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

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Outline

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  – Simulation Model
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Background/Motivation

Background

- NASA's Air Traffic Management – Exploration (ATM-X) project is investigating impact of new entrants to the National Airspace System (NAS)

- The Urban Air Mobility (UAM) sub-project is investigating the services, functions, concepts, and architectures required to enable some of these new operations

- A vertiport scheduling algorithm (Vertiport Scheduler) was developed to support fast-time simulations and analysis of UAM demand scenarios

- The objectives of this study were to:
  - Understand the expected capacity of different vertiport configurations by developing a theoretical capacity model
  - Study the Vertiport Scheduler's ability to achieve the expected capacity by comparing the capacity to the throughput within a simulated UAM demand scenario

Motivation

- Vertiports:
  - Are the designated landing and takeoff locations for UAM operations
  - Can be characterized by the number of vertipads (takeoff and landing areas) and the number of parking spaces (gates)
  - Can have many different surface layouts

- Vertiports are the sources and sinks for UAM operations and, as such, we need to account for these constraints when analyzing UAM airspace operations

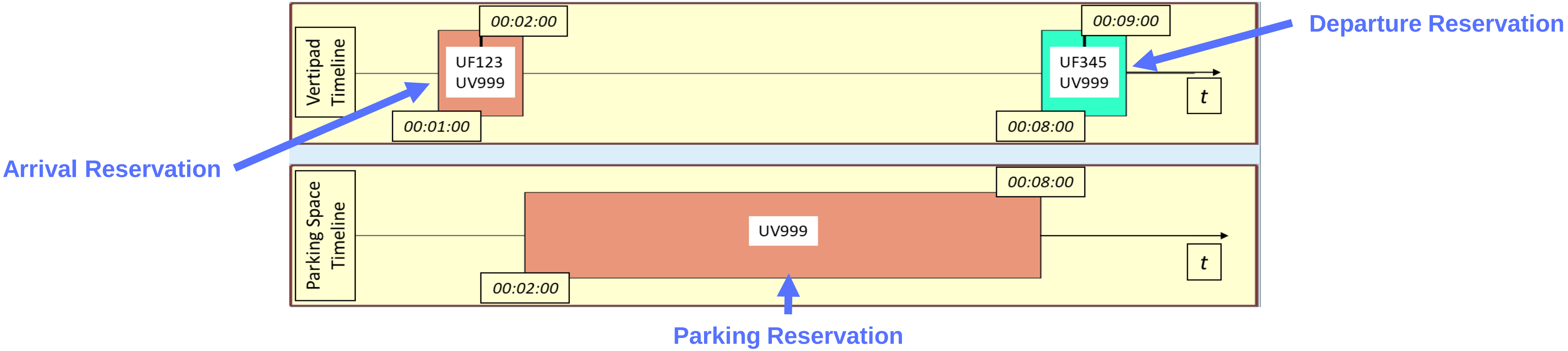
- A simple model for vertiports, and an associated vertiport scheduling algorithm, was needed and developed for fast-time simulation

- This study helps us understand the performance of this simple modeling approach and scheduling algorithm

Vertiport Scheduler

Vertiport Scheduler

- Each vertiport is defined by the number of vertipads and number of parking spaces
- Each vertipad or parking space is modeled by a resource timeline
- The Vertiport Scheduler manages reservations (time blocks) on these timelines
- A typical UAM vehicle operation at a vertiport will have:
  - A vertipad reservation for the landing/arrival operation
  - A parking space reservation for the surface time at the vertiport
  - A vertipad reservation for the takeoff/departure operation



Vertiport Scheduler (2)

- The Vertiport Scheduler algorithm provides interfaces for external planners to:
  - Query the availability of the vertiport resources (next available arrival, next available departure)
  - Make reservations at the vertiport (reserve arrival, reserve departure)

- Other Vertiport Scheduler assumptions:
  - Reservations cannot overlap in time for the same resource
  - Arrivals, departures, and parking reservations are linked to a vehicle identifier (aircraft tail number)
  - Reservations have start and end times that provide a continuous presence on the vertiport resources
  - All surface time at a vertiport is allocated to a parking space timeline (e.g., taxi, passenger loading/un-loading)
  - Initial implementation uses first-come, first-served (FCFS) logic

Analysis Design and Models

Study Approach

- Develop a theoretical model for capacity
- Evaluate the throughput of different vertiport configurations using:
  – A queueing model
  – A simulation model
- Compare the throughput to the expected capacity

Definitions

Operation(s) – an operation is equivalent to a single reservation on a vertipad or a single reservation at a parking space.

Capacity – the estimated number of operations on a resource over a given time period, given some assumptions (e.g., vertipad capacity, surface capacity, vertiport capacity).

Throughput – the observed number of operations on a resource over a given time period (e.g., vertiport throughput).

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).

Theoretical Capacity Model

- Definitions:

N_s - number of parking spaces
N_p - number of vertipads

t_{arr} - arrival time block
t_{dep} - departure time block
t_{surf} - surface time block
t_{win} - time window

- Equations:

Surface Capacity

$$C_{surf} = N_s \cdot \frac{t_{win}}{t_{surf}}$$ → surface operations

Vertipad Capacity

$$C_{pads} = 2 \cdot N_p \cdot \frac{t_{win}}{t_{arr}+t_{dep}}$$ → vertipad operations

Vertiport Capacity

$$C_{port} = min\left(2 \cdot C_{surf}, C_{pads}\right)$$ → vertiport operations

Theoretical Capacity Model (2)

- Theoretical model helps define the boundary between surface limited and vertipad limited for a vertiport
  - A vertiport is considered to be *surface capacity limited* when the following is true:

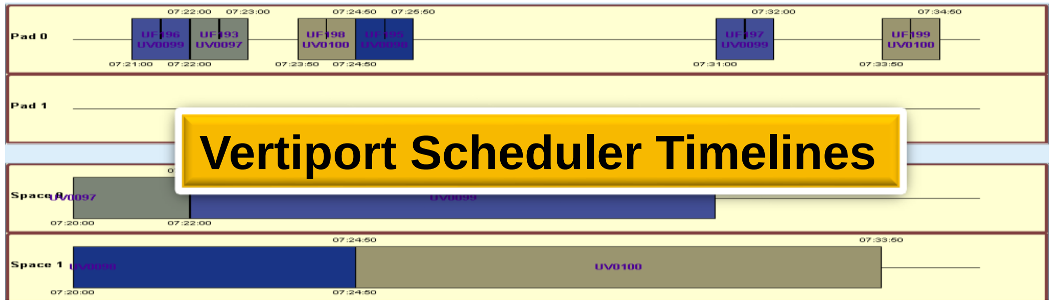
$$\boxed{N_s < N_p \cdot \frac{t_{surf}}{t_{arr} + t_{dep}}}$$

- Model assumptions:
  - Vertiport arrivals and departures are balanced over any given period of time
  - One surface operation is equivalent to two vertipad operations
  - The vertipad usage is 100% for vertipad capacity formula
  - The surface usage is 100% for surface capacity
  - Maximum capacity is calculated using the minimum surface time
  - Nominal capacity is calculated using the average surface time

Queueing Model

- An individual Vertiport Scheduler instance is used
- A large queue of demand is used to fill the Vertiport Scheduler at the next available time
- Requires an assumed surface time distribution
- For each element in the queue and while the vertiport has availability within a desired time block:
  - The next available arrival is queried/identified
  - An arrival reservation is made, along with a surface reservation (initially of infinite duration)
  - A finite surface time is sampled from the distribution
  - The next available departure is queried/identified
  - A departure reservation is made (and the parking reservation’s end time is adjusted)

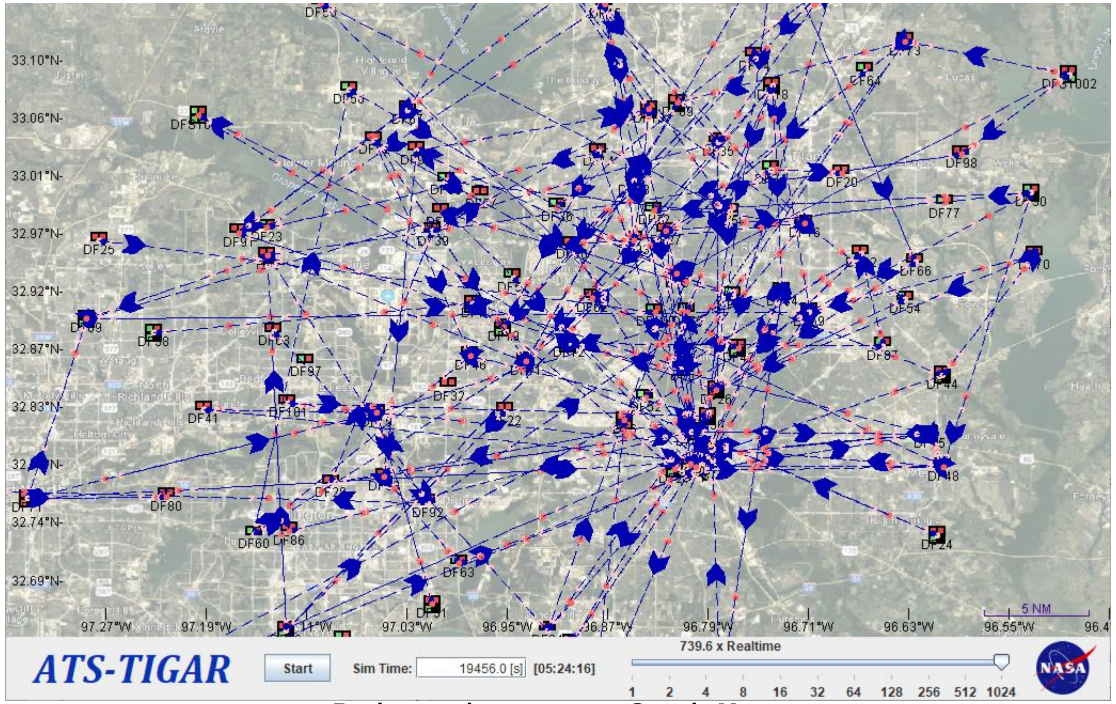
Queue = {operation1, operation2, …}



Simulation Model

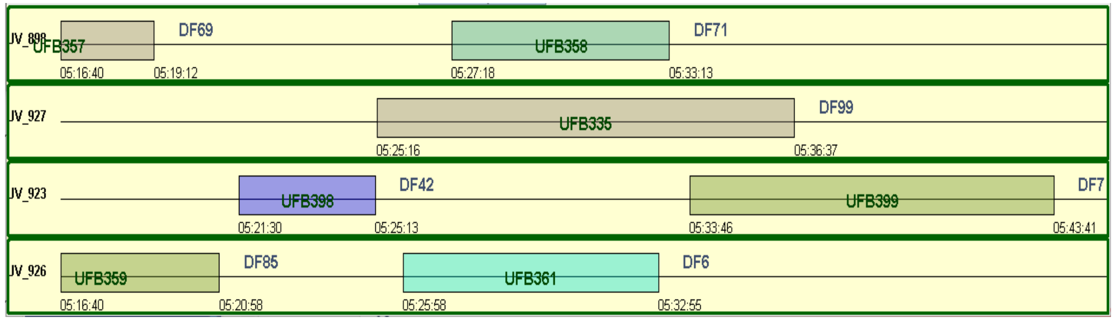
- A scenario analysis tool called ATS-TIGAR was used
  - Uses a mission planning algorithm to plan UAM trips within an airspace region
    - Realistic constraints include:
      - Limited vehicle fleet with fleet management (e.g., tail tracking, passenger load/un-load times)
      - Vertiports with limited resources (parking spaces and vertipads)
      - Trips with different number of passengers
      - 4-D vertical takeoff and landing trajectories for each flight
      - Airspace constraints (disabled for this analysis)
      - Multiple operators sharing resources
  - Implements a Vertiport Scheduler for each vertiport in the scenario
- A single demand scenario with multiple vertiports was run for this study

Scenario Visualization



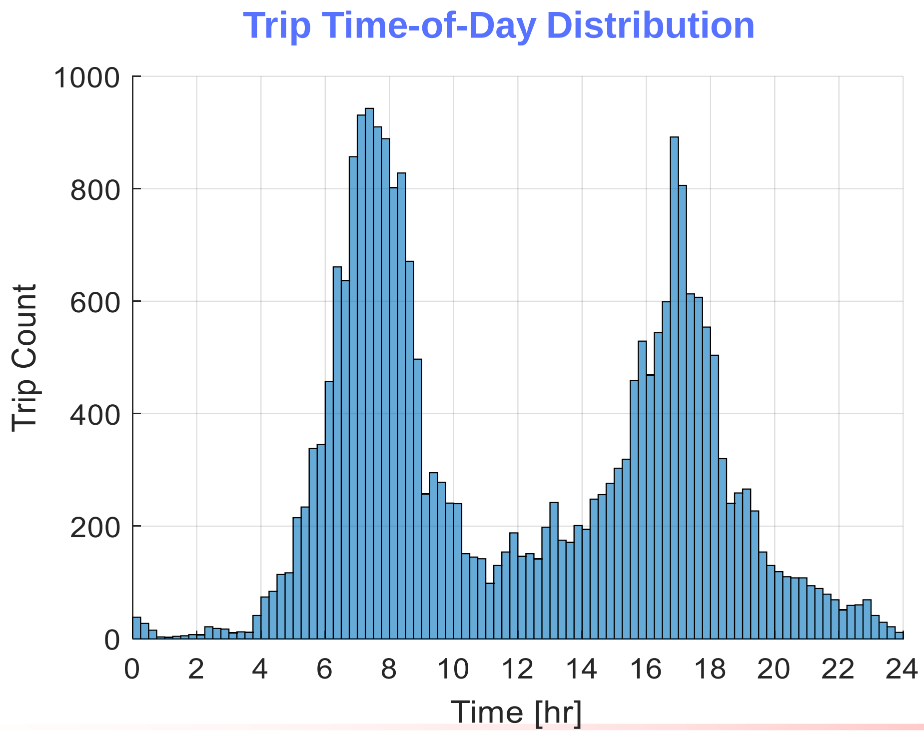
Background map source: Google Maps

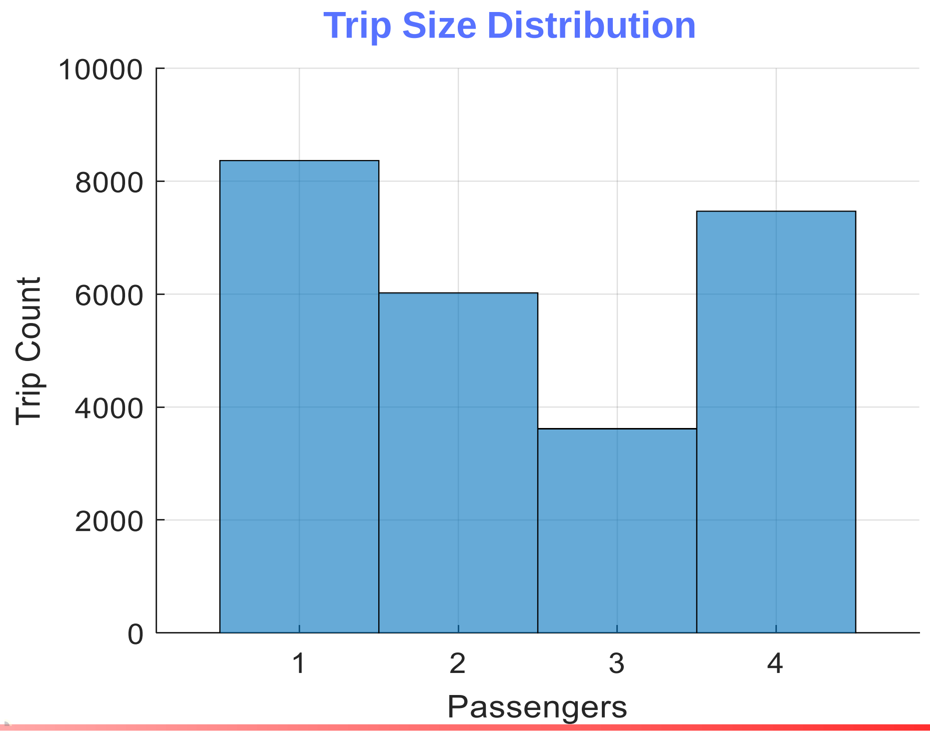
Vehicle Timeline/Schedule View



UAM Demand Scenario

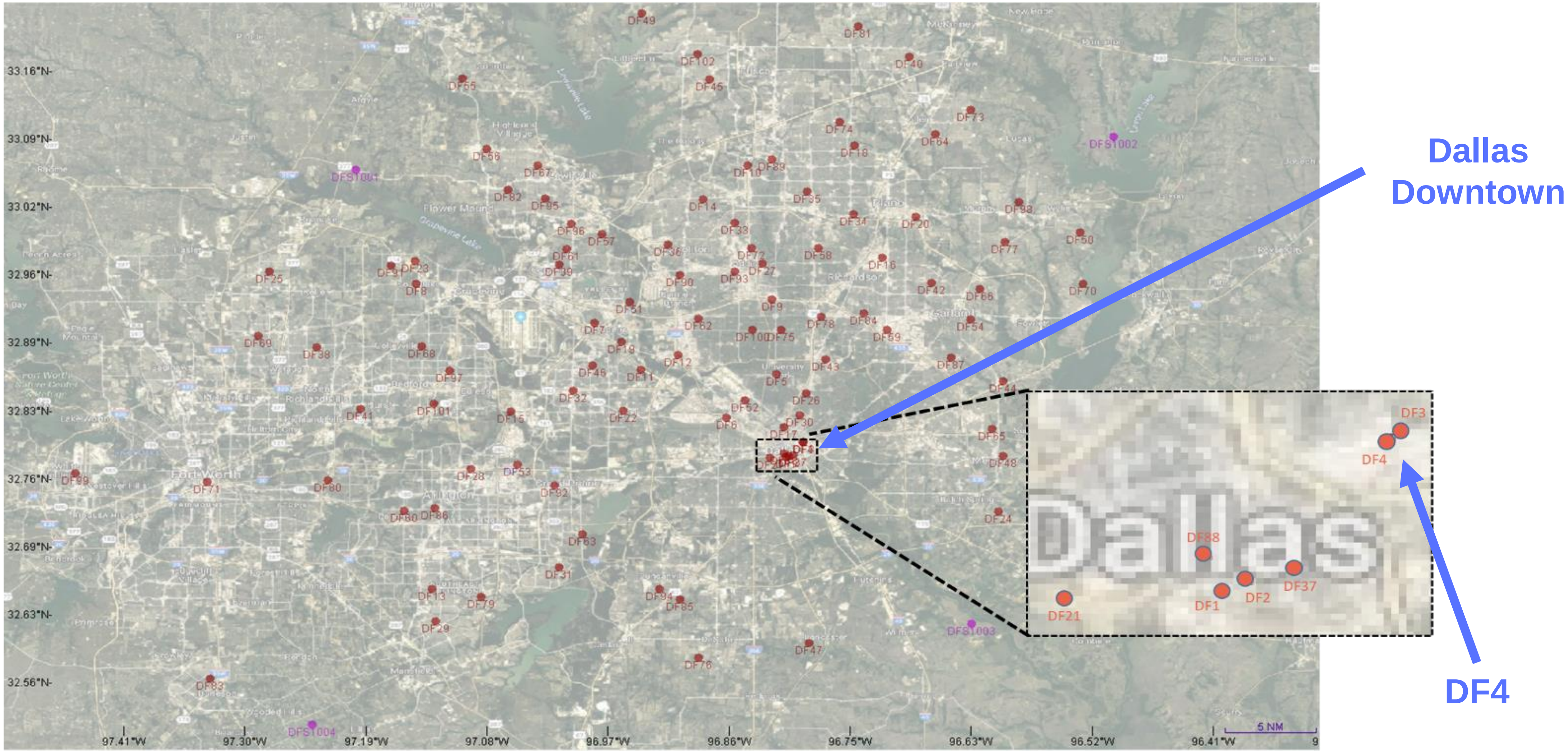
- UAM demand scenario was computed by Virginia Tech for NASA using a mode choice model
- 25,472 daily one-way multi-passenger commuter trips for the Dallas area between 102 vertiports
  - 51,632 total flights planned after including repositioning/clearing flights





UAM Demand Scenario (2)

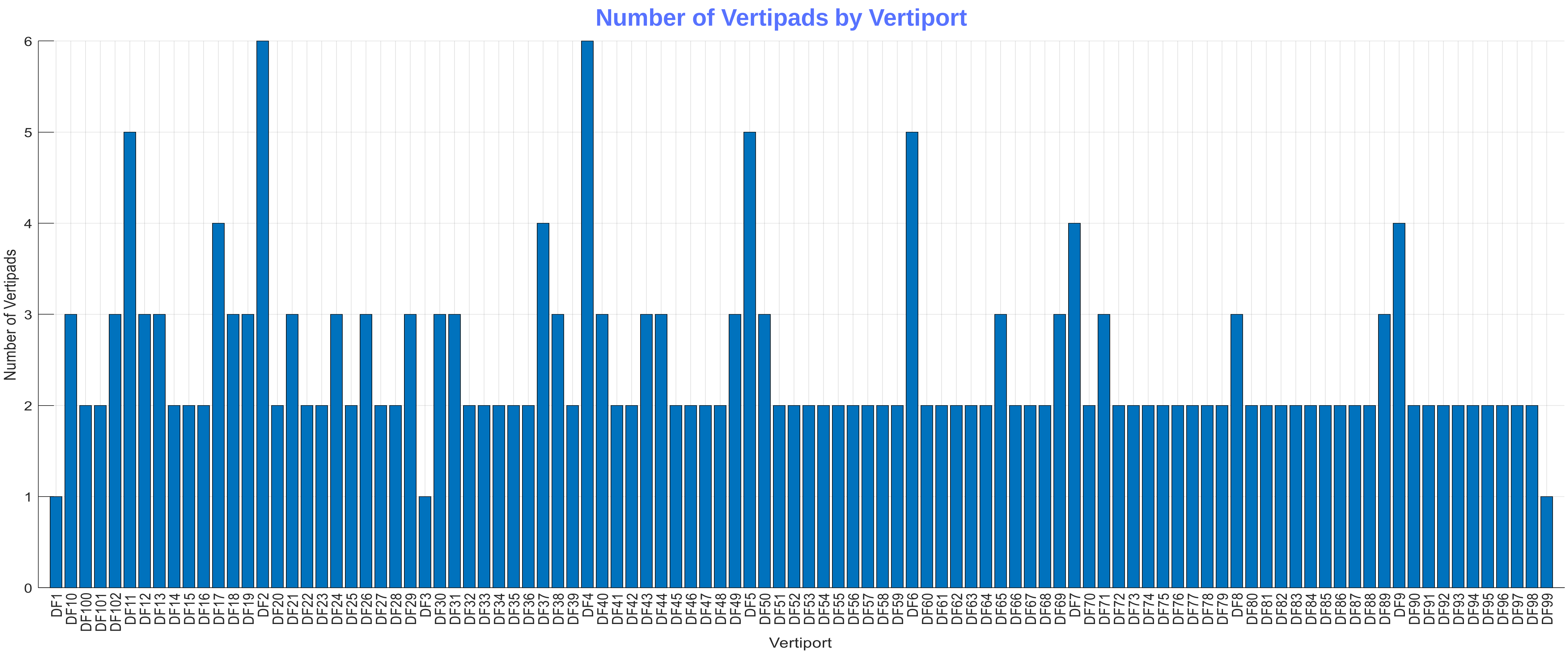
- Vertiport Locations (DF4 is the largest and busiest vertiport)



Background map source: Google Maps

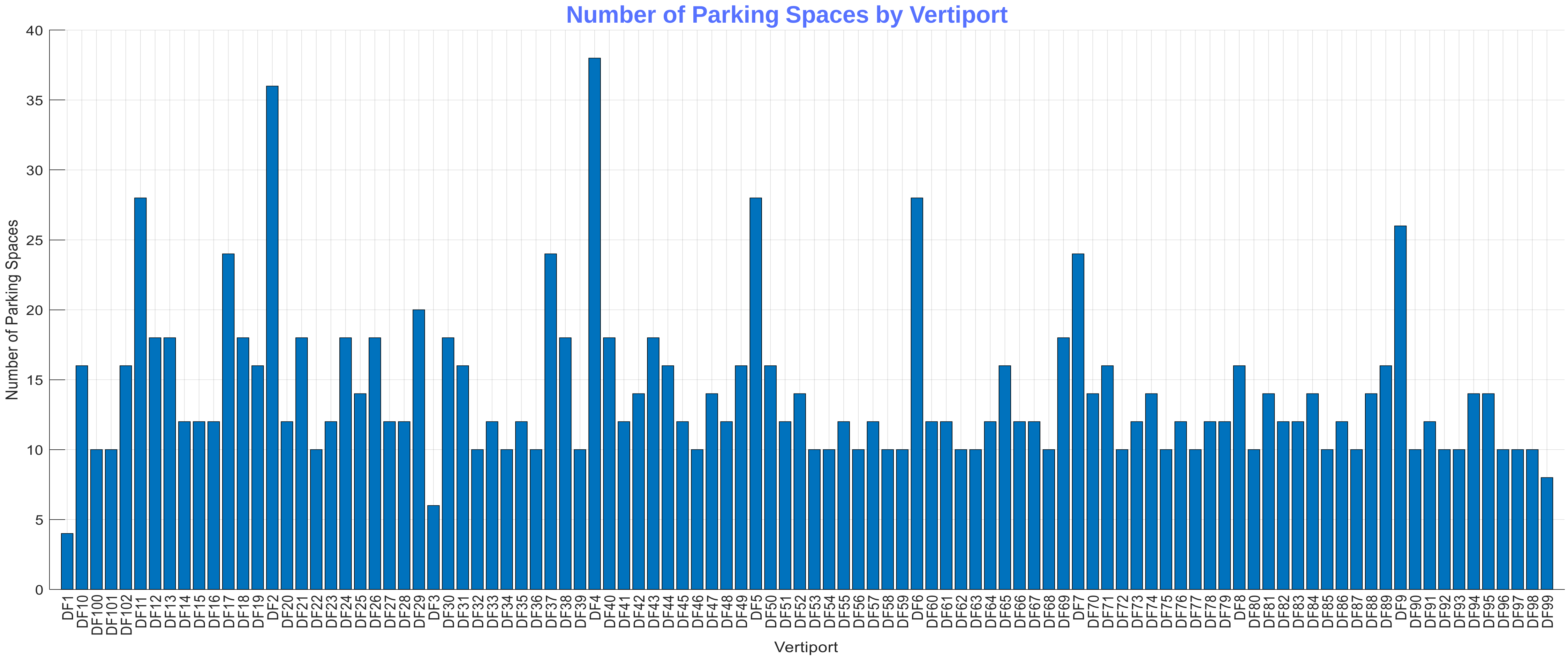
UAM Demand Scenario (3)

- DF2 and DF4 have 6 vertipads



UAM Demand Scenario (4)

- DF4 has 38 parking spaces



Study Parameters/Assumptions

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]

- Two UAM operators with 75/25% split for trips and vehicle fleet

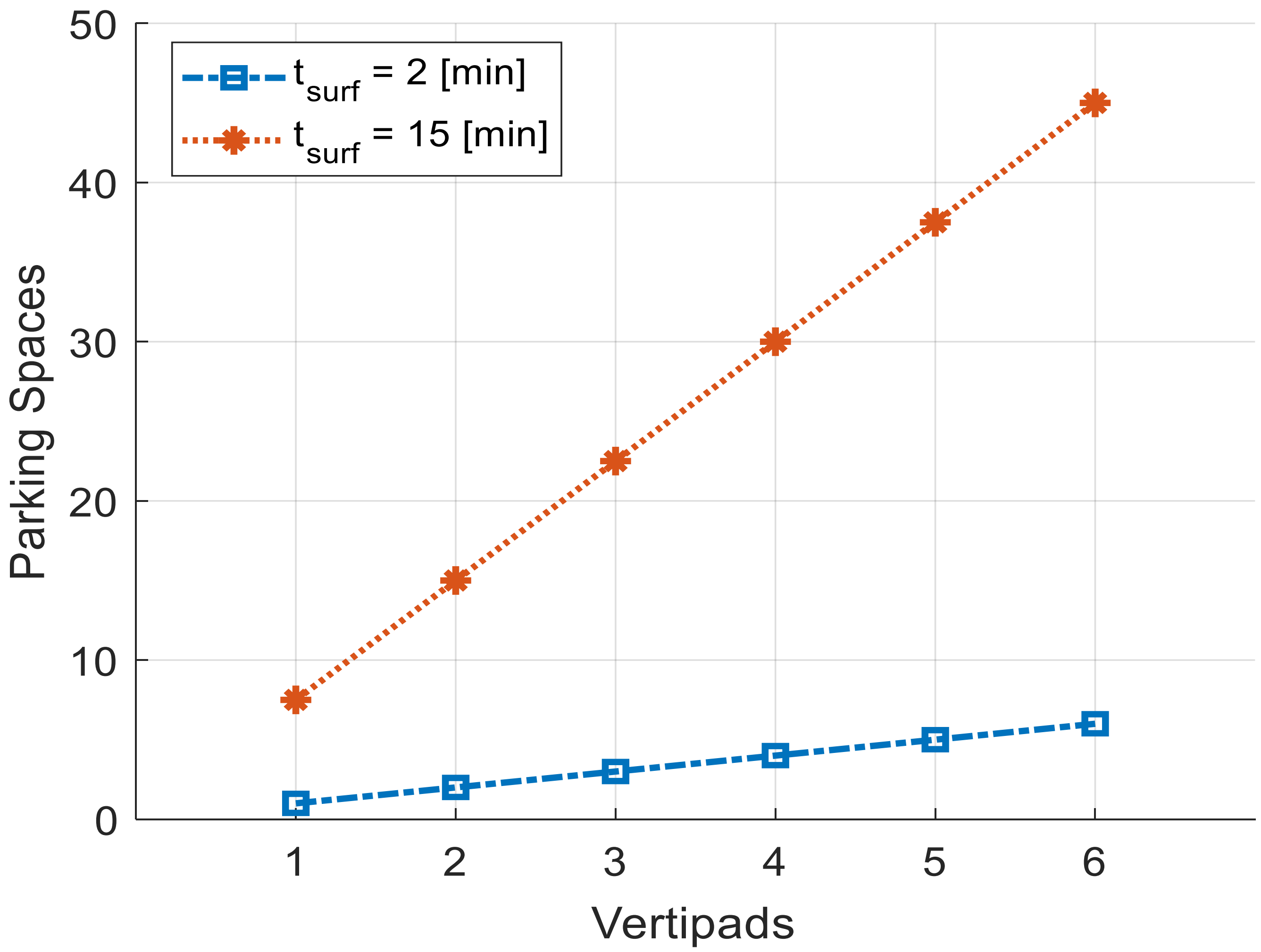
Results

Estimating Required Parking Spaces

- How many parking spaces are required to not be surface capacity limited?

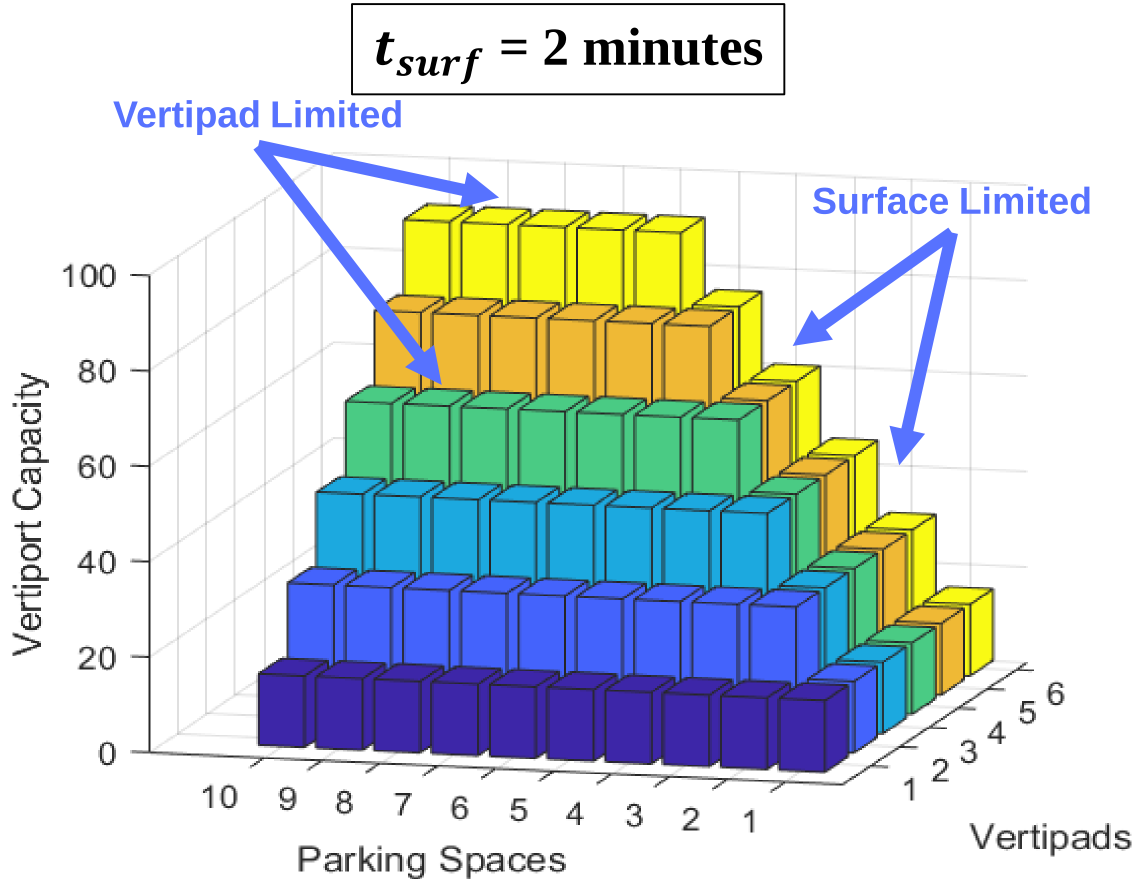
- This is dependent on the surface time spent at a vertiport

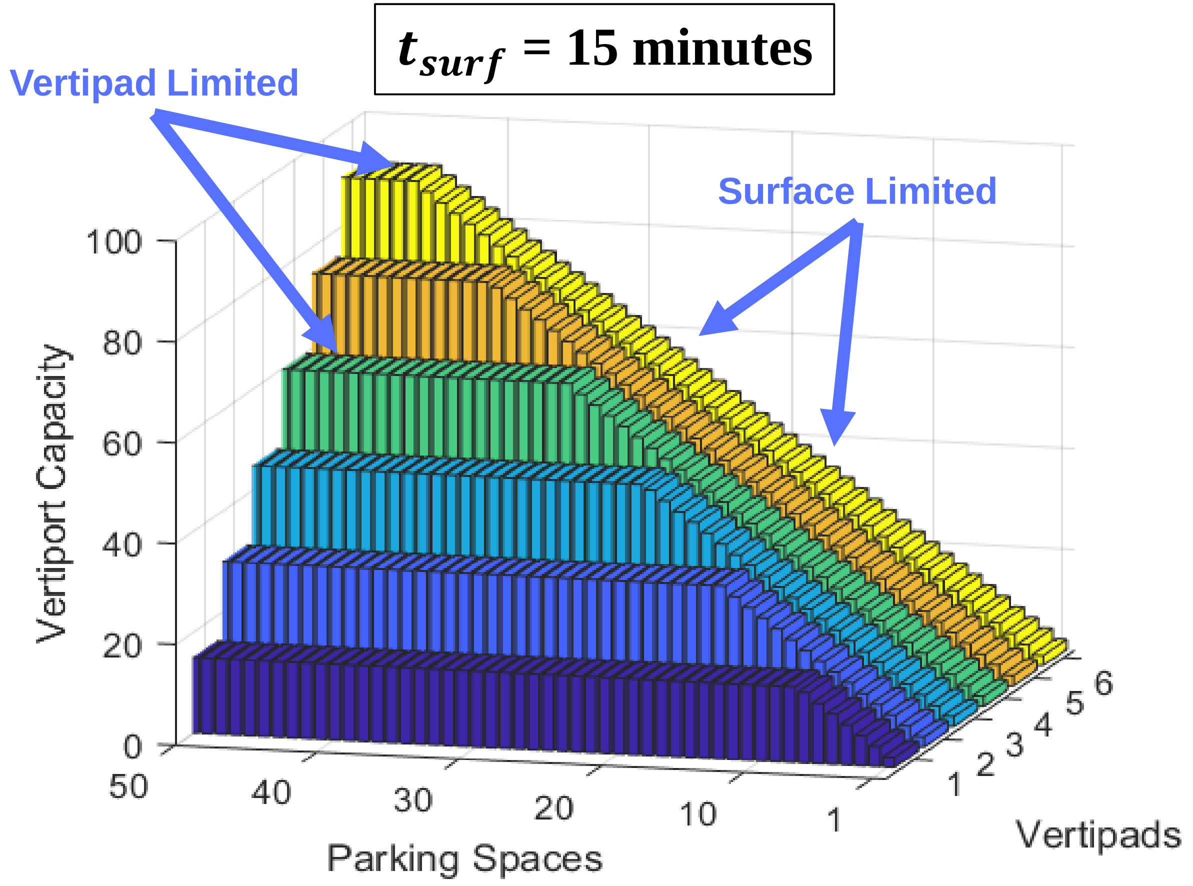
- Figure shows trend using two assumed average surface times (2-minute trend represents the limit for our analysis)



Surface vs. Vertipad Limited Vertiports

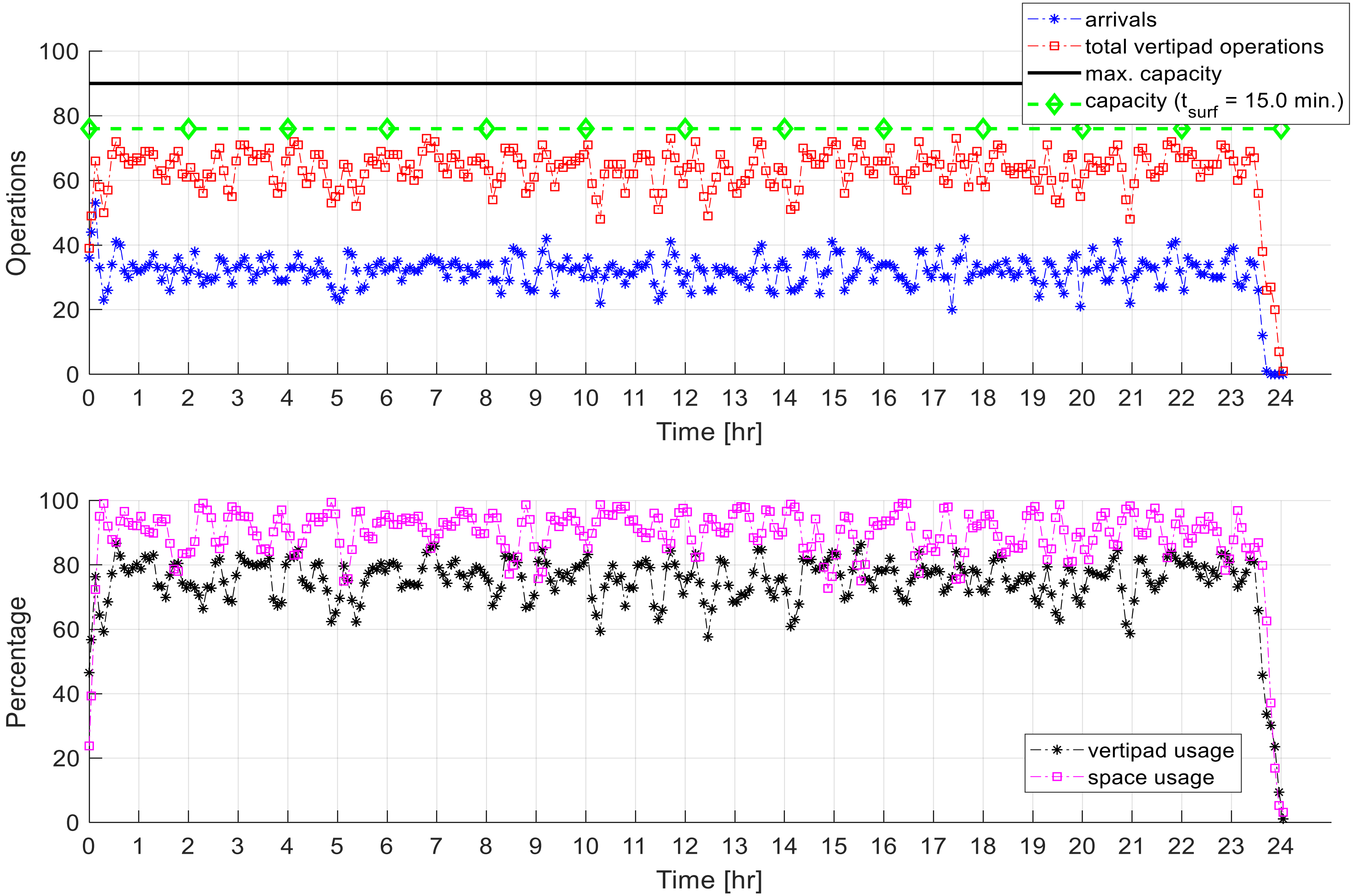
- Plateau regions show vertipad limited vertiport
- Sloped regions indicate surface limited vertiport





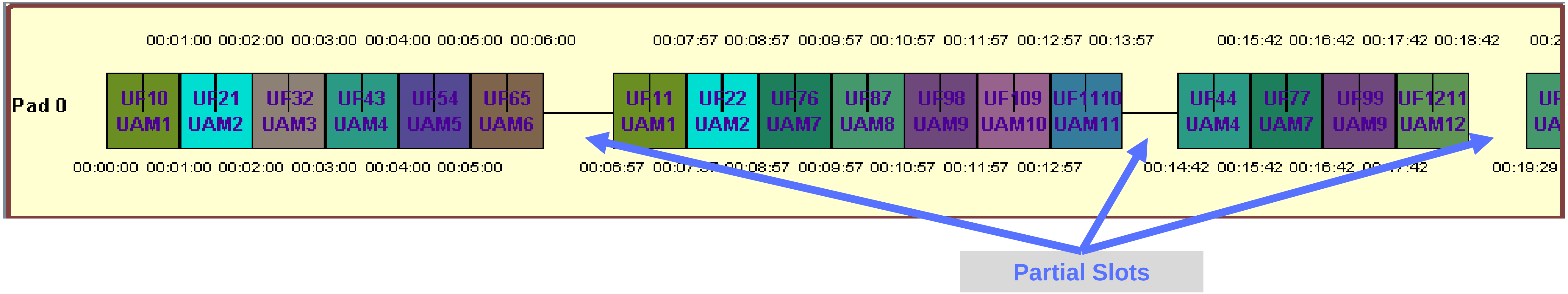
DF4 Configuration Throughput

- DF4:
  - 6 vertipads
  - 38 parking spaces
- **Queueing model** assuming **uniform** surface time 2-28 minutes (15 avg.)
  - Expect surface limited
- Maximum capacity = **90** ops./15-min.
- Nominal Capacity = **76** ops./15-min.
- Observed throughput average ~ **63.9** ops./15-min.
- Vertipad usage ~ **75.9%**
- Space usage ~ **90.5%** (some peaks close to 100%)



Limitations on Throughput

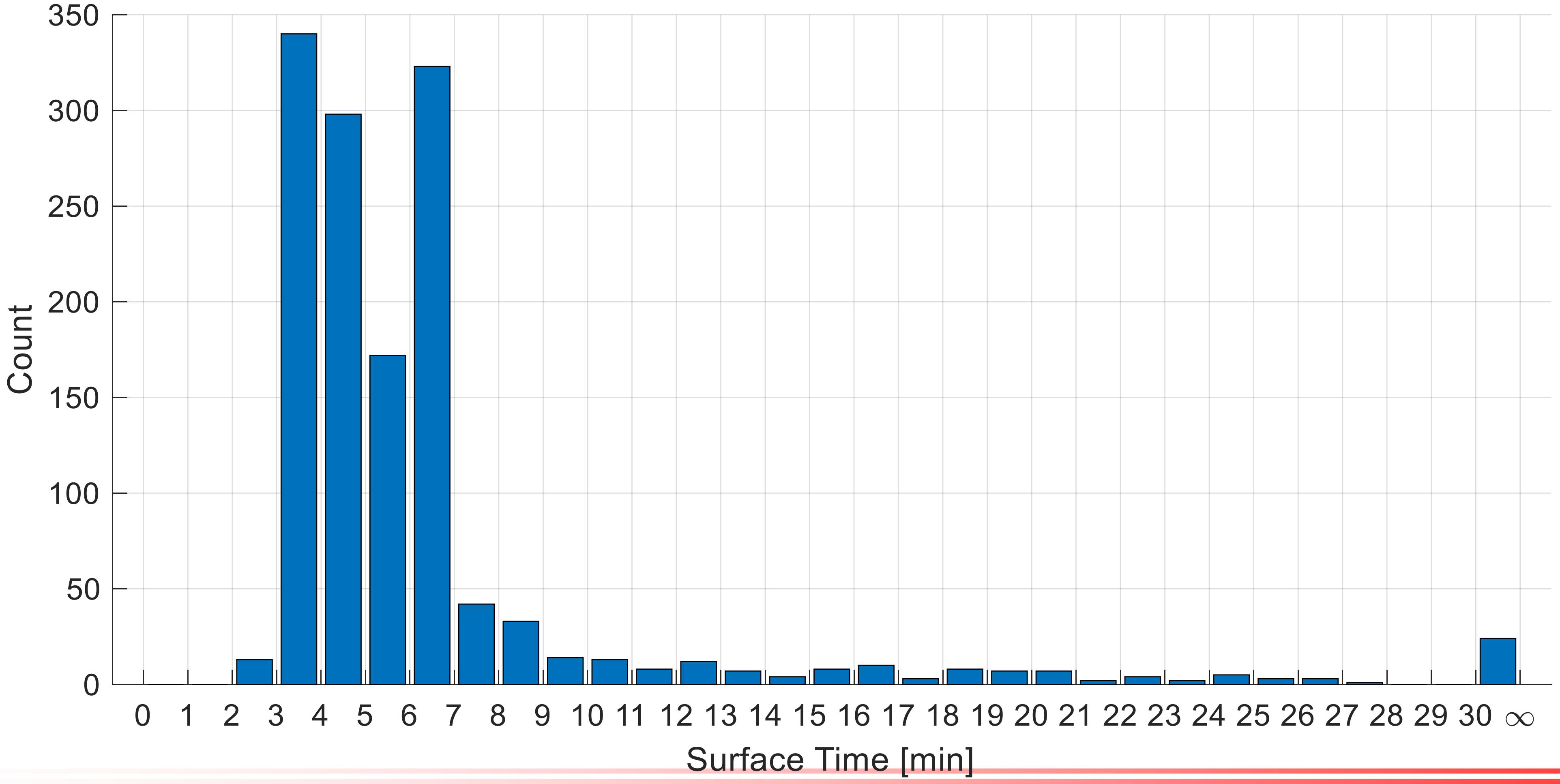
- Why do we not see 100% surface usage in the previous queueing model run for a surface limited vertiport?
- Partial timeline slots can be left behind on the vertipad or parking space timelines due to random surface times and arrival/departure times



- This can be expected in a first-come, first-served scheduler, or one where little to no optimization is used
- Note that an on-demand mode may make optimization difficult

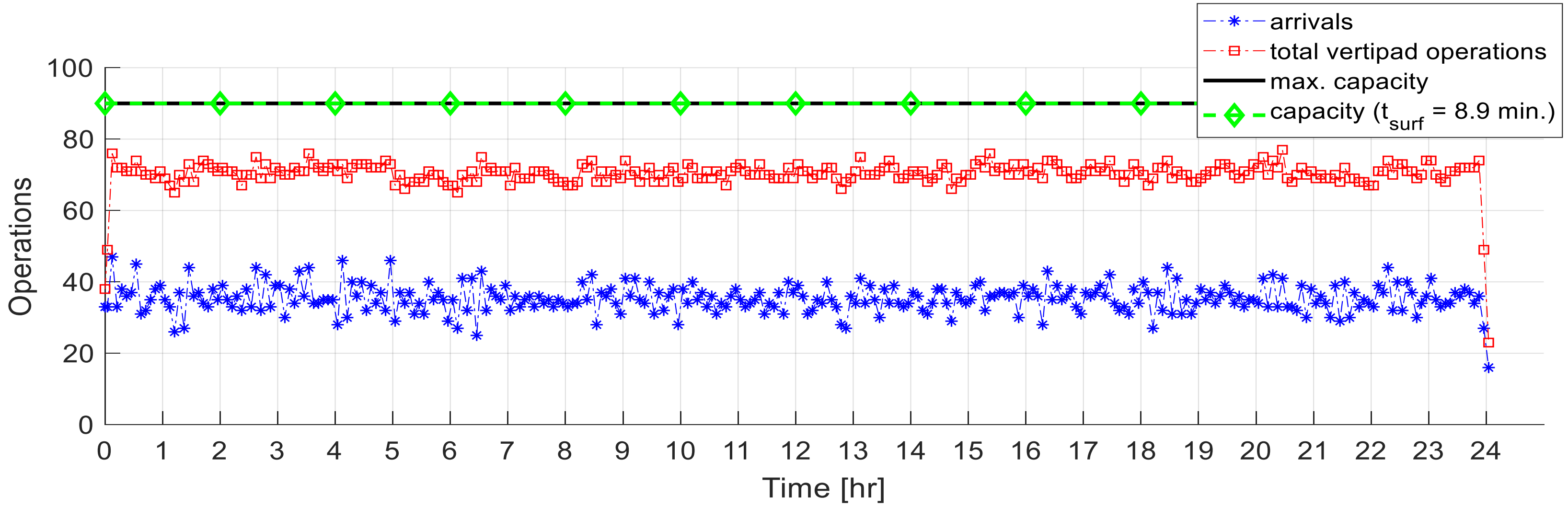
Observed Surface Distribution

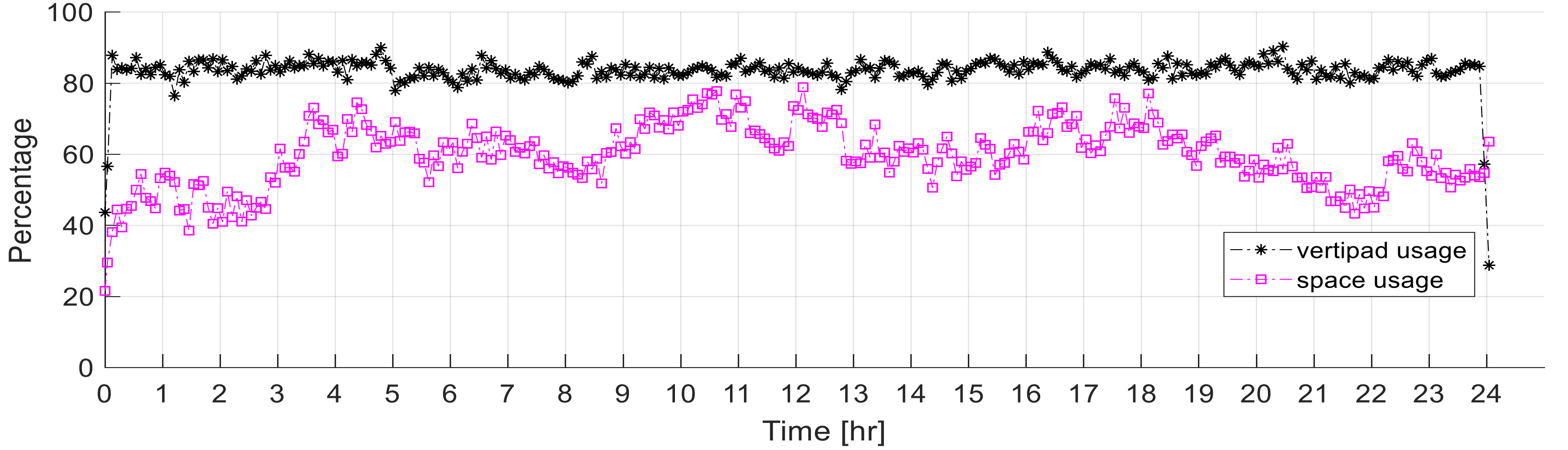
- What if the surface distribution were not uniform?
- Observed surface distribution at DF4 (average surface time = 9.4 minutes) from the simulation model run



DF4 Throughput - Observed Surf. Time Dist.

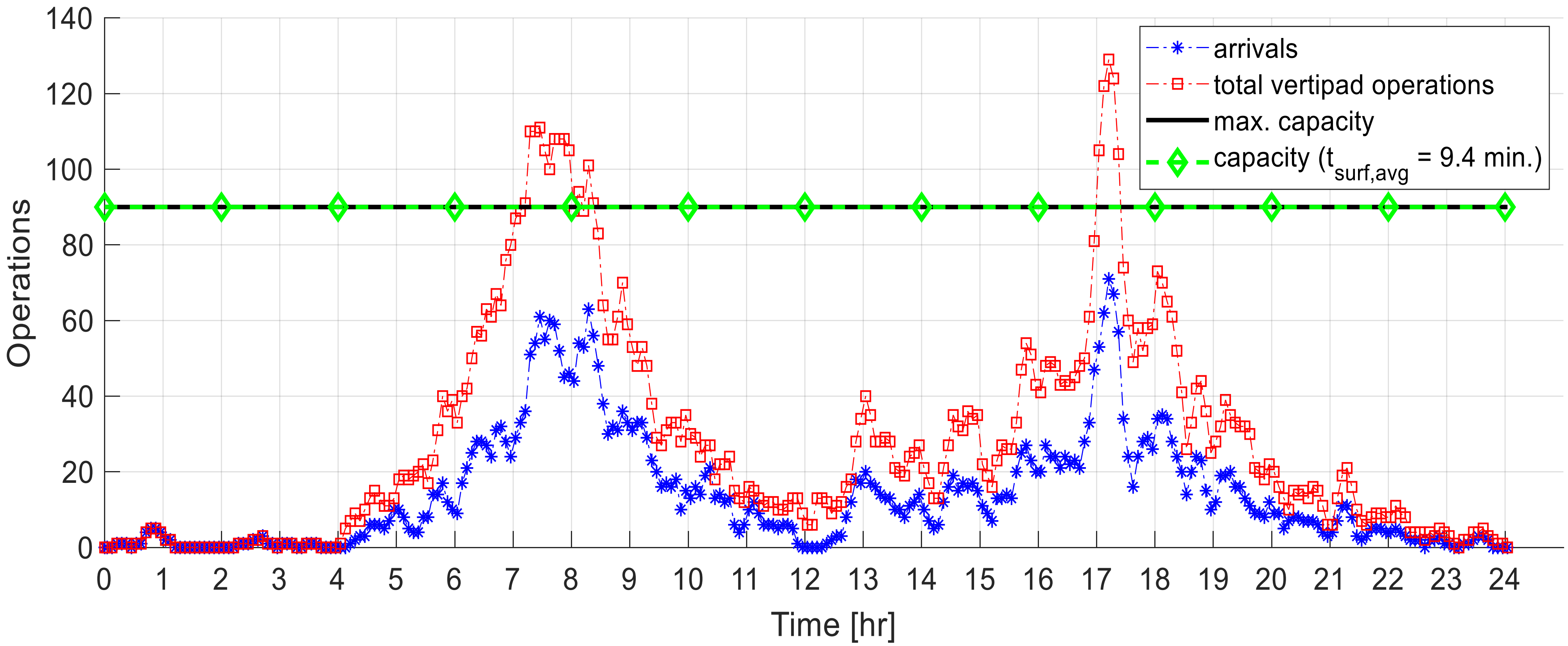
- DF4:
  - 6 vertipads
  - 38 parking spaces
- **Queueing model** using **observed** surface time distribution (9.4 min. avg.)
  - **NOW** we expect vertipad limited
- Maximum capacity = **90** ops./15-min.
- Nominal Capacity = **90** ops./15-min.
- Observed throughput average ~ **70.5** ops./15-min. (~22% less than capacity)
- Vertipad usage ~ **83.8%**
- Space usage ~ **60.9%**





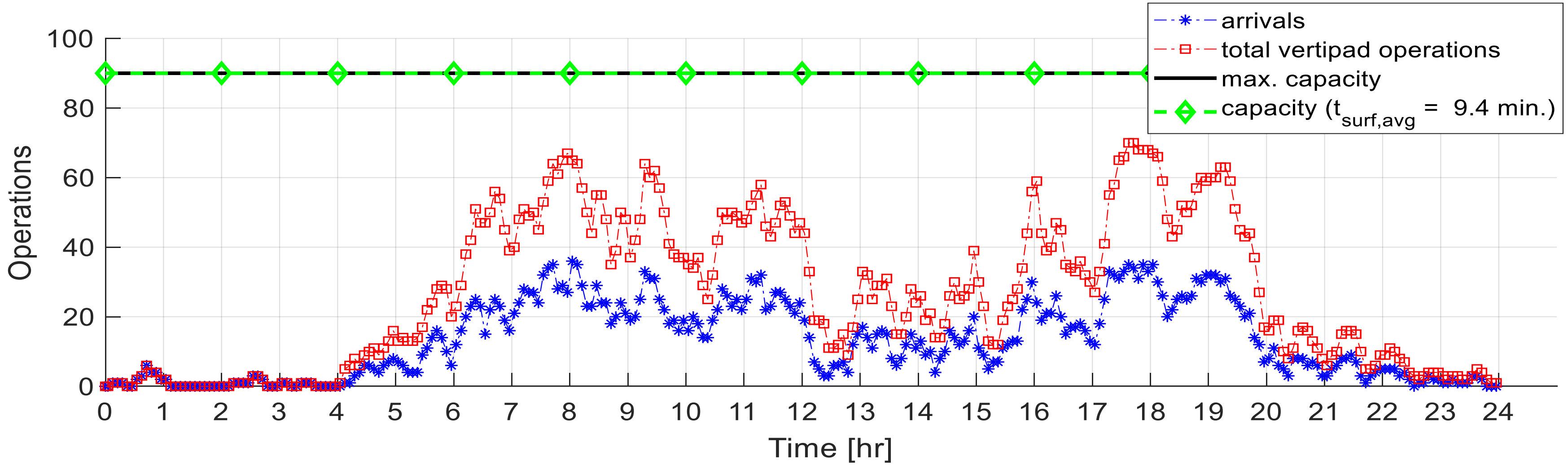
DF4 Demand in Simulation Model

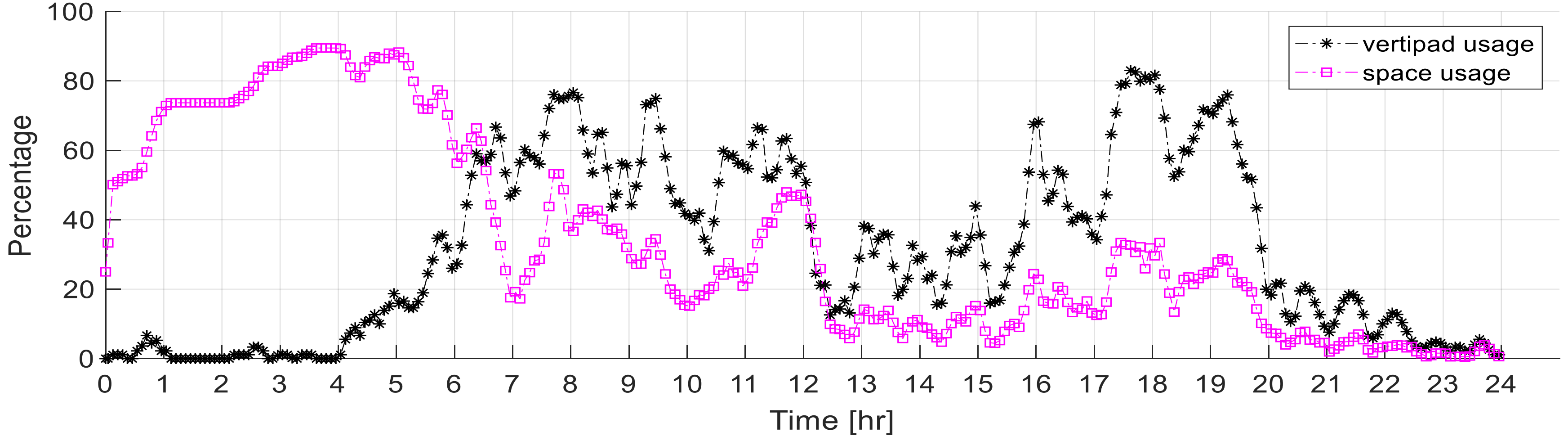
- Un-impeded demand at DF4 exceeds expected capacity in morning and afternoon peaks
- Un-impeded demand includes the repositioning/clearing flights



DF4 Throughput in Simulation Model

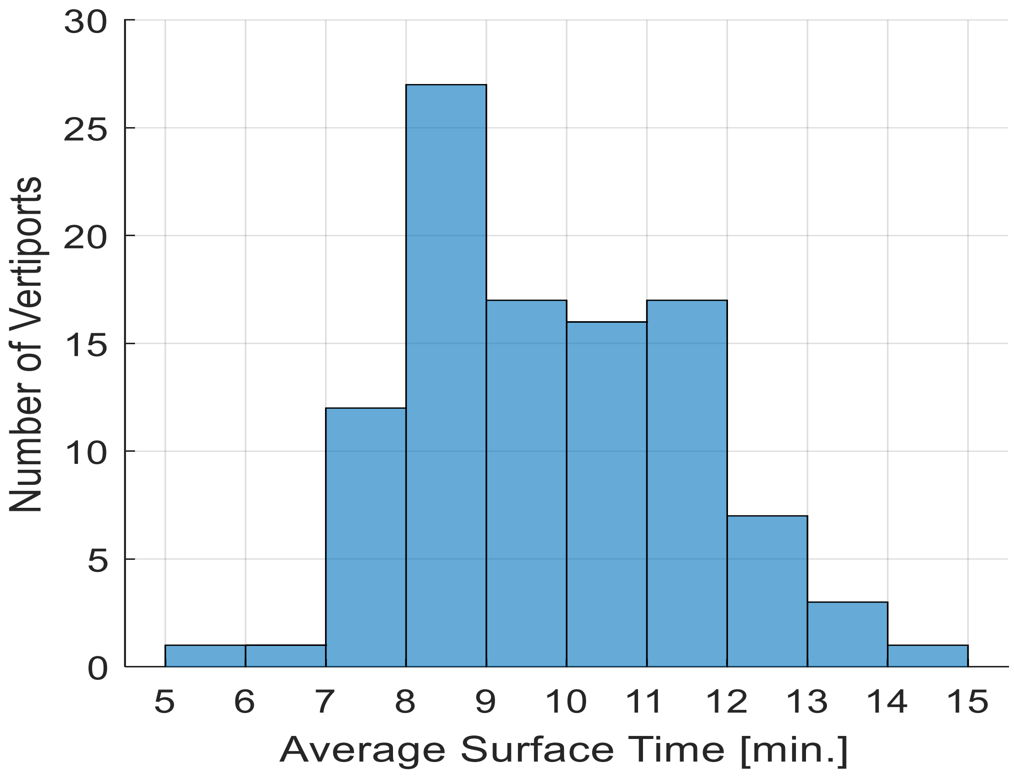
- The demand peaks are reduced by delays due to vertiport availability
- **Simulation model** produces the **observed** surface time distribution (9.4 min. avg.)
  - Vertiport is vertipad limited
- Maximum capacity = **90** ops./15-min.
- Nominal Capacity = **90** ops./15-min.
- Observed ***peak*** throughput is **70** ops./15-min. (~22% less than capacity)
- Vertipad ***peak*** usage is **83.0%**
- Space ***peak*** usage ~ **52%** after 7 A.M.
- Multiple factors contribute to reduced throughput compared to queueing model (e.g., fleet constraints, other end vertiport constraints)

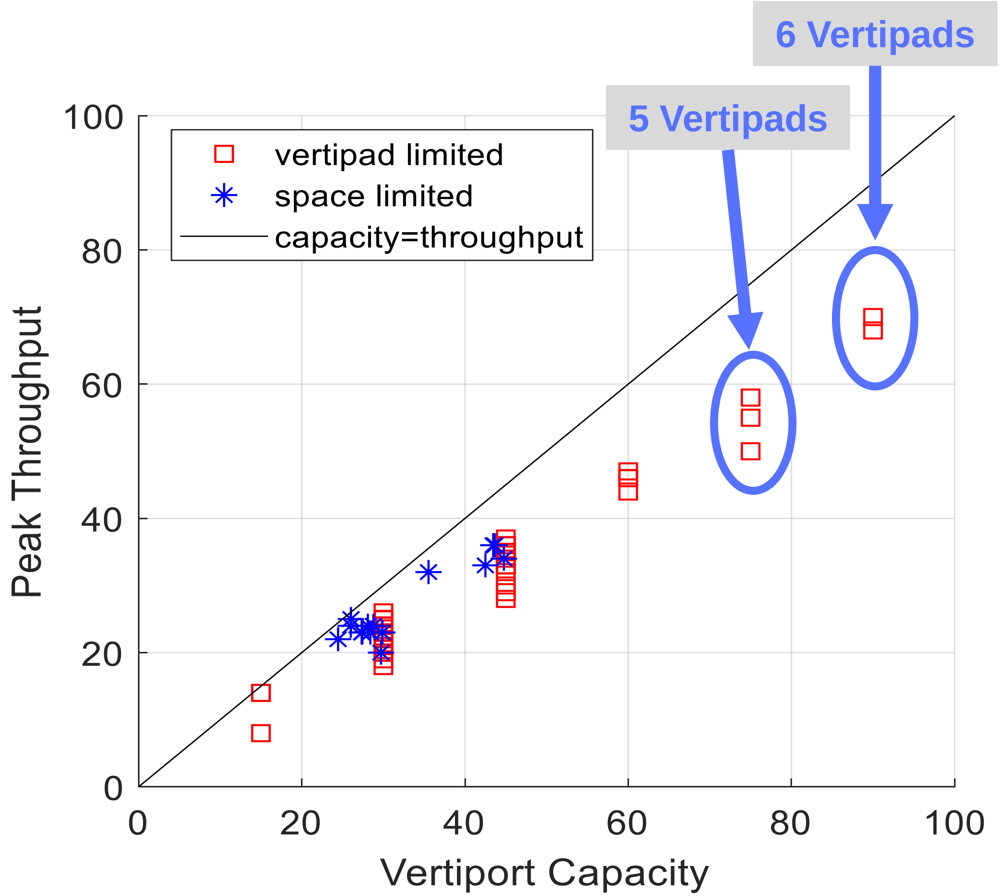




All Vertiports – Simulation Model

- All vertiports had average surface times less than 15 minutes
- Peak throughputs show an increasing loss of efficiency as the number of vertipads increases





Conclusions

Conclusions

- Investigated the capacity and throughput of vertiports under different configurations using the Vertiport Scheduler algorithm
  - Developed theoretical model that provided:
    - A way to estimate the required parking spaces for a vertiport
    - A way to estimate if a vertiport configuration is surface or vertipad capacity limited
  - Analyzed the throughput of vertiport configurations using
    - Queueing model
    - Simulation model
  - Results showed:
    - Resources can be under-utilized due to FCFS or non-optimized scheduling
    - A multi-vertiport simulation model can reveal throughput dependencies not observed in the single vertiport queueing model

- Next Steps:
  - Consider the observed resource usage percentages in future scenarios and analyses
  - Explore alternative algorithms for vertiport scheduling

Thank You

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