be surface capacity limited. The relationship is linear, due to the nature of the capacity equations, but it is clear that the surface time spent at a vertiport has a significant impact on the number of parking spaces required.

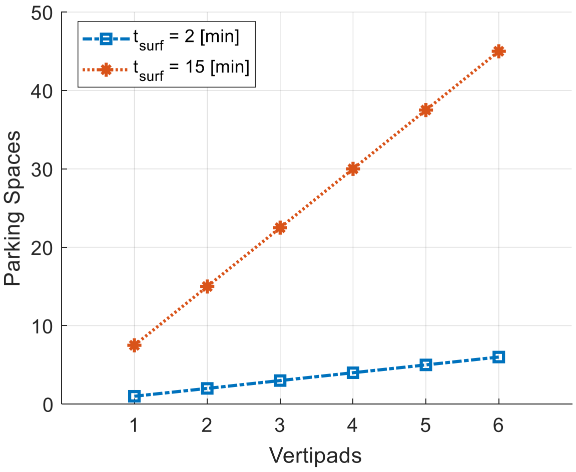

Figure 5. Minimum number of parking required for a vertiport to not be surface capacity limited, under different surface time assumptions.

Figure 6 provides another way to visualize the space-limited and vertipad-limited regions of the various vertipad and parking space combinations. The left figure shows this relationship for a surface time of 2 minutes and the right figure shows the relationship for a surface time of 15 minutes. For any given number of vertipads, as the number of parking spaces is increased, the vertiport capacity increases in a space-limited region until the vertiport capacity reaches a maximum value (plateau) where the vertiport is vertipad capacity limited.

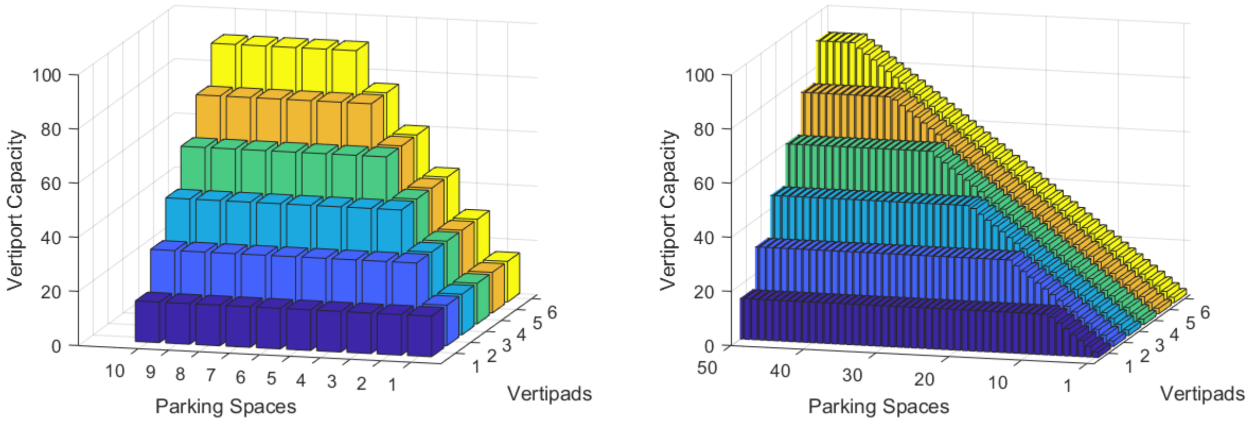

Figure 6. Vertiport capacity by number of vertipads and parking spaces, for surface time of 2 minutes (left) and surface time of 15 minutes (right).

The theoretical capacity equations will be used in the next section to compare the expected capacities to the observed throughput.

B. Vertiport Throughput

The largest vertiport in the demand scenario used in the analysis, by number of total operations, was DF4. This vertiport had 6 vertipads and 38 parking spaces. Figure 7 shows the queueing model throughput for a VS with that configuration and with a uniform surface time distribution between 2 and 28 minutes (15-minute average). The maximum capacity for this vertiport configuration is 90 operations per 15 minutes. However, with the average surface time of 15 minutes, the vertiport is space-limited and the expected capacity under these conditions is only 76 operations per 15 minutes. Note that the average throughput (based on the data between hours 1 and 23), or total operations, is

63.9 operations per 15 minutes (~16% less than the expected capacity of 76), but the maximum observed throughput does approach the expected capacity at times.

Figure 7 also shows the percentage usage of the vertiport resources. The resource usage is defined as the percent used from all available vertipad or parking space timelines over a given time window. The vertipads show an average of 75.9% usage while the parking spaces show an average of 90.5% usage, with some parking space usages approaching 100% for this space-limited vertiport.

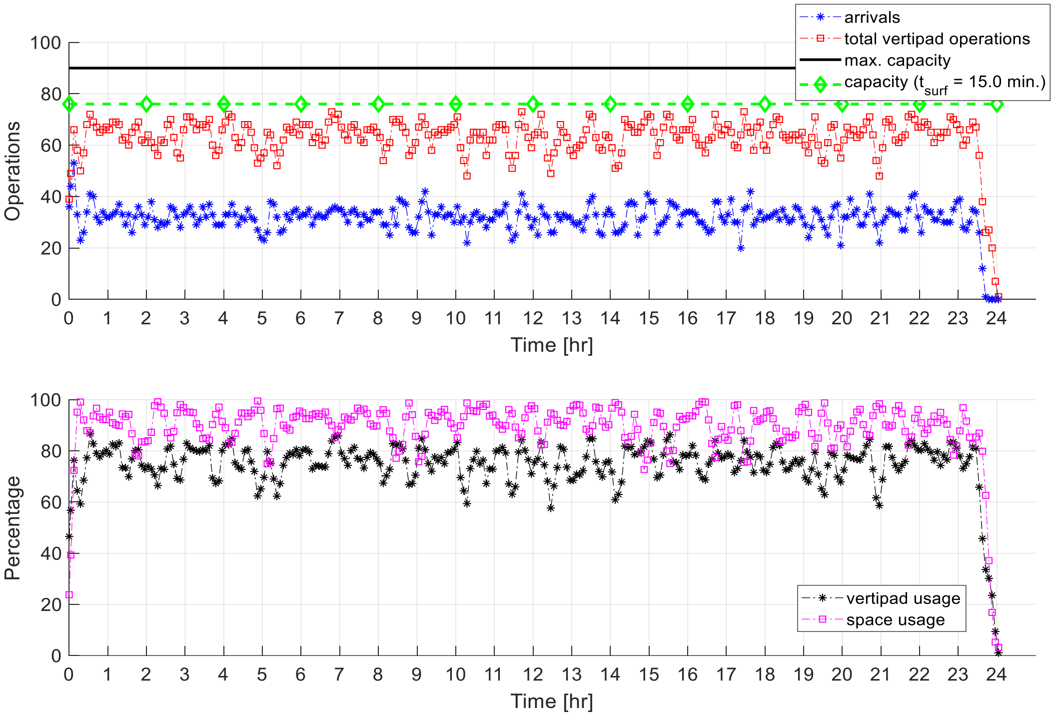

Figure 7. VS throughput (top) and resource usage (bottom) for a vertiport with 6 vertipads and 38 parking spaces using the queueing model and uniform surface time between 2 minutes and 28 minutes (15 minutes average), per 15-minute bins.

Figure 7 demonstrates a limitation of a FCFS scheduling approach. That is, FCFS can result in a loss of capacity. In this particular example, this is the result of the random surface times for each vehicle causing a small loss of vertipad capacity. Figure 8 shows an example of the timeline for a vertiport with a single vertipad where gaps can be left behind that are too small for an arrival or departure operation. In this example, UAM1 arrives at the vertiport via flight UF10 and has a surface time from 00:01:00 through 00:06:57. UAM1 has a departure from the vertiport that starts at 00:06:57, via flight UF11, while the previous arrival reservation (UAM6 via flight UF65) has an end time of 00:06:00, thereby leaving a 57 second gap in the vertipad timeline. Other examples of these gaps can be seen at 00:13:57 and 00:18:42. A similar phenomenon exists in the timeline of the parking spaces. Preventing these gaps could be done with an alternative algorithm, such as an optimizing scheduler with a priori knowledge of upcoming operations within some given optimization window, as well as vehicle and UAM operator constraints.

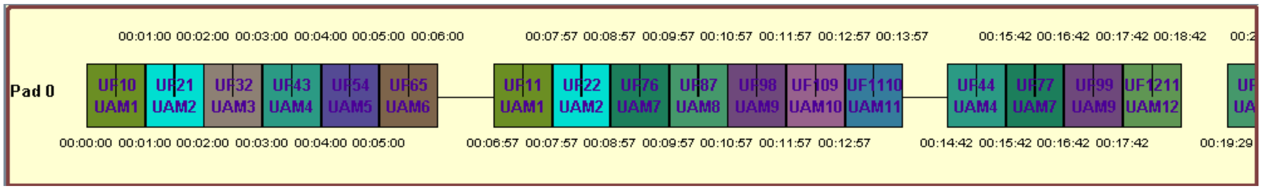

Figure 8. Vertipad timeline for a vertiport with a single vertipad and 20 parking spaces showing timeline gaps too small to be used by an arrival or departure operation.

The simulation model run of the UAM scenario indicated that the average surface time for vertiport DF4 was closer to 9.4 minutes, not 15 minutes. The median surface time was 5 minutes and the maximum surface time was just over 6 hours (due to vehicles parked at the vertiport before the morning peak demand). The observed surface time distribution for DF4 from the simulation model can be seen in Figure 9.

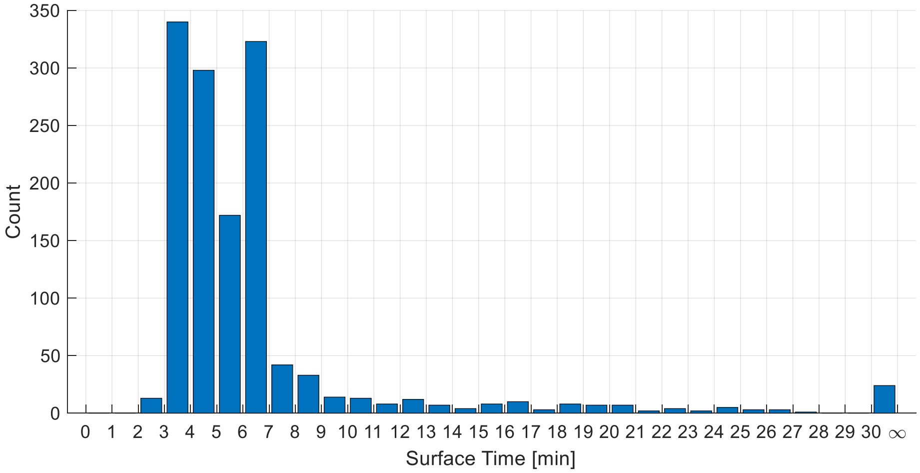

Figure 9. Observed surface time distribution for the DF4 vertiport.

A cumulative distribution function was generated for the observed surface time distribution in Figure 9 and randomly sampled within the queueing model for the same vertiport configuration (6 vertipads and 38 parking spaces). Figure 10 shows the throughput and resource usage from this queueing model run. Note that the resulting average surface time is 8.9 minutes, which is slightly less than the observed average due to the re-sampling of the surface time distribution. With this average surface time, the vertiport configuration is now expected to be vertipad-limited at 90 operations per 15 minutes, as compared to the 76 operations per 15 minutes when the average surface time was 15 minutes. The average throughput in Figure 10 (based on hours 1 to 23) is 70.5 operations per 15 minutes (~22% less than the expected capacity), again indicating a loss in capacity due to the partial arrival and departure slots left in the vertipad timelines due to FCFS. This is confirmed by the average vertipad usage of 83.8% for this vertipad-limited configuration. The average space usage is 60.9% with peaks near 80% and lows near 40%.

Figure 11 shows the simulation model's unimpeded operations for the DF4 vertiport, which includes the demanded trip flights, plus any repositioning and clearing flights to and from the vertiport. The unimpeded operations figure indicates that there are two over-demand periods for the DF4 vertiport; an over-demand state of approximately 23% for the morning peak and approximately 43% for the afternoon peak when compared to the vertiport capacity. The simulation model handles the over-demand situations during mission planning by delaying the operations as necessary to meet the availability of the origin and destination vertiports for any flight.

The observed throughput and resource usage from the simulation model for the DF4 vertiport can be seen in Figure 12. Here the over-demand peaks have been flattened to bring the throughput below the capacity of the vertiport. The peak observed throughput for the DF4 vertiport was 70 operations per 15 minutes, which represents 22.2% less throughput than the expected capacity. However, note that the average throughput is less than this because the simulation model needs to continuously meet not only the constraints of this vertiport but also the constraints at the originating or destination vertiport for flights from/to this vertiport as well as the constraints of the vehicle fleet, which could lead to potentially larger gaps in the resource timelines. The vertipad usage for DF4 is consistent with the throughput for the vertiport, with the peak vertipad usage at 83.0%, but at the peak demand times the vertipad usage is closer to 60% on average as compared to the queuing model with 83.8%. The space usage is fairly low for most of the scenario (60% or below), except near the beginning of the day, where some initially staged vehicles along with a few night arrivals bring the space usage above 80% until the start of the morning demand peak. Most vertiports in the simulation scenario have a high peak space usage due to this transient effect.

Table 2 in the Appendix presents a summary of the throughput and resource usage observations for all vertiports in the simulated scenario. Figure 13 shows the observed peak throughput versus the expected capacity for each of the vertiports. In this figure, the throughput values are clustered at specific capacity values. These clusters represent vertiports with 1 through 6 vertipads as the capacity increases. It can be seen that, as the number of vertipads increases, there is a higher potential for a loss in throughput due to the availability of more vertipad timelines with the potential for small, unusable slots in the FCFS scheduling approach. Figure 13 also shows the distribution of the average surface time for all vertiports. All vertiports had an average surface time of less than 15 minutes for this scenario. In addition, for the 1,190 vehicles in this scenario, each vehicle executed a minimum of 4 flights, a maximum of 74 flights, and a mean and median of 43 flights over the 24-hour period.

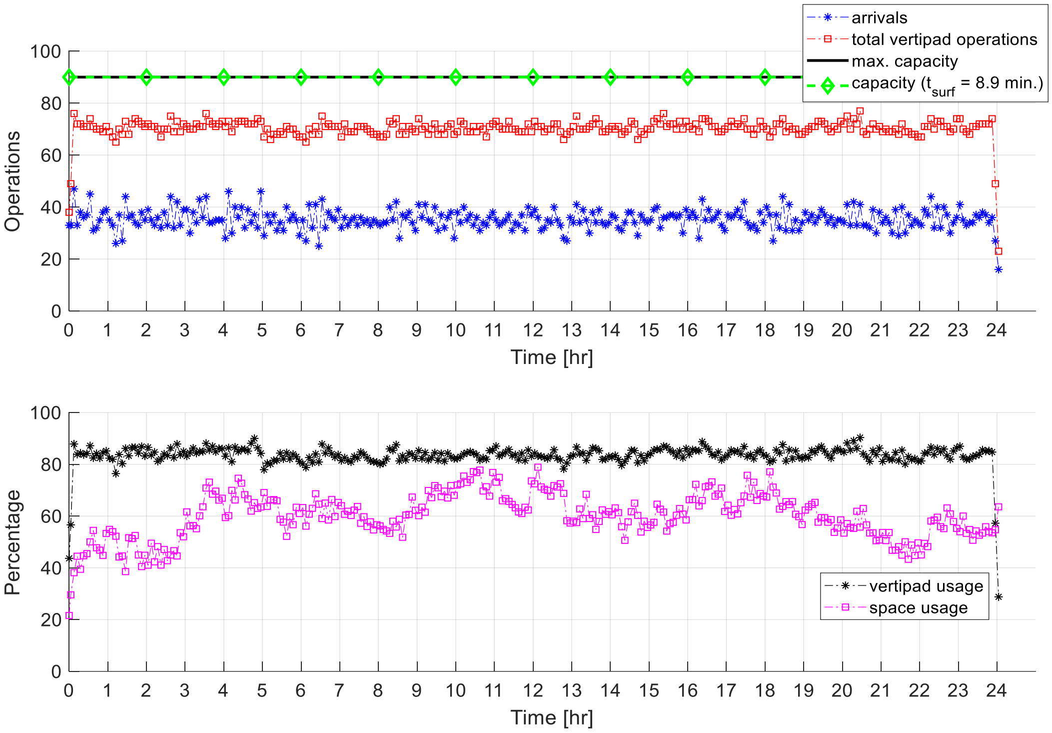

Figure 10. VS throughput (top) and resource usage (bottom) for a vertiport with 6 vertipads and 38 parking spaces using the queueing model and the observed surface time distribution of DF4, per 15-minute bins.

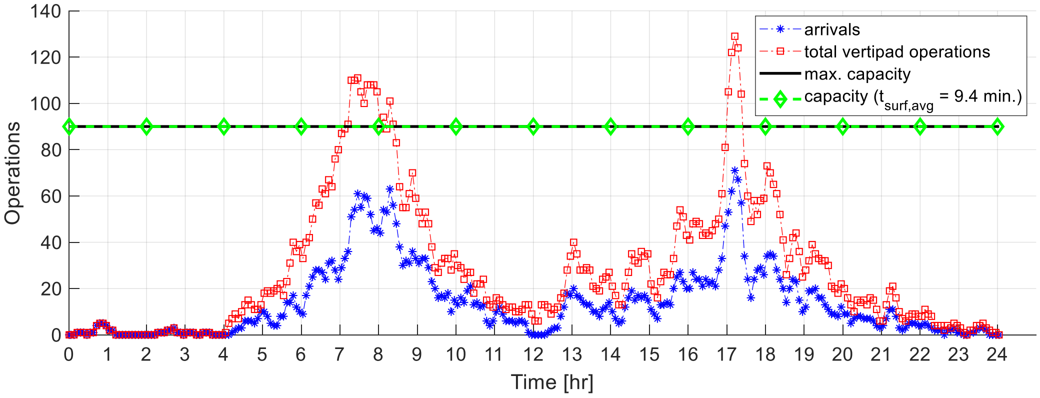

Figure 11. Unimpeded demand for the DF4 vertiport using the simulation model, per 15 minute bins.

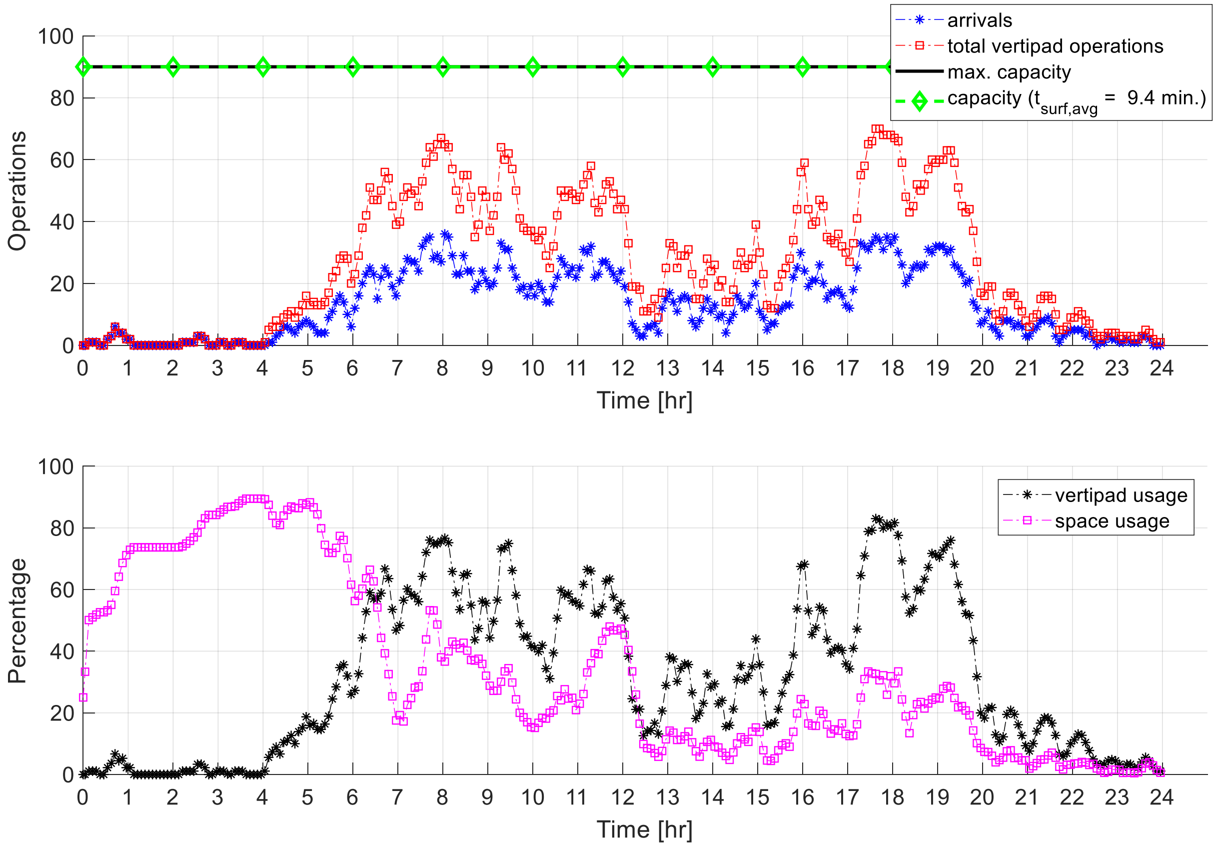

Figure 12. Observed throughput (top) and resource usage (bottom) for the DF4 vertiport using the simulation model, per 15 minute bins.

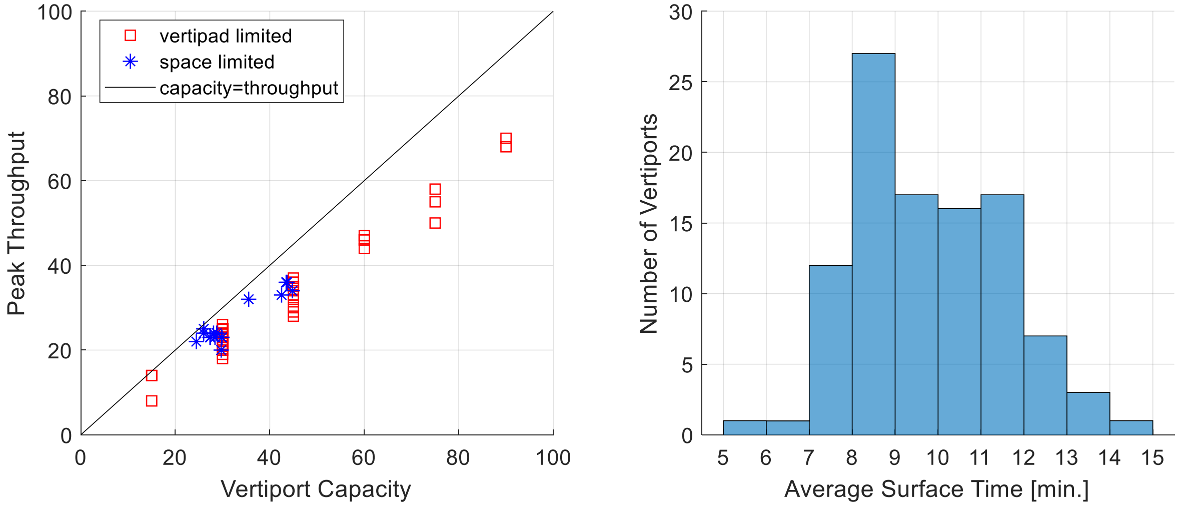

Figure 13. Peak throughput versus capacity (left) per 15 minutes and distribution of average surface times (right) for all vertiports in the simulation scenario.

V. Conclusion

In this paper, a FCFS vertiport scheduling algorithm for UAM was exercised to assess and compare the capacity and throughput of various vertiport configurations. The VS model defines a vertiport by the number of vertipads and parking spaces and manages reservations on timelines for those vertiport resources. The model is agnostic to vertiport layout and, as such, may over- or under-estimate the capacity and throughput of a specific vertiport topology. Nonetheless, the VS model suffices for most fast-time and system-level analyses of UAM concepts and other airspace studies.

The paper defined the theoretical model that can be used to estimate the capacity of various vertiport configurations. The theoretical model provided an understanding of the conditions that can lead to either a parking space-limited or a vertipad-limited vertiport. This boundary is dependent on the ratio of the surface time to the vertipad time used by a vehicle at a vertiport.

Examples of potential throughput for various vertiport configurations were provided using both a queuing approach as well as a simulated UAM demand scenario. The models revealed that the FCFS scheduling approach can have inefficiencies in the use of the vertiport resources. The inefficiencies can increase as the number of resources increase. Nonetheless, the FCFS VS model can capture 80% or better throughput to capacity ratio in most cases and may be the only suitable alternative in on-demand UAM operations. More sophisticated scheduling approaches may be possible with other algorithms, especially in cases where the demand is known a priori and the arrival and departure slots can be optimized with appropriate knowledge of the relevant operator and airspace constraints. In addition, the availability of some unused times on vertipad timelines may provide a useful mechanism by which operations can be adjusted slightly to support off-nominal conditions, such as missed approaches that need to be re-inserted into a vertiport's arrival schedule, for example.

Future work with respect to this FCFS VS algorithm may include improvements to support higher throughput to capacity ratios without the need for optimization techniques. These may include arrival and departure slot restrictions that try to reduce partial slots on a timeline and similar strategies for surface time on parking spaces.

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Appendix

Table 2. Vertiport information and results for the 102 vertiports in the simulation model scenario, based on a 15-minute window.

Vertiport	N_p	N_s	Total Vertipad Operations	$t_{surf,avg}$	$C_{port,max}$	C_{port}	Peak Throughput	Peak Vertipad Usage (%)	Peak Parking Space Usage (%)	Space-Limited?
DF4	6	38	2770	9.4	90	90	70	83.0	89.5	false
DF2	6	36	2474	8.0	90	90	68	80.2	89.7	false
DF6	5	28	1947	8.8	75	75	55	79.7	88.4	false
DF11	5	28	1868	8.0	75	75	58	81.9	75.4	false
DF9	4	26	1756	8.8	60	60	46	80.5	88.6	false
DF37	4	24	1734	8.1	60	60	47	82.7	81.3	false
DF17	4	24	1733	9.7	60	60	46	81.1	88.8	false
DF5	5	28	1691	8.9	75	75	50	69.9	91.5	false
DF7	4	24	1603	8.8	60	60	44	78.9	82.1	false
DF21	3	18	1455	7.6	45	45	35	82.9	87.4	false
DF71	3	16	1379	10.2	45	45	37	86.9	90.5	false
DF43	3	18	1267	8.9	45	45	35	83.9	86.2	false
DF89	3	16	1226	9.4	45	45	35	81.2	74.2	false
DF8	3	16	1171	8.4	45	45	33	79.0	83.4	false
DF13	3	18	1146	11.8	45	45	35	84.9	78.3	false
DF30	3	18	1119	9.4	45	45	32	78.1	89.2	false
DF26	3	18	1116	7.7	45	45	33	75.3	82.8	false
DF18	3	18	1114	11.8	45	45	36	82.1	92.5	false
DF40	3	18	1114	11.2	45	45	36	85.3	89.6	false
DF69	3	18	1112	11.4	45	45	33	78.2	83.7	false
DF31	3	16	1108	9.3	45	45	36	83.6	84.9	false
DF10	3	16	1103	10.7	45	44.8	34	77.2	71.4	true
DF38	3	18	1084	12.4	45	43.6	36	83.2	82.3	true
DF24	3	18	1080	8.9	45	45	34	81.0	78.1	false
DF65	3	16	1078	8.3	45	45	35	78.9	75.8	false
DF12	3	18	1070	7.4	45	45	30	71.7	78.8	false
DF102	3	16	1060	11.3	45	42.5	33	77.6	77.2	true
DF94	2	14	1042	8.5	30	30	25	86.0	66.3	false
DF84	2	14	1037	7.7	30	30	24	83.6	85.1	false
DF16	2	12	1011	8.4	30	30	25	84.6	68.2	false
DF35	2	12	1007	10.5	30	30	23	84.2	84.6	false
DF29	3	20	1002	13.8	45	43.5	36	82.6	90.8	true
DF44	3	16	998	8.8	45	45	35	83.9	84.3	false
DF27	2	12	994	9.5	30	30	25	86.4	97.8	false
DF22	2	10	973	7.1	30	30	22	75.9	71.7	false
DF19	3	16	970	8.7	45	45	28	69.1	71.5	false
DF15	2	12	963	10.0	30	30	25	88.8	90.3	false
DF14	2	12	960	9.3	30	30	25	90.7	87.1	false
DF42	2	14	956	10.5	30	30	24	83.3	84.6	false
DF49	3	16	928	10.6	45	45	29	68.6	79.8	false
DF33	2	12	910	9.4	30	30	24	83.4	81.7	false
DF25	2	14	908	12.0	30	30	26	90.8	83.1	false
DF59	2	10	906	6.5	30	30	23	84.3	84.0	false
DF20	2	12	905	12.1	30	29.8	23	81.5	84.9	true
DF58	2	10	902	8.0	30	30	22	77.3	66.7	false
DF74	2	14	876	11.3	30	30	24	84.4	89.0	false

Vertiport	N_p	N_s	Total Vertipad Operations	$t_{surf,avg}$	$C_{port,max}$	C_{port}	Peak Throughput	Peak Vertipad Usage (%)	Peak Parking Space Usage (%)	Space-Limited?
DF46	2	10	869	8.3	30	30	24	84.8	76.0	false
DF45	2	12	861	12.0	30	30	25	88.5	85.8	false
DF34	2	10	860	9.8	30	30	23	82.9	79.8	false
DF76	2	12	856	9.4	30	30	25	91.6	84.7	false
DF93	2	10	853	9.7	30	30	24	83.5	82.9	false
DF50	3	16	852	13.5	45	35.5	32	76.1	92.0	true
DF51	2	12	851	11.0	30	30	24	84.3	72.7	false
DF88	2	14	846	8.8	30	30	25	85.7	89.0	false
DF52	2	14	836	8.9	30	30	24	90.3	92.7	false
DF48	2	12	834	8.6	30	30	24	83.1	95.3	false
DF28	2	12	831	9.0	30	30	22	77.2	84.4	false
DF87	2	10	831	7.5	30	30	23	82.3	79.6	false
DF78	2	12	820	7.8	30	30	23	76.7	80.6	false
DF57	2	12	817	11.4	30	30	22	78.3	86.8	false
DF32	2	10	807	8.3	30	30	23	81.5	82.8	false
DF85	2	10	803	9.3	30	30	23	78.9	80.0	false
DF64	2	12	798	11.6	30	30	23	86.0	78.4	false
DF55	2	12	794	11.5	30	30	24	85.3	88.0	false
DF70	2	14	794	10.9	30	30	25	87.4	89.8	false
DF47	2	14	792	10.8	30	30	24	83.7	83.9	false
DF91	2	12	780	10.1	30	30	23	79.9	90.8	false
DF23	2	12	778	11.4	30	30	21	78.1	95.8	false
DF54	2	10	778	8.9	30	30	22	77.6	98.0	false
DF82	2	12	773	13.2	30	27.3	23	85.3	78.8	true
DF81	2	14	769	12.5	30	30	21	79.3	77.6	false
DF63	2	10	756	10.0	30	29.9	23	78.5	85.8	true
DF95	2	14	740	12.8	30	30	25	87.4	86.2	false
DF60	2	12	738	11.7	30	30	23	80.4	84.3	false
DF36	2	10	732	9.4	30	30	21	74.1	91.1	false
DF79	2	12	724	10.2	30	30	24	84.9	81.1	false
DF41	2	12	723	14.7	30	24.5	22	78.9	82.4	true
DF86	2	12	722	12.5	30	28.8	24	82.3	76.1	true
DF101	2	10	720	11.5	30	26.0	24	85.8	96.9	true
DF66	2	12	720	11.5	30	30	23	81.4	85.1	false
DF68	2	10	720	9.5	30	30	21	77.4	61.3	false
DF73	2	12	716	10.9	30	30	24	83.7	87.8	false
DF39	2	10	710	10.9	30	27.4	23	83.3	92.3	true
DF72	2	10	695	8.4	30	30	22	75.8	76.2	false
DF56	2	10	688	11.5	30	26.0	25	88.8	80.0	true
DF77	2	10	682	10.7	30	28.1	24	83.0	85.2	true
DF92	2	10	682	8.8	30	30	22	78.2	86.2	false
DF61	2	12	681	7.8	30	30	25	83.4	50.0	false
DF67	2	12	676	11.4	30	30	23	79.4	85.9	false
DF75	2	10	670	7.3	30	30	23	77.6	70.0	false
DF53	2	10	668	9.9	30	30	20	69.4	91.3	false
DF62	2	10	658	7.8	30	30	20	72.0	69.7	false
DF83	2	12	650	12.7	30	28.4	23	79.1	88.9	true
DF97	2	10	648	10.0	30	30	23	79.4	83.3	false
DF96	2	10	644	8.6	30	30	23	78.7	58.6	false
DF80	2	10	640	9.9	30	30	18	62.9	71.5	false

Vertiport	N_p	N_s	Total Vertipad Operations	$t_{surf,avg}$	$C_{port,max}$	C_{port}	Peak Throughput	Peak Vertipad Usage (%)	Peak Parking Space Usage (%)	Space-Limited?
DF98	2	10	628	10.1	30	29.7	20	68.4	82.8	true
DF90	2	10	622	8.7	30	30	19	71.3	60.0	false
DF100	2	10	555	7.7	30	30	21	72.2	78.8	false
DF3	1	6	496	8.3	15	15	14	95.6	87.9	false
DF99	1	8	436	11.6	15	15	14	97.3	80.3	false
DF1	1	4	209	5.7	15	15	8	53.3	89.1	false

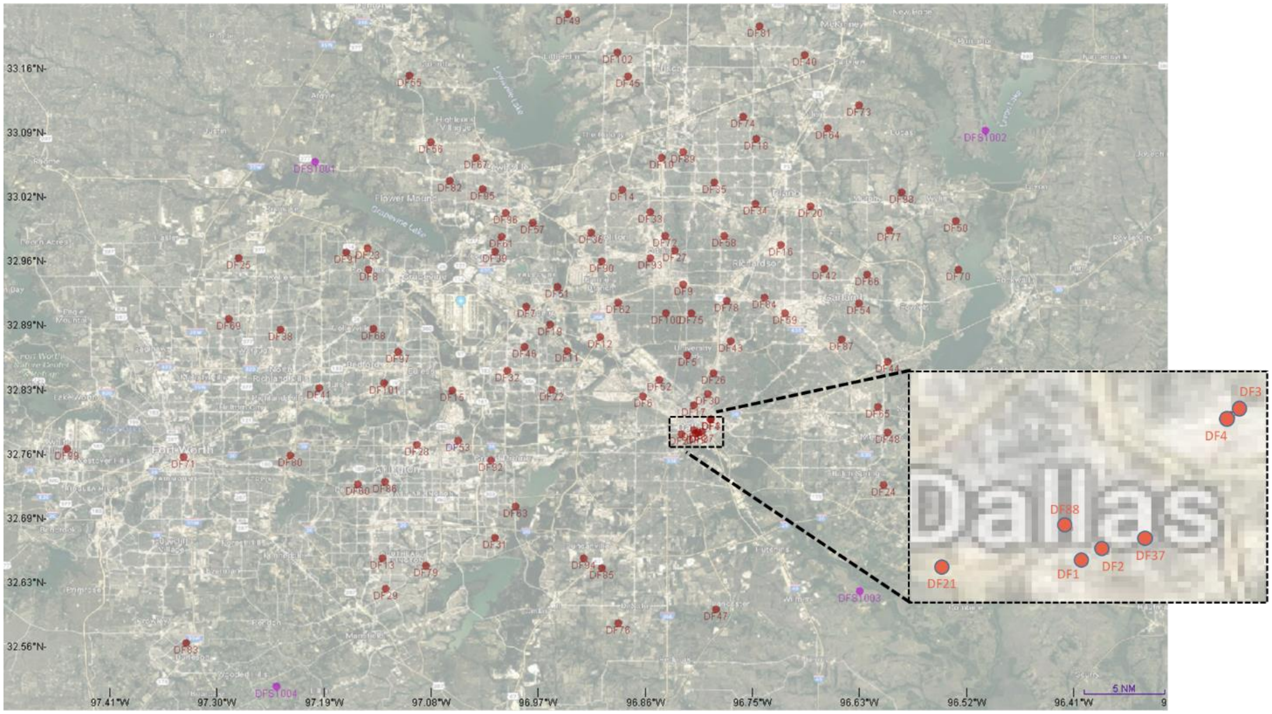

Figure 14. Vertiport locations in the Dallas/Ft. Worth UAM scenario. Note that DFS1001, DFS1002, DFS1003, and DFS1004 (in magenta) are storage vertiports with unlimited surface capacity [background map source: Google Maps].