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ANALYSIS OF THEIR SENSITIVITY TO TOPOLOGICAL AND
OPERATIONAL FACTORS**

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Development of Vertiport Capacity Envelopes and Analysis of Their Sensitivity to Topological and Operational Factors

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This study develops an Integer Programming (IP) approach to analytically estimate vertiport capacity envelopes. The approach is used to determine the sensitivity of vertiport capacity to the number and layout of touchdown and liftoff pads, taxiways, gates, and parking pads (i.e. the vertiport topology). The study also assesses the sensitivity of vertiport capacity to operational parameters including taxi time, turnaround time, pre-staged aircraft, and approach/departure procedure independence, among others. Findings indicate the importance of balancing the number of touchdown and liftoff pads with the number of gates to achieve maximum aircraft throughput per vertiport footprint. Furthermore, simultaneous paired arrivals or departures provide significant throughput gains without the need for fully independent approach and departure procedures. The methodology and findings introduced in this paper support the development of concepts of operation to maximize throughput for a given vertiport footprint and demand scenario. While throughput has been extensively researched for fixed-wing operations, little research has been dedicated to the operation of infrastructure for Vertical Takeoff and Landing (VTOL) aircraft. The emergence of new VTOL aircraft to conduct a potentially large number of urban air mobility operations creates a need to better understand the operation and throughput capacity of vertiports, especially in space constrained inner-city locations. This paper reviews numerous existing heliport designs to derive four topology classes of vertiport layouts. The IP formulation of vertiport operations is readily adapted to represent the infrastructure and operations of these layouts.

I. Introduction

URBAN Air Mobility (UAM) is a concept that proposes to develop short-range, point-to-point transportation systems in metropolitan areas using Vertical Takeoff and Landing (VTOL) or Short Takeoff and Landing (STOL) aircraft. Proponents of UAM anticipate that advancements in electric aircraft, automation, and telecommunications driven by unmanned aircraft and automobile applications may support the introduction of prototype systems and service networks as soon as 2020. However, systems-level analysis of potential UAM operations identified eight constraints that may hinder the implementation or scaling of these systems [1].

This paper focuses on the “Takeoff and Landing Area (TOLA) availability” constraint of Ref. [1] which was proposed as the “greatest operational barrier to deploying [UAM] in cities” in the 2016 Uber white paper [2]. In order to support a viable UAM system, TOLAs such as airports, heliports, or vertiports³ must be strategically located in proximity to areas of user demand and have sufficient aircraft and passenger throughput to support at-scale UAM operations [3].

Significant research has been conducted to address the siting challenge of vertiports. Seventeen studies were funded in the U.S. and Canada as part of the Civil Tiltrotor (CTR) program in the late 1980’s and early 1990’s that found significant variance in the ability of cities to locate vertiports as a function of available space, economics, and public

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³ The findings of the paper are relevant to the underlying concept of UAM TOLA operation, independent the naming convention used. A variety of VTOL or STOL infrastructure could support UAM operations including heliports, vertiports, skyports, skyparks, STOLports, pocket airports, airparks, metroparks, nodes, air harbors, and portals.

acceptance [4]. Georgia Tech developed an integer programming approach to determine optimal vertiport placement based on customer demand [5] and also identified substantial siting opportunities for STOL infrastructure with runways of 300 ft or less in the Miami metropolitan area [6]. MIT corroborated significant opportunity for UAM infrastructure on rooftop facilities if footprints of less than 300 ft could be achieved [7]. Finally, MIT and NASA explored opportunities for vertiport placement in Los Angeles and San Francisco, respectively [8,9].

In addition to their location, vertiports must also be capable of sufficient aircraft and passenger throughput to support the operational tempo of an at-scale UAM system that far exceeds traditional heliport capabilities. Uber has proposed that by 2025 their network may have 300-500 aircraft conducting up to 27,000 flights per day between 10 vertiports in Dallas [10]. This would correspond to an average of 338 movements per vertiport per hour over a 16 hour day; peak loads would be larger, however. Researchers at NASA simulated an even more dense UAM network with 15,000 flights per vertiport per day equating to an average demand of 1250 movements per vertiport per hour over a 24 hour day [11]. For perspective, Denver International Airport currently has the highest estimated throughput rate of 298 movements per hour [12], and Silverstone heliport holds the world record having achieved 4200 helicopter movements in 17 hours with a peak of approximately 600 movements per hour.

Providing reliable estimates of airport or vertiport throughput capacity is a critical component of flight scheduling and airline planning. By design, runway throughput is the limiting throughput factor of the air transportation system. Terminals, air traffic control, and flight scheduling are all designed around this capacity constraining measure [13]. While airport capacity profiles are routinely developed either analytically or empirically [14], they have not been developed for heliports or other VTOL-specialized facilities. The CTR program identified the need for a methodology to define vertiport capacity [15], and the FAA stated in 1997 that no advisory circular or material sufficiently addressed the question of estimating and maximizing vertiport capacity [16].

Considering this research gap and its renewed relevance with respect to proposed UAM operations, this paper develops an approach to analytically assess vertiport capacity profiles. The approach determines the maximum throughput for a given vertiport and the optimal operational scheme to achieve that throughput. The approach is generalizable to nearly any vertiport configuration. The capacity estimation approach is used to characterize relationships between various vertiport infrastructure design attributes (including the number of touchdown and liftoff pads, gates, and staging stands), the specific throughput that may be achieved, and the physical footprint that is required.

II. Study Scoping

This study is focused on vertiport throughput capacity and addresses the following three questions:

1. What infrastructure variables and operational parameters is vertiport throughput most sensitive to?
2. What infrastructure variables and operational parameters exhibit correlated influence on throughput?
3. What vertiport topologies maximize throughput for a given footprint and parameter scenario?

The *infrastructure variables* are physical attributes of vertiport design including the number of Touchdown and Liftoff (TLOF) pads, the number of aircraft gates, and the number of aircraft staging stands (i.e. parking spaces). The *operational parameters* represent the time required to complete specific operations such as taxiing, aircraft turnaround, or arriving and departing, among others. Various Concept of Operations (ConOps) policies concerning independent and dependent procedures are also considered as operational parameters.

For the purposes of this study, “vertiport throughput” refers to the number of aircraft movements (where a movement is an arrival or departure) that may be conducted at a vertiport in a given time period. Fig. 1 displays four system-level processes that may constrain vertiport throughput by limiting either aircraft or passenger throughput. A description of each of these four processes may be found in the appendix.

This paper focuses exclusively on the airfield capacity process of a vertiport. Airfield capacity has historically been the primary capacity bottleneck for commercial aviation operations and is anticipated to similarly constrain UAM. Furthermore, airfield infrastructure is expected to drive vertiport footprint sizing which influences where urban vertiports may be located. Finally, it is unclear how TLOF pads, taxiways, gates, and approach and departure procedures may be configured and managed to relieve airfield congestion.

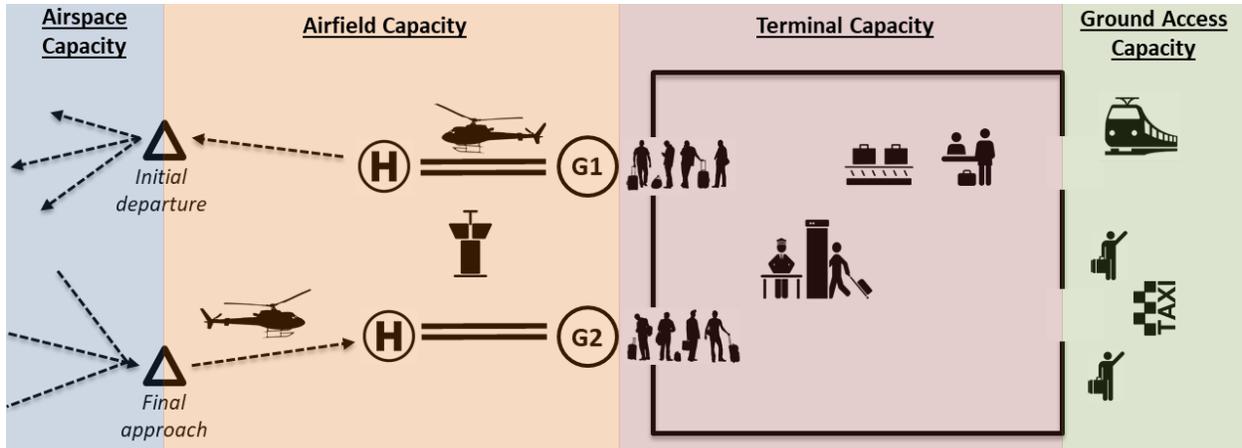


Fig. 1. Diagram of the four capacity limiting processes of vertiport (or airport) operation.

The remainder of this study assesses the achievable airfield capacity of a vertiport assuming that passengers are always available to load aircraft and unlimited passengers can disembark into the terminal (i.e. unconstrained terminal and ground access capacity). It is also assumed that aircraft are always ready to enter the final approach or can be accepted from the initial departure into the surrounding airspace (i.e. unconstrained airspace capacity).

III. Research Approach

Fig. 2 displays the approach taken in this paper to represent vertiport operations, analytically calculate deterministic capacity envelopes, and assess the sensitivity of throughput and footprint to various design and operational variables.

First, existing and historic heliports were reviewed to assess variation in operational concepts and topologies. Heliport design literature was also reviewed to determine recommended design, sizing, and spacing of heliport physical components. This information was used to develop a representative baseline ConOps for UAM vertiports. The ConOps was defined based upon the number and layout of the physical components of a vertiport (i.e. the *infrastructure variables*) as well as the various activities an aircraft may conduct at the vertiport (i.e. the *operational parameters*).

The second step of the study converted the generic vertiport ConOps into a node-link network model. The three vertiport infrastructure variables were cast as the nodes of the network. The six operational parameters were cast as either the links between the nodes, initial conditions, or model constraints. The network model constituted a compact representation of vertiport operations that could be handled mathematically.

The third step of the study developed an Integer Program (IP) of the vertiport network model. The IP determined optimal aircraft assignment to each link of the network at each time step with the objective of maximizing aircraft throughput. The IP was repeatedly solved to develop the capacity envelope of each vertiport considered. In addition to the capacity envelope for each vertiport, the utilization of each vertiport component and link was also determined. The IP was used to conduct a sensitivity analysis of vertiport throughput capacity to variations in the infrastructure variables and operational parameters.

The final step of the study reviewed implications of the sensitivity analysis results for each vertiport topology class identified in step 1.

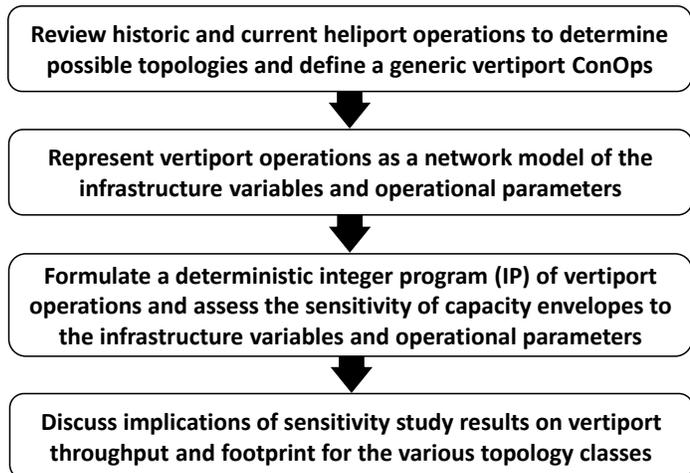


Fig. 2 Vertiport capacity envelope definition and sensitivity study approach.

IV. Review of Vertiport Operations and Development of a Generic ConOps

A representative ConOps was defined that included the key infrastructure elements and operations of a vertiport. This generic ConOps was required to be flexible enough to consider common variations in vertiport physical layout and operational procedures. To identify the infrastructure variables and operational parameters that were to be included in the ConOps, existing heliport operations were reviewed, relevant heliport design literature was evaluated, and helicopter pilots were interviewed.

A. Review of Existing Heliport Operations

While none of the electric Vertical Takeoff and Landing (eVTOL) aircraft proposed for UAM are currently in commercial operation, helicopters routinely conduct UAM missions and are an effective proxy for future UAM services. Adopting this assumption, 27 high throughput capacity heliports were reviewed to assess different physical topologies of vertiports, the movement of aircraft among the various infrastructure components, and the footprint the facilities require. Through this analysis four “classes” of topologies with unique properties were identified. The authors sought to relate the vertiport topology classes to the airport layout literature by using similar names as presented in Ref. [17] to describe related topology concepts. This was done by considering the TLOF pads as akin to airport runways, the gates akin to gates, and the staging stands akin to aprons, hangars, or ramps.

Table 1 displays the heliports reviewed in this analysis. Key infrastructure variables of each facility and its topology classification are listed. The 27 high-capacity heliports selected for this study had readily available information, displayed a range of topologies, or had been proposed as examples of infrastructure that could serve UAM systems. Further attributes of each topology class are introduced in the following sub-sections.

Table 1 Heliport topology review.

Heliport	TLOF Pads	Gates	Staging Stands	Topology Class
Dallas Downtown Public Heliport, TX	2	5	0	Satellite
Monaco Heliport	8	0	14+	Linear
Los Angeles Hooper Heliport, CA	2	16	0	Pier
Haungzhuangcun Air Base, China	44	40	80+	Remote Apron
Los Angeles Airport Heliport (2015), CA	2	8	0	Pier
Portland Downtown Heliport, OR	1	4	0	Satellite
Silverstone Heliport (2018), England	10	0	0+	Linear
Downtown Manhattan Heliport, NY	1	13+	0	Pier
Manhattan East 34 th St. Heliport, NY	4	0	0	Linear
Manhattan West 30 th St. Heliport, NY	10	0	2+	Linear
NYPD Air Operations Heliport, NY	1	4+	9+	Pier
Helo Holdings Inc. Heliport, NJ	2	6	22+	Pier
Dempsey Army Heliport (1977), TX	12	500	50+	Pier
Redmond Taylor AHP Heliport, TX	8	19	12+	Remote Apron
Dallas Cowboys Heliport, TX	1	2	0	Satellite
London Heliport	1	3	0+	Pier
Gagetown Heliport, New Brunswick	1	14	5+	Pier
Helicidade Heliport, São Paulo	2	11	80+	Satellite
Helipark Heliport, São Paulo	1	10	200+	Pier
Aeroporto Campo de Marte, São Paulo	1	82+	250+	Remote Apron
Auckland Heliport, New Zealand	4	0	7+	Linear
Balikpapan Airport, Indonesia	2	15	20+	Pier
Shimotsuma Heliport, Japan	1	2	20+	Pier
Northwest Helicopter Heliport, WA	1	16	30+	Pier
Airjamban Heliport, Indonesia	7	4	15+	Linear
Rohini Heliport, India	3	12	16+	Pier
Picacho Stagefield Heliport, AZ	4	16	0+	Pier

“+” indicates that additional non-marked, ad-hoc gates or staging stands may be available

1. Linear Topology

Fig. 3 displays the Monaco heliport. The heliport is laid out in a linear fashion with eight TLOF pads, no dedicated gates, and numerous staging areas in hangars and on tarmac. The TLOF pads are 75 ft apart. From operational videos it appears that helicopters will takeoff or land one at a time from the six upper TLOF pads and simultaneously from the two TLOF pads extended over the water. The linear topology can achieve high throughput due to the large number of TLOF pads, however throughput is reduced if independent approaches and departures are not possible. Furthermore, if no gates are associated with each TLOF pad, then vehicle turnaround operations must also be conducted on the TLOF pad decreasing throughput potential. The linear topology is most useful when vehicle turnaround times are short and where there is a thin but long available footprint, such as on a highway or railway right of way.

2. Satellite Topology

In the satellite topology, as represented by the Dallas downtown public heliport in Fig. 4, one or more TLOF pads are associated with gates distributed circumferentially around them. If multiple TLOF pads are present, they may or may not have independent approach and departure procedures. Furthermore, depending upon the direction of approach and departure, some gates underneath the flight path may not be available. The satellite topology is one of the most compact layouts and its form factor (roughly square) lends itself to potential implementation on rooftops and land parcels in urban and suburban gridded areas, as was the case for the Helicidade Heliport in São Paulo.

3. Pier Topology

In the pier topology one or more TLOF pads feed aircraft into a potentially long corridor of gates. The pier concept may be beneficial for facilities that expect to have longer vehicle turnaround times or desire to stage multiple aircraft onsite as they can physically accommodate more gates and aircraft than the satellite layout. Fig. 5 displays the Hooper Heliport in Los Angeles which is located on top of a parking facility and is the largest rooftop heliport in the world.

4. Remote Apron Topology

The final vertiport layout identified is the “remote apron” topology. This defining feature of this topology is that the TLOF pad(s) is located separately from the gates and may require significant ground or hover taxiing between the two. This topology potentially supports simultaneous takeoffs and landings by allowing greater separation between TLOF pad procedures. The remote apron concept requires a significant footprint to implement, but may not necessitate this footprint to be improved as vehicles may hover taxi over unimproved areas. Furthermore, it may provide opportunities to reduce noise exposure to communities. The remote apron topology also may advantageously support vertiport integration at airports by allowing VTOL aircraft to land or depart beyond the separation minima for the runways and then access the terminals via hover taxiing (with less restrictive separation requirements).

Fig. 6 displays the Aeroporto Campo de Marte in São Paulo and many of the features of the remote apron topology. Notice how the single TLOF pad in the upper left of the facility serves dozens of gates and staging stands through a single hover taxi way indicated by lights and a paved line in the grass.

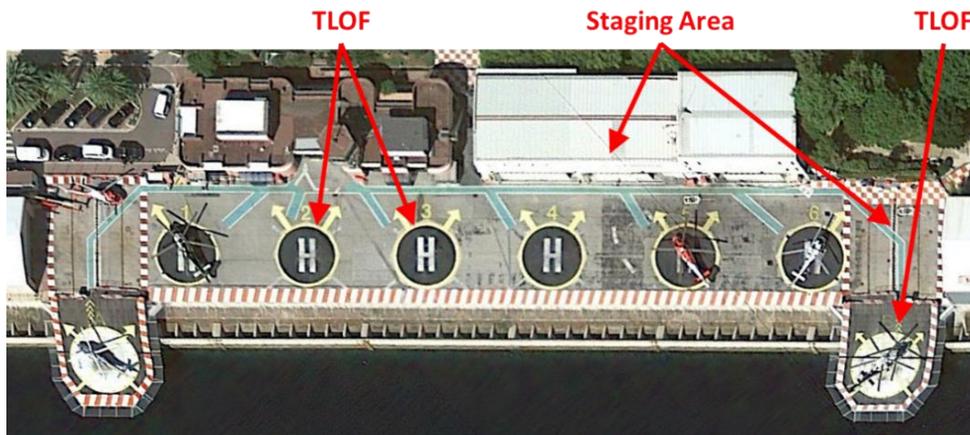


Fig. 3. Monaco heliport displaying attributes of a “linear” topology.
Map © 2018 Google. © 2018 DigitalGlobe.

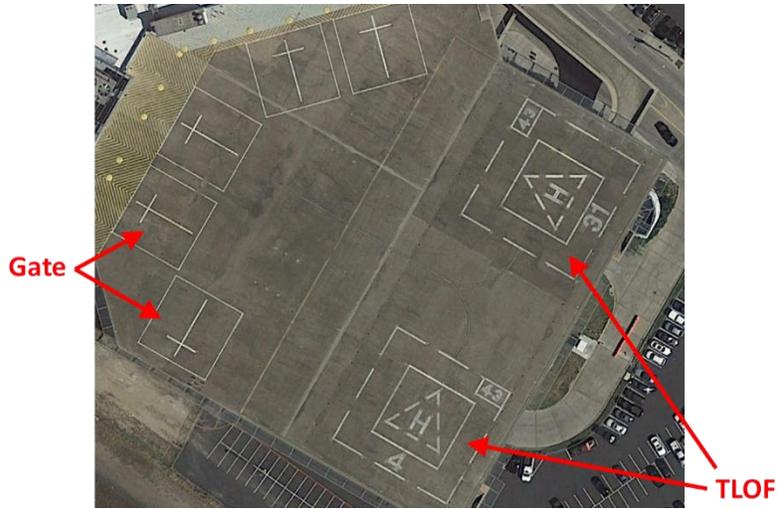


Fig. 4. Dallas downtown public heliport displaying attributes of a “satellite” topology.
Map © 2018 Google.

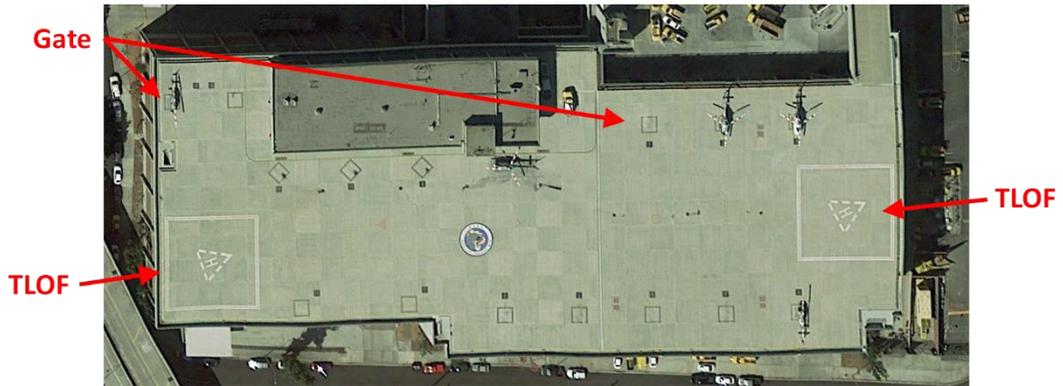


Fig. 5. Los Angeles Hooper Heliport displaying attributes of a “pier” topology.
Map © 2018 Google



Fig. 6. Aeropuerto Campo de Marte displaying attributes of a “remote apron” topology.
Map © 2018 Google. © 2018 DigitalGlobe.

B. Review of Heliport Design Literature

In order to assess design qualities of TLOF pads, gates, and staging stands, future UAM vertiports were assumed to have design requirements similar to those prescribed for general aviation, VFR heliports in AC 150/5390-2C. Current helicopter charter services operate as Title 14 of the Code of Federal Regulations (CFR)⁴ Part 135 certificate holders from general aviation heliports as long as they do not conduct scheduled passenger service [18]. While UAM services also anticipate operating as Part 135 operators, if these services are required to use “transport heliports” then infrastructure footprints may be larger than presented in this paper. UAM aircraft are assumed to be classified as “small helicopters” as most proposed vehicles have a maximum takeoff weight of less than 7001 lbs.

1. Touchdown and Liftoff (TLOF) Pad

For the purposes of this analysis, a TLOF pad consists of one or more viable approach/departure paths, a final approach and takeoff area, a touchdown and liftoff area, and a safety area as defined below based upon recommendations from AC 150/5390-2C [18]. A summary of the TLOF pad properties are displayed in Fig. 7.

- **Touchdown and Liftoff Area (TLOF):** “A load-bearing, generally paved area... on which the [aircraft] lands and/or takes off.” While this area traditionally has a minimum length and width of one rotor diameter for helicopters, for emerging multirotor aircraft the rotor diameter may be quite small. Therefore, the minimum length and width of the TLOF was assumed to be one “tip-to-tip span” (previously called “rotor span in the retired FAA AC on vertiports) which is defined as “the span (distance) between the extreme edges of the plane(s) generated by spinning rotors or proprotors” [19]. Note that tip-to-tip span was not defined to include propellers that do not provide vertical lift; an example is shown in Fig. 8.
- **Final Approach and Takeoff Area (FATO):** “A defined area over which the pilot completes the final phase of the approach to a hover or a landing and from which the pilot initiates takeoff.” There is one FATO centered above every touchdown and liftoff area. Although AC 150/5390-2C currently has a more complex formula for FATO size concerning helicopter overall length and rotor diameter, because emerging eVTOL aircraft may have rotor spans greater than, equal to, or less than their overall length, this study (conservatively) assumed the FATO width and length must be 1.5x the largest dimension of the vehicle. Furthermore, this study ignored required increases in FATO size that occur for facilities located above 1000 ft MSL.
- **Safety Area:** “A defined area on a heliport surrounding the FATO intended to reduce the risk of damage to helicopters accidentally diverging from the FATO.” There is one safety area per TLOF pad and it extends beyond the edge of a FATO for the larger of 20 ft or 1/3 rotor spans (for a fully marked pad).
- **Approach/departure path:** “The flight track helicopters follow when landing at or departing from a heliport. The approach/departure paths may be straight or curved.” Multiple approach/departure paths to a single TLOF pad are always dependent, while paths to different TLOF pads at the same vertiport may or may not be dependent. An approach/departure path must be clear of obstacles spanning from the edge for the FATO sloping upward at an 8:1 slope for 4000 ft. The width of the approach/departure surface expands linearly from the width of the FATO to 500 ft. Finally, transitional surfaces extend outward at a slope of 2:1 from the FATO edges and the edges of the approach/departure surface out to 250 ft from the path centerline.

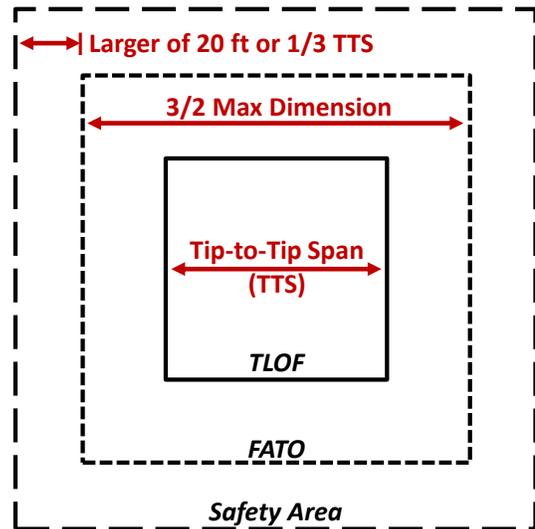


Fig. 7. TLOF pad design elements and dimensions.

⁴ All Title 14 references in this paper were from the electronic Code of Federal Regulations, <http://www.ecfr.gov>, retrieved from the version updated May 5, 2018.

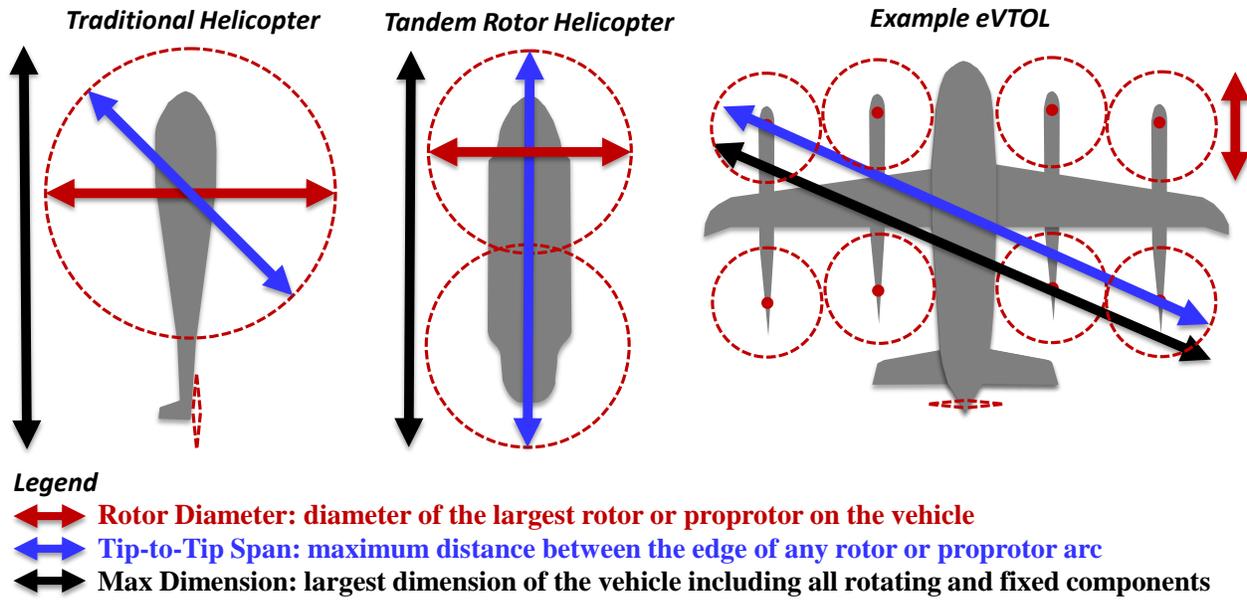


Fig. 8. Vertiport design measurements for example eVTOL aircraft.

Only one aircraft is allowed to reside within a FATO, TLOF pad, or safety area (whether airborne or on the surface) at a time [18]. According to FAA Joint Order 7110.65W, Section 3-11-5, aircraft may conduct simultaneous landings or takeoffs for TLOF pads with centerlines that are separated by at least 200 ft [20]. However, interviews with two helicopter pilots from the U.S. Marine Corps and U.S. Army indicated that the military conducts simultaneous operations at TLOF pads 150 ft apart, and even formation operations to/from TLOF pads 75 ft apart. While it is unclear if this reduced separation would be possible for UAM due to the passenger carrying formation flight restriction in CFR §91.111, large commercial jets have set a precedent for simultaneous arrivals to closely spaced parallel runways.

Based upon the review of seven proposed 2-6 passenger eVTOL aircraft displayed in Table 2, the maximum dimension of any of the vehicles was 45 ft. Furthermore, 45 ft was also the maximum allowed dimension proposed by Uber in their ConOps⁵. Adopting this sizing assumption, TLOF, FATO, and safety area diameters of 45, 68, and 88 ft, respectively, are reasonable sizing estimates for future UAM vertiport components.

Table 2 Review of seven proposed 2-6 passenger eVTOL aircraft.

Vehicle	PAX	Configuration	Tip-to-Tip Span (ft)	Body Dimension (ft)	Max Dimension (ft)
A ³ Vahana Beta	2	Tile Wing	28.5 <i>est.</i>	20.6 (wingspan)	28.5
AirSpaceX MOBi	4	Tilt Wing	40	40 (wingspan)	40
Carter Air Taxi	6	Compound Heli	45	42 (wingspan)	45
Joby S4	4	Tilt Rotor	43 <i>est.</i>	35 (wingspan)	43
Aurora (June 2017)	2	Lift + Cruise	29.2 <i>est.</i>	26.2 (length, wingspan)	29.2
Kitty Hawk Cora	2	Lift + Cruise	33.5 <i>est.</i>	35 (wingspan)	35
Volocopter 2X	2	Multirotor	32 <i>est.</i>	30 (superstructure)	32

2. Gates and Taxiways

The second infrastructure variable considered in this analysis is the number (and layout) of gates. In addition to the physical footprint required for gate operations, gate placement at a vertiport is influenced by taxiway design requirements and minimum separation distances from TLOF pads and other gates.

There are two types of taxiways defined by the FAA. The first is a “ground” taxiway where aircraft equipped with wheels are either self-propelled or tugged along a hardened surface. The second is a “hover” taxiway (also referred to

⁵ <https://s3.amazonaws.com/uber-static/elevate/Summary+Mission+and+Requirements.pdf>

as an “air” taxiway) where a hover-capable aircraft may move above the surface with a recommended “wheel/skid height of 1 to 5 feet and at a ground speed of less than 20 knots” [18].

A “taxi route” includes the taxiway plus the required clearances on each side of the taxiway. The minimum dimensions of a hover taxi and ground taxi route are 2 and 1.5 rotor diameters (tip-to-tip spans) of the design aircraft, respectively. Furthermore, previous studies determined that hover taxiing exposes passengers to greater rotorwash and requires more energy expenditure (which is especially challenging for electric aircraft). Ground taxiing was recommended for high throughput, public vertiport operations [21,22]. Uber has also adopted a ground taxi requirement⁶.

Vertiport gates (referred to as “parking positions” in the FAA heliport literature) must be sized to provide a minimum obstruction-free area for aircraft maneuvering and parking. Although current standards prescribe slight variations in gate sizing based upon how the gate is accessed (i.e. a “turn around”, “taxi-through”, or “back-out” gate), this research assumes gates have a diameter equal to the maximum vehicle dimension plus either 10 ft for ground taxi operations, or the greater of 10 ft or 1/3 rotor span for hover taxi operations.

No object, building, safety area, or other parking position may reside within a gate’s protected diameter. Furthermore, no taxi route (except for the one leading to the gate) may come within 1/3 tip-to-tip span of a “turn around” or “taxi through” gate, or 1/2 tip-to-tip span for a “back-out” gate. Aircraft cannot use gates that are under the active approach/departure surface(s). Furthermore, previous research of commuter air carrier ramp operations found that procedures did not allow passenger boarding or deplaning from the tarmac if a propeller was turning on any aircraft within 200 ft [23]. To date this restriction has not been applied to heliport operations, however future commercial vertiports may or may not find such a restriction appropriate.

Fig. 9 displays the key sizing and spacing attributes used in this analysis for vertiport gates and taxiways for both hover and ground taxi operational ConOps. Please note that there are minor variations between the dimensions proposed in Fig. 9 and those currently applied to heliports in AC 150/5390-2C. These variations were made for simplicity as well as to accommodate differences between helicopters and emerging eVTOL aircraft.

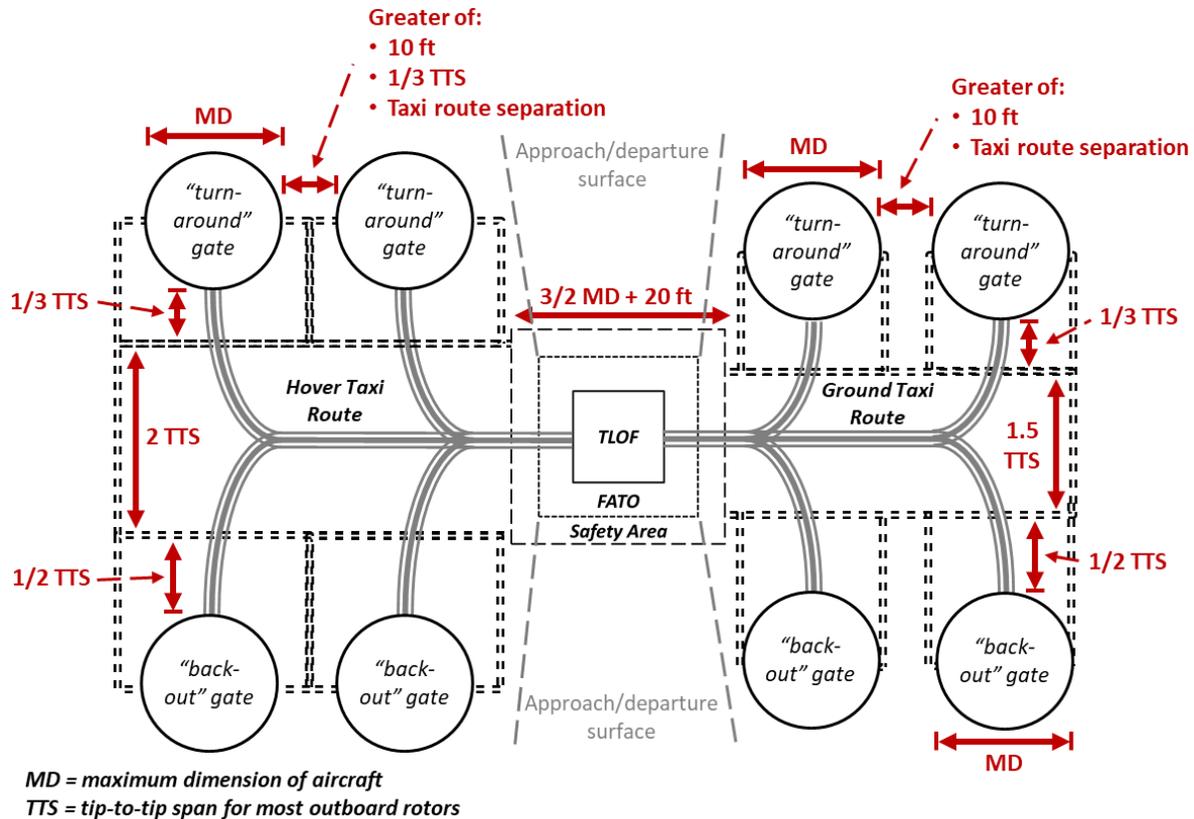


Fig. 9. Sizing and spacing attributes assumed for vertiport gates and taxiways

3. Staging Stands

The final infrastructure variable is the number of staging stands that a vertiport is outfitted with. Staging stands, unlike gates, are areas where an aircraft may be parked and perhaps serviced (charging, fueling, maintenance, etc.) but where no passenger activities may happen. Staging stands may take the form of hangars, aprons, fields, or other possible spaces where aircraft may be parked. Staging stands that are accessed directly by an aircraft through rotor-powered taxiing have the same footprint requirements as a gate. Staging stands where aircraft are moved into or out of via a tug or wheel driven taxiing may have significantly reduced footprint requirements on the order of the vehicle footprint.

4. Heliport Design Literature Summary

The key findings from the review of heliport design standards include:

- Based upon current UAM vehicles, TLOF pads will require an approximately 90 ft by 90 ft physical footprint plus at least one unobstructed approach/departure path. Only the central 45 ft by 45 ft section of the TLOF pad must be lead bearing (or even a physical surface).
- Ground taxiways require a smaller footprint and reduce hazards from rotorwash compared to hover taxiways.
- “Turn-around” gates require a smaller total footprint (considering spacing and packing requirements) than either “taxi through” or “back out” gates.
- Gates accepting hover taxiing aircraft require a similar footprint to that of a TLOF pad; gates accepting only ground taxiing aircraft require marginally less footprint than either.
- Staging stands are more space efficient than gates for parking aircraft.

C. Generic Vertiport ConOps

Fig. 10 displays the representative ConOps defined for a generic UAM vertiport based upon the interviews, empirical analysis of current operations, and review of heliport standards presented above.

Aircraft are held in an arrival queue until authorized to conduct the final approach. Aircraft then arrive to one or more TLOF pads through the use of one or more approach procedures. If the vertiport is equipped with gates, then the aircraft may taxi off the TLOF pad to an available gate; if no gates exist or are available then it may be possible to conduct aircraft turnaround on the TLOF pad. A minimum turnaround time is required to complete a variety of activities potentially including unloading passengers and baggage, fueling (recharging) the aircraft, cleaning the cabin and replenishing consumables, and loading new passengers and luggage. Once the turn has been completed the aircraft may taxi to the same or a different TLOF pad and depart. If staging stands are available (in addition to the gates), then aircraft may also be prepositioned there and deployed, or aircraft may be extracted from service to the staging areas. Although not indicated in this high-level ConOps, landing and departure procedures, TLOF operations, and gate operations may or may not be independent of one another.

V. Deterministic Integer Program of Vertiport Operations

After considering a variety of modeling options, an Integer Programming (IP) formulation of vertiport operations was selected to develop throughput capacity envelopes and efficient operational schemes. Queuing theory and agent-based simulation were also considered, however an IP formulation provides the greatest insight into the operations, requires the fewest assumptions, and was guaranteed to find optimal solutions for the given conditions.

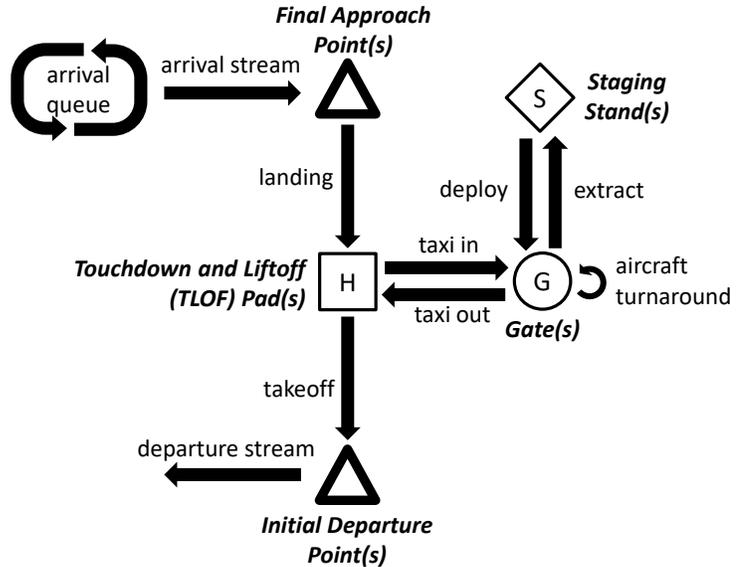


Fig. 10 Generic vertiport ConOps displaying operational interactions between the infrastructure variables.

A. Infrastructure Variable & Operational Parameter Definition and Bounding

Infrastructure variables represent the physical components of a vertiport. Three key infrastructure variables were considered in this analysis:

- 1) TLOF Pads: “touchdown and liftoff” pads are the marked location to which an aircraft conducts its approach, or from which it conducts its departure. An aircraft does not necessarily actually touch down or lift off at this location, such as when it is transitioning to/from a hover taxi. Vertiports with one to three TLOF pads were considered in this analysis.
- 2) Gates: locations distinct from TLOF pads where aircraft may taxi to and conduct various tasks such as passenger/luggage unloading and loading, charging, and consumable replenishment. Vertiport topologies with zero to 12 gates were considered in this analysis.
- 3) Staging Stands: locations distinct from TLOF pads and gates where aircraft without passengers may taxi to and park. Staging stands do not provide any relevant services to “turn” the aircraft (passenger services, refueling, etc.), although the stand could represent a maintenance hangar, for example. Vertiport topologies with zero to nine staging stands were considered in this analysis.

Operational parameters represent the activities of aircraft on or near vertiports. Some operational parameters define the time required to complete a specific task, while others define rules for which tasks may be conducted simultaneously, and yet other define the initial conditions at the vertiport (such as the number of pre-staged aircraft).

Based upon the generic vertiport ConOps presented in Fig. 10, seven operational parameters were defined for this analysis. Through the interviews and observations of high-capacity heliport operations, upper and lower bounds for each parameter were set for testing in the sensitivity analysis.

- 1) Arrival Time: the time required for an aircraft to proceed from the final approach fix, alight on or hover above the TLOF pad, and taxi to the edge of the TLOF pad safety area. Arrival times between 15s and 90s were considered in this analysis.
- 2) Departure Time: the time required for an aircraft to taxi onto the TLOF pad from immediately outside the safety area, liftoff, and reach the “initial departure point” which is defined in this research as the point at which another aircraft may enter the TLOF pad safety area for the next departure or pass the final approach point on arrival. Departure times between 15s and 90s were considered in this analysis.
- 3) Gate Taxi Time: the time required to taxi from the edge of the TLOF pad safety area to the edge of the gate, or vice versa. Gate taxi times of 5s to 90s were considered in this analysis.
- 4) Staging Stand Taxi Time: the time required to taxi from the edge of the gate to the staging area, or vice versa. Staging stand taxi time from a gate to the staging stands was defined in this analysis as the minimum of either 90s or half the turnaround time of the aircraft (to represent the requirement to unload passengers at the gate before proceeding to the staging area) plus the gate taxi time. Taxi time from the staging stands to the gate was assumed to be the same as the taxi time from the TLOF pad to the gate.
- 5) Turnaround Time: the time required at each gate to park the aircraft, spin down the rotors (if necessary), conduct various tasks such as passenger/luggage unloading and loading, charging, etc., and then exit the gate area. Turnaround times of 30s to 600s were considered in this analysis.
- 6) Number of Pre-Staged Aircraft: the number of aircraft that are positioned at the vertiport (either at the gates or staging areas) before the study period begins. All pre-staged aircraft at the gates were assumed to be instantly prepared to taxi-out to the TLOF pad. Zero staged aircraft to the maximum number of staged aircraft supportable by the vertiport topology were considered.
- 7) Simultaneous Operations Policies: the policies dictating where and when simultaneous aircraft movements may occur at the vertiport. Seven different policies were considered that controlled the dependency of approach and departure procedures to nearby TLOF pads and the simultaneous use of taxiways. These policies are discussed in Section VI.C.

B. Network Flow Model of Vertiport Operations

The IP was developed for vertiport operations based upon the Bertsimas-Stock multi-commodity flow formulation proposed for traffic flow management [24]. This formulation began with the development of a generalized network flow model of vertiport operations. As a representative example, Fig. 11 presents the network flow representation of a vertiport with one TLOF pad, two gates, one set of approach and departure procedures, and at least one staging stand.

The representation is characterized by seven types of nodes representing the physical components of the vertiport and its airspace. These nodes are connected by arcs that represent actions an aircraft must complete to transition between the nodes. The “origin” and “sink” nodes represent aircraft entering the vertiport system from the arrival queue and departing the vertiport into the surrounding airspace system, respectively. Vertiports of dramatically different design and complexity may be represented through this network flow model notation by varying the number of each type of node and connecting arc to represent the topology and operations of the vertiport.

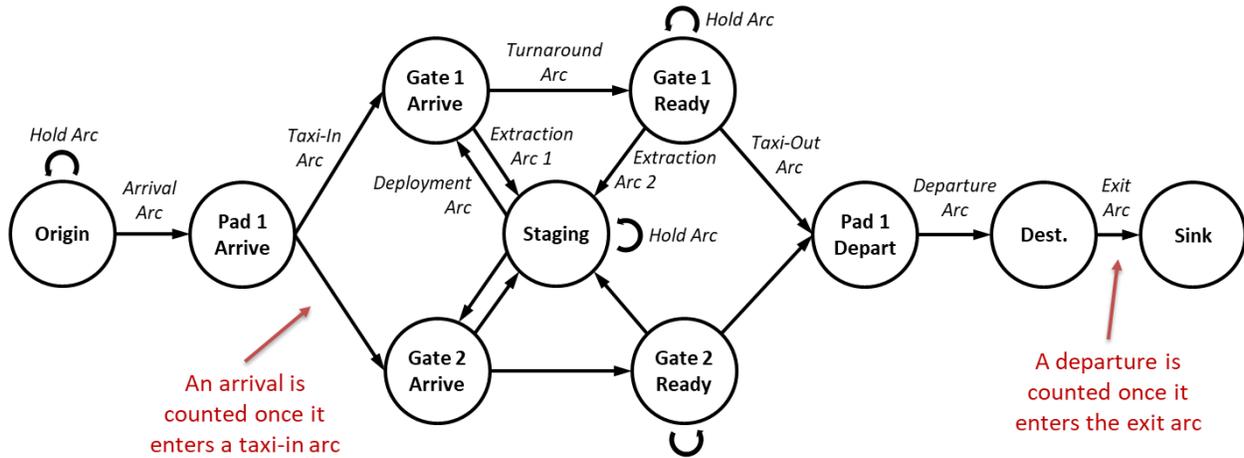


Fig. 11. Network flow representation of vertiport operations.

A few attributes and assumptions of the IP network flow model may be noted from Fig. 11. First, while the vertiport considered only has a single TLOF pad, two different nodes are used to represent aircraft arriving on the pad and departing from the pad. The model is constrained to limit the number of aircraft than can simultaneously conduct an arrival or departure from nodes associated with a common TLOF pad to one. Each gate is similarly split into two nodes in the network model even though these nodes represent a single vertiport element. The first gate node represents aircraft arriving at an empty gate while the second node represent aircraft loaded and prepared to depart from the gate.

Each arc of the network flow model is associated with a travel time required for the aircraft to traverse it. These travel times correspond to the operational parameters presented in sub-section A. Aircraft never stay at a node, but rather transition through a node instantaneously from one arc to another connecting arc at the node. All arcs are unidirectional and are generally limited to a capacity of one aircraft. The “hold” arcs at the origin and staging nodes may have capacities of greater than one to represent multiple aircraft waiting in the arrival queue or in staging, respectively.

C. Multi-Commodity Flow Formulation

A multi-commodity flow formulation was developed to describe the flow of aircraft through the vertiport network model. A multi-commodity flow formulation was selected as it describes the exact path that each aircraft takes through the vertiport’s network. Furthermore, the formulation enables different types of aircraft to be modeled as different commodities with different turnaround times and other operational parameters.

At a high level, the IP assigns aircraft to each arc of the vertiport network model at every time step of the simulated operational period in order to maximize the value of its objective. More formally, the *decision variables* of the IP are the number of aircraft of each commodity enter each arc in each time step. The number of decision variables is the number of arcs in a given network times the number of aircraft commodities being considered times the number of

time steps under consideration. Typical IP formulations in this study were solved for between 1500 and 8000 decision variables.

The *objective* of the IP is to maximize value where a reward value is specified for each arrival and departure completed. Fig. 11 displays that an arrival is rewarded the moment an aircraft completes the arrival arc and transitions to the taxi-in arc. A departure is rewarded the moment an aircraft completes the departure arc and transitions to the exit arc. The award schemes for arrivals and departures are discussed below in sub-section D. It should be noted that further secondary objectives could be applied, such as minimizing the amount of ground hold time assigned to aircraft.

The *constraints* of the IP ensure that physical realities are met (such as prohibiting two aircraft from simultaneously parking at a gate). Constraints also enforce the simultaneous operations policies by controlling which arcs in the model aircraft may simultaneously be occupied by aircraft. Typical IP formulations in this study had roughly 1.5 to two times as many constraints as decision variables.

These IP was formulated using the following variables:

- S = set of vertiport elements except the “sink” node
- $k(f)$ = aircraft type of flight f (i.e. the commodity type)
- $N(k)$ = set of arcs that aircraft of type k can use
- $C_i(t)$ = capacity of vertiport element i at time t
- $t_{i,j}$ = travel time on arc (i,j)
- $arr(k)$ = arrival node (i.e. TLOF pad) for aircraft type k
- $dest(k)$ = destination node for aircraft type k
- $I_j^k(t)$ = external inflow of aircraft of type k into node j at time t
- $c^d(k)$ = benefit of an aircraft of type k departing per unit time
- $c^a(k)$ = benefit of an aircraft of type k arriving per unit time
- $x_{i,j}^k(t)$ = (decision variable) number of flights of type k that depart from vertiport node i at time t and arrive at node j at time $t+t_{i,j}$

Equations 1 through 6 describe the general IP formulation for vertiport operations used in this analysis. A verbal description is provided above each equation.

Objective Function: Maximize the total value awarded for aircraft arrivals and departures.

$$maximize \left(\sum_{\{k,t,i=dest(k)\}} c^d x_{i,j}^k(t) + \sum_{\{k,t,i=arr(k)\}} c^a x_{i,j}^k(t) \right) \quad (\text{Eqn. 1})$$

Flow Conservation Constraint: for each commodity, flow into each node plus external inflow equals flow out.

$$\sum_{\{j:(i,j) \in N(k)\}} x_{i,j}^k(t) - \sum_{\{j:(j,i) \in N(k)\}} x_{j,i}^k(t - t_{j,i}) + I_j^k(t) = 0 \quad \forall S, k, t \quad (\text{Eqn. 2})$$

TLOF Conflict Constraint: only one aircraft can be on the approach, taxi-in, taxi-out, or departure arcs associated with a TLOF node at a time (note that this constraint varies depending upon the simultaneous operations policy in effect – the presented constraint is for fully dependent operations at a TLOF pad). This constraint is repeated for each TLOF pad in the model.

$$\sum_k \sum_{\{t': t-t_{i,j} < t' \leq t\}} \left(\sum_{\{i:(i,pad1arr) \in N(k)\}} x_{i,pad1arr}^k(t') + \sum_{\{j:(pad1arr,j) \in N(k)\}} x_{pad1arr,j}^k(t') + \sum_{\{i:(i,pad1dep) \in N(k)\}} x_{i,pad1dep}^k(t') + \sum_{\{j:(pad1dep,j) \in N(k)\}} x_{pad1dep,j}^k(t') \right) \leq 1 \quad \forall t, i \quad (\text{Eqn. 3})$$

Gate Conflict Constraint: only one aircraft can be on the taxi-in, taxi-out, staging taxi-in/out, turnaround, or hold arcs for each gate node at a time (this constraint varies depending upon the simultaneous operations policy in effect – the presented constraint is for fully dependent operations at a gate). This constraint is repeated for each gate in the model.

$$\sum_k \sum_{\{t': t-t_{i,j} < t' \leq t\}} \left(\sum_{\{i: (i, gate1arr) \in N(k)\}} x_{i, gate1arr}^k(t') + \sum_{\{j: (gate1arr, j) \in N(k)\}} x_{gate1arr, j}^k(t') + \sum_{\{i: (i, gate1rdy) \in N(k)\}} x_{i, gate1rdy}^k(t') + \sum_{\{j: (gate1rdy, j) \in N(k)\}} x_{gate1rdy, j}^k(t') \right) \leq 1 \quad \forall t, i \quad (\text{Eqn. 4})$$

Arc Capacity Constraint: the sum of flow of all aircraft commodities on each arc must be less than or equal to the capacity of that arc.

$$\sum_k \sum_{\{j: (i, j) \in N(k)\}} \sum_{\{t': t-t_{i,j} < t' \leq t\}} x_{i,j}^k(t') \leq C_i(t) \quad \forall t, i \quad (\text{Eqn. 5})$$

Positive Integer Constraint: decision variables must be non-negative and integer.

$$x_{i,j}^k(t) \geq 0, \text{ integer } \forall i, j, k, t \quad (\text{Eqn. 6})$$

D. Developing a Vertiport Capacity Envelope

In order to develop the capacity envelope of a given vertiport and parameter setting, the IP was solved numerous times to determine each feasible arrival and departure performance point on the envelope. A complicating factor was that initial testing found vertiport capacity envelopes differ from the envelopes of traditional airports in that the number of departures is not always a monotonically decreasing function of arrivals [3]. In other words, the capacity envelopes have distinct upper and lower surfaces that create a non-unique relation of arrivals to departures.

Considering this attribute of vertiport capacity envelopes, the approach taken in this analysis to define the entire capacity envelope was to repeatedly solve the IP with a sweep of scheduled arrivals from zero up to the maximum vertiport acceptance rate for the given time period. This sweep of scheduled arrivals was repeated with two objective functions for the IP. The first objective function awarded arrivals while penalizing departures to find the lower surface of the capacity envelope as displayed in blue in Fig. 12. The second objective function awarded both arrivals and departures in order to find the upper surface of the capacity envelope. Arrivals were always valued higher than departures in order to prevent an indeterminate solution where arrivals and departures could be traded.

E. Model Analysis

The IP formulation presented in equations 1 through 6 was implemented in Python 3.6.6. using Gurobi 8.0.1 as the solver. A different formulation of the model was developed for each vertiport considered. A vertiport consisted of a specified number of gates, TLOF pads, and staging stands. Furthermore, each vertiport design was solved for multiple sets of operational parameters that varied the travel time and simultaneous operating constraints for each arc.

In total, the IP was formulated for 156 different vertiports. Each was solved for up to 146 different operational parameter settings. The full sensitivity analysis of vertiport throughput constituted the development of 8866 capacity envelopes representing the solution of the IP approximately 213,000 times.

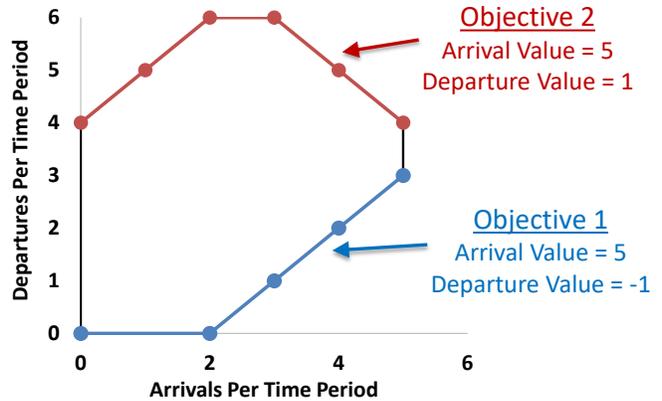


Fig. 12 The capacity envelope upper and lower surfaces were determined through separate IP objectives.

VI. Vertipoint Capacity Envelope Sensitivity Study Results

The deterministic throughput capacity of a vertipoint was found to respond non-linearly to each of the three infrastructure variables and the seven operational parameters tested in the sensitivity study. The non-linear behavior emerged due to the discrete nature of aircraft arrivals and departures, as well as the correlated influence of many of the variables and parameters. This section provides an overview of the key results from the sensitivity study.

A. The Vertipoint Capacity Envelope

A capacity envelope defines the set of arrival and departure acceptance rates that a vertipoint may potentially operate at under the assumed conditions (i.e. weather, traffic mix, sequencing, etc.). Fig. 13 presents a representative capacity envelope displaying the shape and attributes of the envelopes developed in this study. Key characteristics of the envelopes and the underlying factors that drive them are discussed below.

Feasible Operating Region: feasible vertipoint operating scenarios are represented as integer ordered pairs either on or within the envelope boundaries. The envelope expands in volume with additional infrastructure capacity (gates, staging, TLOF pads), reduced operational parameter times, or additional pre-staged aircraft, among other opportunities.

Unbalanced Operations: “unbalanced” arrivals occur when the vertipoint accepts only arrivals with no corresponding departures. Unbalanced arrivals are maximized at the non-origin x-intercept of the envelope; unbalanced departures are similarly maximized at the y-intercept point. The maximum number of unbalanced departures is initially linearly dependent on the number of aircraft that could be pre-staged at the vertipoint. The maximum number of unbalanced arrivals is initially linearly dependent on the number of aircraft that the vertipoint can hold after landing.

Free Operations: “free” arrivals occur when an arrival can be accommodated without reducing the number of supported departures (and vice-versa for free departures). The number of free arrivals and departures is dependent upon the number of pre-staged aircraft, the number of aircraft that may be accommodated at the vertipoint (at gates or staging), and the arrival time, turnaround time, and departure time.

Maximum Throughput: the ordered pair (or linear series of points) that represent the maximum throughput potential of the vertipoint in terms of the sum of arrivals and departures. The point of maximum throughput will skew towards more arrivals than departures if few aircraft are pre-staged and departure or turnaround time is long; it will skew towards more departures than arrivals in the opposite conditions. If the arrival and departure times are roughly equal, then numerous points may have the same maximum throughput as arrivals may be traded for departures.

Cutout Region: while a defining characteristic of traditional airport capacity envelopes is that the number of departures is always a monotonically decreasing function of arrivals, the x and y-intercepts for vertipoint envelopes may reside below the maximum arrival or departure acceptance rate, respectively. The result, as pictured in Fig. 13, are regions of positive slope in the capacity envelope that “cut out” operations with either a high number of departures and low number of arrivals, or vice versa. This occurs because, unlike airports, small or moderately sized UAM vertipoints are unlikely to have sufficient gates or staging areas to accommodate the number or arrivals or departures the TLOF pad(s) could support.

B. Impact of Gate to TLOF Pad Ratio

Vertipoint throughput capacity and overall performance was found to be highly sensitive to the ratio of gates to TLOF pads. The most “efficient” ratio in terms of throughput provides just enough gates so that the TLOF pad is constantly supporting takeoffs or landings (i.e. is the bottleneck element of the vertipoint). The operational parameters that influence this efficient ratio and the consequences of inefficient design are introduced in brief below:

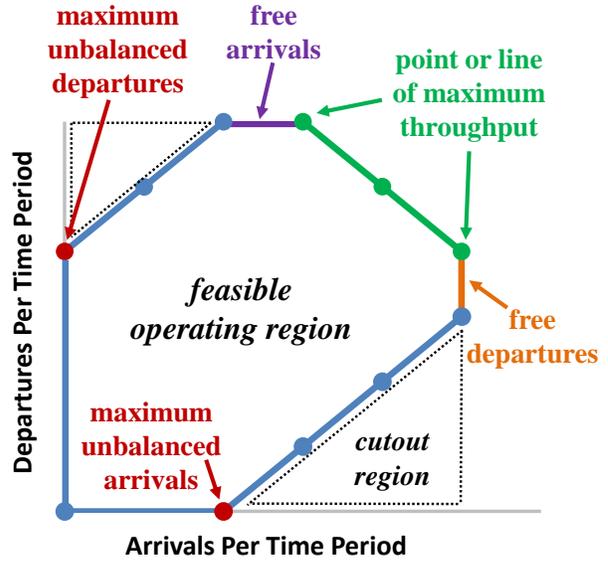


Fig. 13 Representative vertipoint capacity envelope.

- Too few gates per TLOF pad significantly reduces achievable throughput.
 - The gate(s) become the vertiport bottleneck and are highly utilized
 - The TLOF pad is “starved” of aircraft and underutilized
 - The average aircraft ground holding time at the gates due to TLOF pad congestion is small
- Too many gates per TLOF pad has a minor influence on the throughput, but a large influence on the vertiport footprint and efficiency of aircraft usage.
 - The TLOF pad becomes fully utilized maximizing vertiport throughput potential
 - Each additional gate supports another unbalanced arrival (or departure if aircraft are pre-staged)
 - The gates become underutilized and extensive aircraft ground holding at the gate may occur

Fig. 14 displays these general trends concerning the gate to TLOF pad ratio at a vertiport. The nine capacity envelopes presented correspond to vertiports with one TLOF pad and zero to eight gates. The utilization of each vertiport infrastructure component is displayed in the table on the right. The operational parameters for this example were set to 60s arrivals and departures, 15s taxiing, 300s aircraft turnaround, and only one aircraft simultaneously authorized to approach, depart, or taxi to/from the TLOF pad.

Adding the first gate reduces maximum throughput due to the extra taxi time required to access the gate compared to turning the aircraft directly on the TLOF pad. Each additional gate up to five gates (for this set of operational parameters) increases the vertiport’s achievable throughput. With each additional gate the TLOF pad utilization increases as it is more efficiently used. Adding a sixth gate, however, does not further increase the maximum achievable throughput or TLOF pad utilization. At this point the TLOF pad had become fully utilized, or saturated, and can no longer accept further arrivals or departures even given the additional sixth gate.

Any number of additional gates beyond this efficient gate to TLOF pad ratio provide no marginal increase in maximum throughput, although they do provide the ability to handle additional unbalanced operations (displayed as extra arrivals in these capacity envelopes). Furthermore, the average holding time for the aircraft at the gate dramatically increases as aircraft are waiting to access the TLOF pad for takeoff. On average, gate utilization was also found to decrease beyond the efficient gate to TLOF pad ratio.

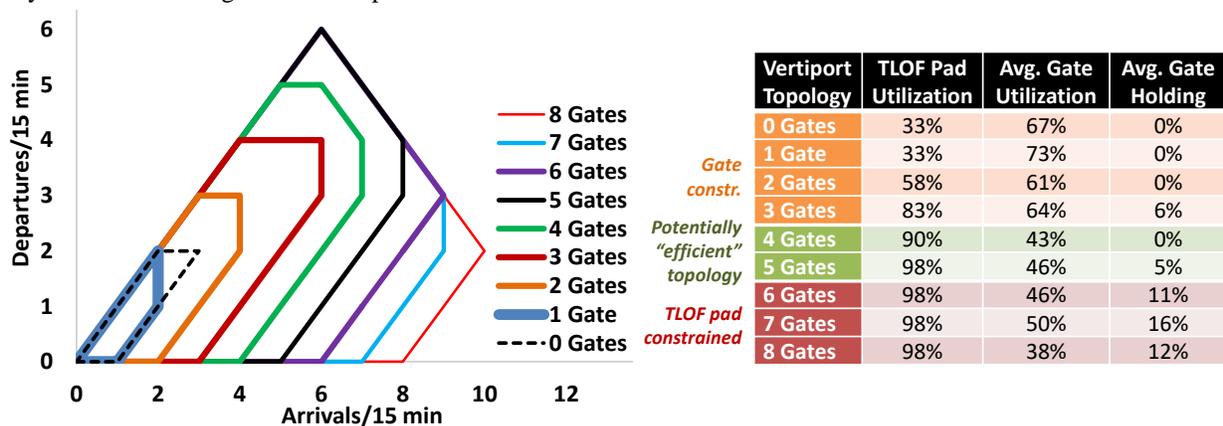


Fig. 14 Capacity envelopes and component utilizations for vertiports with varying gate to TLOF pad ratios.

The efficient gate to TLOF pad ratio is influenced by the operational parameters of the vertiport as follows:

- Increasing the arrival or departure time decreases the number of gates required per TLOF pad for efficient throughput performance. Fig. 15 displays the capacity envelopes developed for the same infrastructure and parameter settings as Fig. 14, except the arrival and departure times have both been reduced from 60s to 30s. As may be seen in Fig. 15, the maximum throughput is dramatically increased as the vertiports with a higher gate to TLOF pad ratios are no longer constrained by saturation of the TLOF pad.

Fig. 16 displays how the maximum throughput of six vertiports with different gate to TLOF pad ratios responds to a sweep of aircraft arrival times (with 30s departures and no pre-staged aircraft). As anticipated, the vertiports

with many gates quickly become TLOF pad constrained and experience a decline in throughput as their extra gates are starved for aircraft. Vertiports with few gates remain gate constrained and experience little to no throughput reduction in response to increasing arrival time.

- Increasing the vehicle turnaround time increases the number of gates required per TLOF pad for efficient throughput performance. This is a result of each aircraft requiring more time on each gate, thereby making that gate unavailable to support other operations and starving the TLOF pad of aircraft. Fig. 17 displays a sweep of aircraft turnaround time and its influence on the maximum throughput of various vertiports. A key takeaway from Fig. 17 is that vertiports with higher gate to TLOF pad ratios, even those which are beyond an efficient ratio for standard operations, are more robust to potential increases in aircraft turnaround time. This may be important for UAM vertiports as factors such as elderly passengers, extended onboard safety briefings, or longer than expected re-charging times may all increase aircraft turnaround time compared to the design condition.
- Increasing the taxi time between the TLOF and gate(s) may reduce the number of gates required per TLOF pad for efficient throughput performance, depending upon the simultaneous operating policies. For operating policies that prohibit simultaneous arrivals, departures, or taxiing to/from the TLOF pad, increased taxi times essentially results in increased arrival and departure times; this artificially enhances the utilization of the TLOF pad for fewer actual operations. If simultaneous taxiing is allowed, then increased taxi time has a negligible effect on optimal gate to TLOF pad ratio. The next section will discuss the influence of different simultaneous operating rules in greater detail.

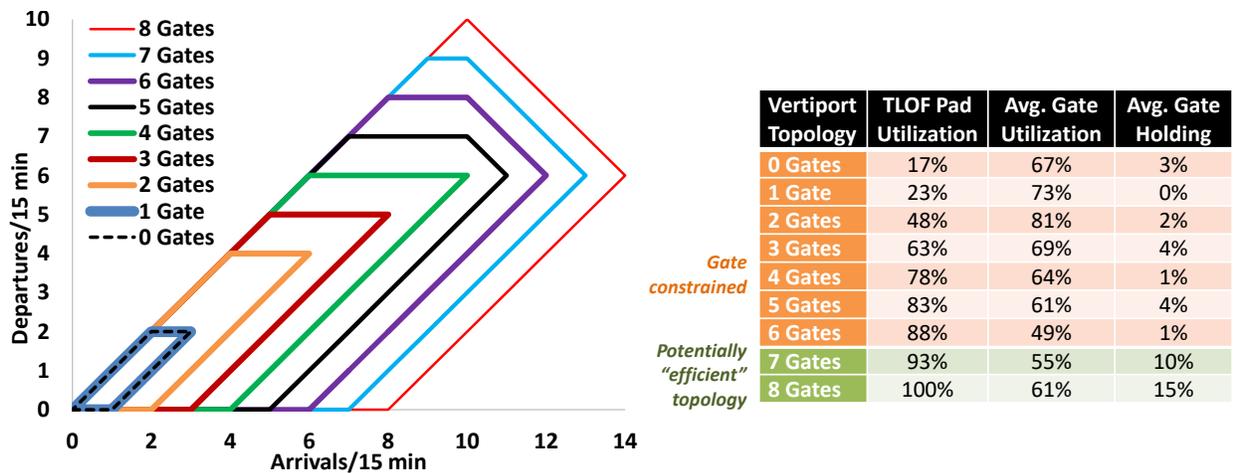


Fig. 15 Decreasing arrival and departure times increases throughput and requires more gates per TLOF pad to maximize vertiport efficiency.

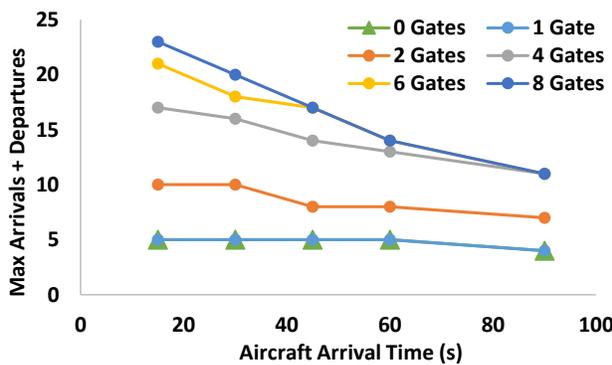


Fig. 16 Variance in maximum operations to increasing arrival time for six gate/TLOF pad ratios.

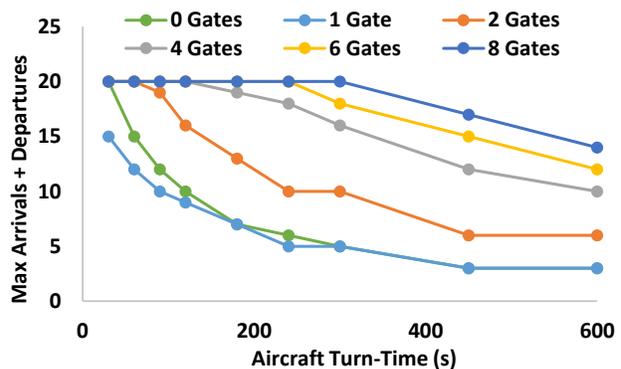


Fig. 17 Variance in max. operations to increasing turnaround time for six gate/TLOF pad ratios.

Equation 7 provides a useful heuristic to estimate the number of gates required to maximize the throughput of a TLOF pad for a given parameter scenario. Equation 7 assumes that approach, departure, and taxiing to/from the TLOF pad are all dependent operations. If aircraft are allowed to taxi to/from the TLOF pad simultaneously with aircraft arriving or departing the TLOF pad, then Equation 8 should be used.

$$\text{Gates Required} = \text{Ceiling} \left(\frac{\text{Aircraft Turnaround Time}}{\max(\text{Arrival Time}, \text{Departure Time}) + \text{Taxi Time}} \right) + 1 \quad (\text{Eqn. 7})$$

$$\text{Gates Required} = \text{Ceiling} \left(\frac{\text{Aircraft Turnaround Time}}{\max(\text{Arrival Time}, \text{Departure Time})} \right) + 1 \quad (\text{Eqn. 8})$$

C. Impact of Simultaneous Operating Policies

Simultaneous operating policies affect how aircraft may move at a vertiport. These policies may represent physical realities, such as prohibiting two aircraft from simultaneously using the same taxiway in opposite directions. The policies may also represent regulatory requirements, such as prohibiting two aircraft from simultaneously executing approaches to closely spaced, dependent TLOF pads.

The sensitivity study conducted in this paper considered seven different simultaneous operating policies. Four concerned dependencies between taxiways and approach/departure procedures for a single TLOF pad. The remaining three evaluated dependencies between approach and departure procedures for adjacent TLOF pads. The policies controlling approach/departure procedures and taxiways were found to influence vertiport throughput less than the policies for approach and departures to adjacent TLOF pads.

1. Impact of Policies for a Single TLOF Pad

Fig. 18 displays three of the simultaneous operating policies tested for a single TLOF pad; only one aircraft is allowed to operate in a colored box at a time. A modest throughput increase is gained by making the airborne and airside operations independent. The effects of long taxi times are also partially mitigated through this independence as displayed in Fig. 19. However, the taxi time for most vertiports is anticipated to be much less than the approach, departure, or turn time of the aircraft, so this benefit may be small. Adding further independence between airside taxi operations provides little benefit unless the vertiport is equipped with numerous staging stands.

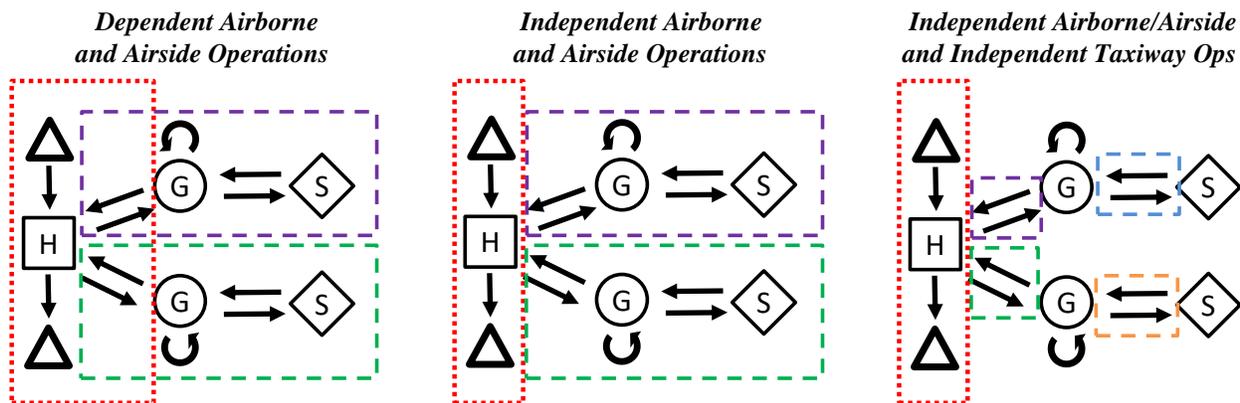


Fig. 18 Three of the four TLOF pad and taxiway simultaneous operating policies considered. “H” are TLOF pads, “G” are gates, “S” are staging stands, and triangles are approach or departure fixes. Only one operation is simultaneously allowed in a colored box at a time.

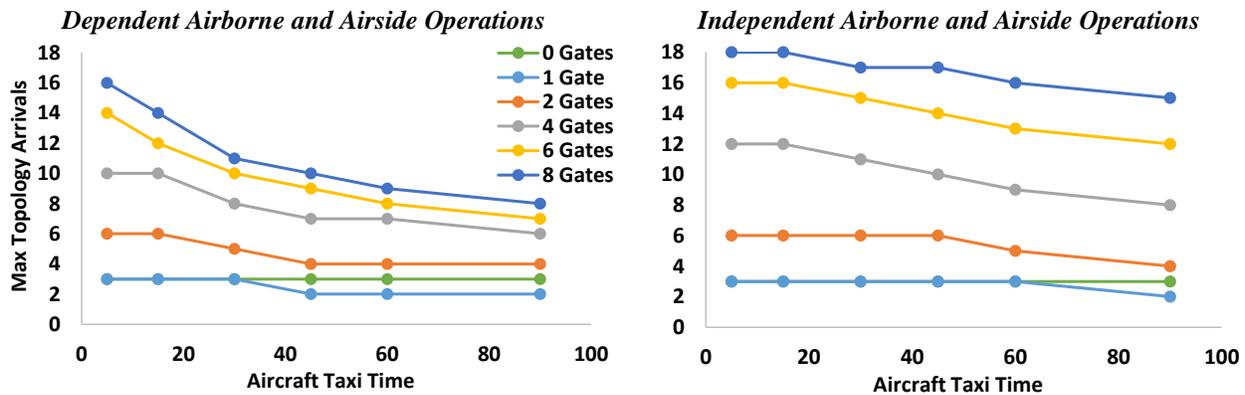


Fig. 19 Enabling independent airborne and airside operations increases the robustness of vertiport throughput to increasing aircraft taxi times.

2. Impact of Policies for Adjacent TLOF Pads

The simultaneous operating policies for adjacent TLOF pad approach and departure procedures were found to be more influential on vertiport throughput than the single TLOF pad policies. This finding is consistent with literature on the significant influence that simultaneous operations to parallel runways have for conventional airport throughput. The three policies considered are pictured in Fig. 20 and the general impact of each is described in brief below:

- 1) **Fully Independent Operations:** The most effective scenario to maximize vertiport throughput is to enable fully independent TLOF pad operations where arrivals or departures can occur at one pad without relation to what is occurring at any other pad. If independent TLOF pads do not share gates, then the facility will function as two completely separate vertiports and support precisely double the throughput of a single pad and set of gates. If the TLOF pads share gates (such as in the Pier Topology displayed in Fig. 5), then the throughput of the vertiport may more than double due to marginal efficiency gains in gate usage under some circumstances.

Furthermore, connecting multiple independent TLOF pads to the same set of gates increases the robustness of throughput performance to fluctuations in arrival, departure, and taxi time. Operationally, if an aircraft were to become disabled on a TLOF pad, taxiway, or gate, such a configuration also provides greater flexibility for off-nominal operations. Section IV.B. introduced potential requirements for independent TLOF pad operations and Section VII expands upon these requirements.

Fig. 21 displays the maximum throughput (sum of feasible arrivals and departures) of three vertiports compared to a baseline vertiport with one TLOF pad and four gates. The first grouping of bars corresponds to an operating scenario where each TLOF pad (if there are more than one) operates independently, but with shared gates. As shown, the maximum throughput potential increases only by 15% if four additional gates are added with no additional TLOF pad, but doubles with the addition of a second TLOF pad with four gates, and triples with the addition of a third TLOF pad with four more gates.

- 2) **Fully Dependent Operations:** Adding a fully dependent TLOF pad to a vertiport (to which no arrivals or departures may occur if another arrival or departure is occurring on an adjacent TLOF pad) provides comparatively little throughput increase to the facility. Displayed in the third set of bars in Fig. 21, the maximum throughput increase for all three vertiport layouts was a constant 15%, independent of the number of TLOF pads or gates added. The throughput gain is small because all three of the vertiports are constrained due to the bottlenecking of arrivals and departures at the TLOF pad. Therefore, adding additional gates has a marginal effect on throughput, and adding additional TLOF pads that cannot be used independently of the already saturated pad also has a marginal effect on throughput.

While adding additional, dependent TLOF pads and gates does not significantly increase the maximum potential aircraft throughput at a vertiport, it does increase the number of unbalanced arrivals or departures that may be supported by the facility; this effect is shown in Fig. 22. This trend results because the primary driver to increase unbalanced operations is the addition of staging stands or gates. The increase in unbalanced operations for the

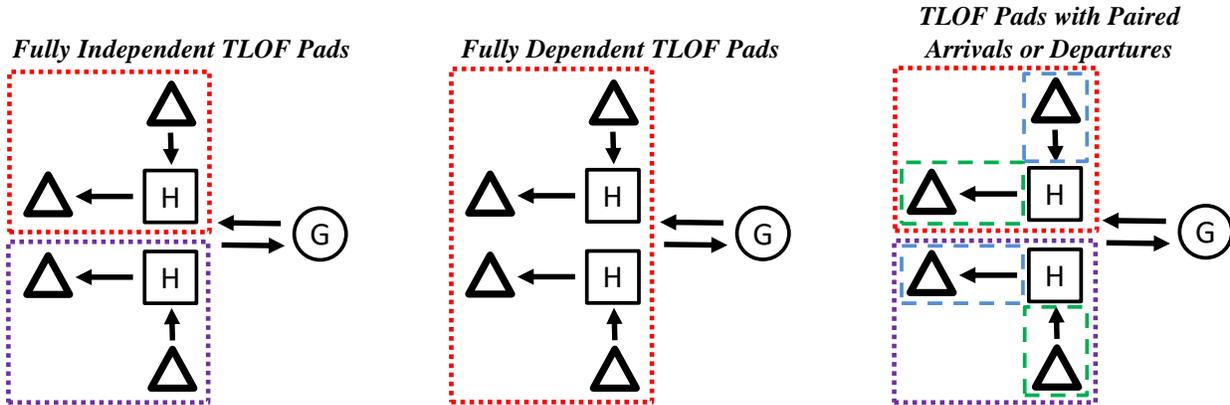


Fig. 20 Three simultaneous operating policies for adjacent Touchdown and Liftoff (TLOF) pads. “H” are TLOF pads, “G” are gates, and triangles are approach or departure fixes. Only one operation is simultaneously allowed in a colored box at a time.

two and three TLOF pad vertiports is not as large for the fully dependent scenario as the independent scenario because aircraft that unloaded passengers must remain at the gate and are not allowed to be parked on unused TLOF pads adjacent to pads supporting arriving flights (a result of the modeling constraint).

- 3) Partially Dependent Operations: This scenario enables adjacent TLOF pads to support paired arriving flights or paired departing flights. The potential throughput gains for the three vertiports are presented as the middle set of bars in Fig. 21 and Fig. 22. Interestingly, the maximum throughput performance improvement of paired arrivals or departures to a TLOF pad may provide significant throughput gains without the need to ensure fully independent approach and departure procedures. Once again, unbalanced arrivals for this operating policy are less than those for independent TLOF pads as unloaded aircraft cannot be positioned on TLOF pads while flights are arriving to adjacent pads. Unbalanced departures is identical for the two policies.

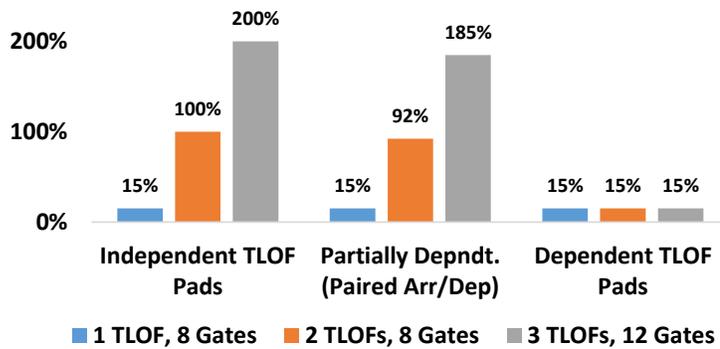


Fig. 21 Effect of adjacent TLOF pad operating policies on the maximum throughput of three vertiports compared to a vertiport with one TLOF pad and four gates.

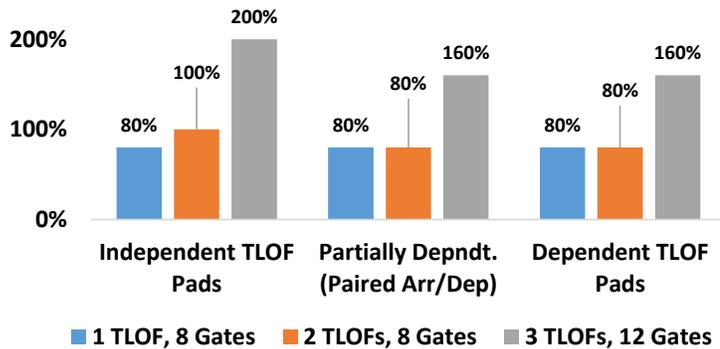


Fig. 22 Effect of adjacent TLOF pad operating policies on the maximum number of unbalanced arrivals at three vertiports compared to a vertiport with one TLOF pad and four gates.

D. Impact of Staging Stands and Pre-Staged Aircraft

The final infrastructure variable and operational parameter that significantly influence vertiport throughput is the number of staging stands at the facility and the number of aircraft pre-staged on the vertiport, respectively.

Fig. 23 displays the effect of adding up to eight staging stands to a vertiport with one TLOF pad and four gates. Each staging stand that is added enables one additional unbalanced arrival to be conducted. This appears as a widening of the capacity envelope. This trend will continue until the TLOF pad is saturated supporting only arriving aircraft (not shown in this diagram, but the point when the maximum throughput line intersects the x-axis). If the TLOF pad is not saturated, then an additional staging stand may also increase the total number of operations (arrivals plus departures) that may be conducted. This condition occurred in Fig. 23 between the 0 and 1 stand scenario, and again between the 1 and 2 stand scenario.

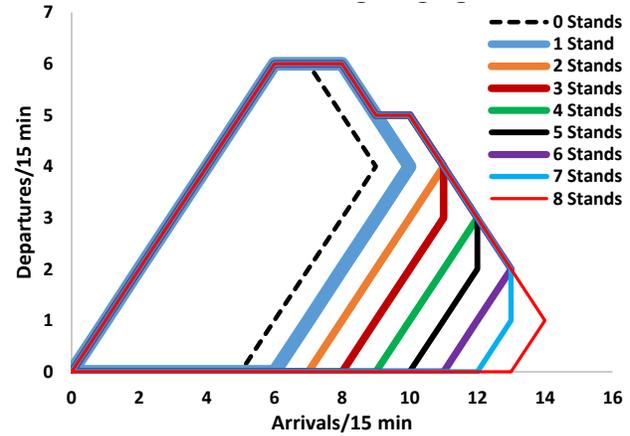


Fig. 23 Effect of adding staging stands to a vertiport topology with one TLOF pad and four gates.

Fig. 24 displays the effect of adding pre-staged aircraft to a vertiport with one TLOF pad, two gates, and two staging stands. For the first two pre-staged aircraft added to the vertiport the entire capacity envelope shifts vertically upwards. This indicates an additional departure may be supported on the upper surface of the envelope, and one less arrival may be supported on the lower surface of the envelope. The maximum throughput point also increases by one operation for each of these initial two pre-staged aircraft. Additional pre-staged aircraft beyond these initial two actually reduce the maximum throughput point, but continue to increase the number of unbalanced departures and reduce the number of arrivals that may be supported.

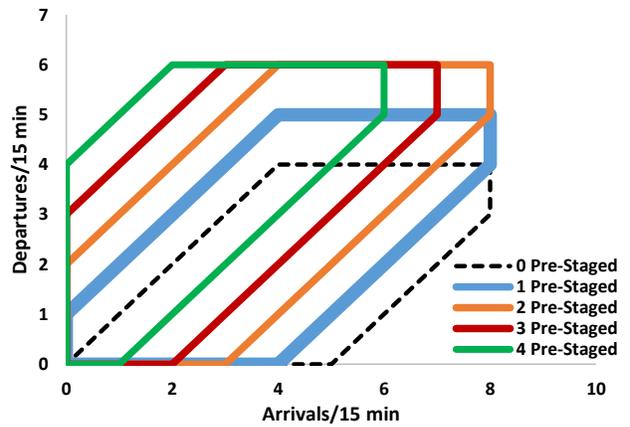


Fig. 24 Effect of adding pre-staged a/c to a vertiport with one TLOF pad, two gates, and two staging stands.

As displayed in Fig. 23 and Fig. 24, the number of staging stands and pre-staged aircraft play a significant role in the throughput potential of a vertiport. Staging stands typically provide a marginal maximum throughput gain, but they increase the number of unbalanced operations that may occur effectively “filling out” the capacity envelope (note this is also a feature of adding additional gates). The ability to support highly unbalanced arrivals or departures is especially critical for vertiport operations during morning or evening commuting hours or during airline flight banking periods where UAM traffic may be highly directional. Pre-staged aircraft are the only feature of vertiport operations that may shift the capacity envelope to enable additional unbalanced departures.

VII. Implications of Sensitivity Study Results for Performance and Footprint of the Four Vertiport Topology Classes

Unlike airports, which have traditionally been developed on or beyond the periphery of urban areas, vertiports for UAM services are expected to be integrated directly into densely populated regions. This requirement results in significant design pressure to minimize the physical footprint of the vertiport due to land availability, cost, and community acceptance constraints. This section discusses the implications of key findings from the vertiport capacity envelope sensitivity study for the performance and footprint of each of the four vertiport topology classes.

1. Satellite Topology Class

In terms of layout, the satellite topology class is the most compact arrangement for vertiports with one TLOF pad and up to approximately eight gates. As such, it is well suited for small footprint applications such as on rooftops. However, if UAM aircraft require very long turnaround times compared to approach and departure times (perhaps due to slow charging), then a satellite topology may not be able to support enough gates for efficient TLOF pad utilization.

Due to the close proximity of the TLOF pad to the gates, ground taxiing is appropriate to reduce required footprint and minimize rotor downwash compared to hover taxiing. Approach and departure path integration with satellite topology vertiports may prohibit the use of some gates that reside beneath the active flight path. Furthermore, the satellite topology is potentially not well suited for multi-TLOF pad vertiports as enabling independent arrival and departure paths may be difficult. While the satellite topology class has limited space for gates, the sensitivity study suggested that adding staging stands significantly increases the unbalanced throughput of the topology class with little additional footprint requirements.

Finally, it was estimated that a 190 ft by 200 ft footprint could likely support a satellite topology vertiport with one TLOF pad, four usable gates, two active approach and departure paths, and ground taxiways. Increasing the footprint to approximately 190 ft by 315 ft could support an additional four useable gates.

2. Pier Topology Class

The pier topology is most efficient for larger facilities with many TLOF pads and gates. It is therefore better suited for surface facilities or facilities on large footprint rooftops. The pier topology readily supports sufficient TLOF pad spacing for partially or fully independent operations. Furthermore, it provides operational robustness gains by connecting sets of gates to multiple TLOF pads. The pier topology class may have limited performance for small throughput facilities that cannot support a second TLOF pad as taxiway congestion may occur. Furthermore, if aircraft turnaround time is very short, then the high ratio of gates to TLOF pads enabled by the pier topology may not be efficient from a throughput standpoint.

It was estimated that a vertiport with a pier topology could support one TLOF pad and four usable gates with ground taxiways with a required footprint of approximately 190 ft by 225 ft. Sets of two additional gates could be added to the facility for an additional footprint requirement of approximately 190 ft by 70 ft.

3. Linear Topology Class

The linear topology is well-suited for situations where aircraft have very short turn-times (usually when they do not recharge or refuel onsite) such as experienced at the Silverstone Heliport during the British Grand Prix. In such cases the taxi-time required between a gate and the TLOF pad becomes a significant proportion of the TLOF pad utilization time. The linear topology is not highly space efficient, especially if partially or fully independent TLOF pad operations are desired. However, the installation of staging areas in the required space between independent TLOF pads is one way to utilize this space and will significantly increase the unbalanced throughput of the vertiport.

It was estimated that a linear topology would require approximately 90 ft by 180 ft for each pair of dependent TLOF pads, or 90 ft by 270 ft for one pair of independent TLOF pads and 90 ft by 180 ft for each additional independent TLOF pad beyond two.

4. Remote Apron Topology Class

The remote apron topology sacrifices footprint and throughput efficiency in order to meet other design requirements such as noise abatement, airport integration, or safety. By locating the TLOF pads in a different location from the gates (perhaps a few hundred to a few thousand feet away), the time and footprint requirements for the taxiways dramatically increase. This creates a few unique requirements and opportunities for vertiports of this topology.

First, enabling independent airborne and airborne operations is a critical requirement to increase throughput at remote apron vertiports. Next, it is likely that supporting hover taxiing at such facilities would be necessary to increase taxi speed. Especially for vertiports integrated at airports, hover taxiways may be an effective means to connect TLOF pads located far away from the conventional runways (for ATC separation purposes) to the airport terminal. It could even be proposed that “elevated” hover taxiways consisting solely of navigation lights (no load bearing surface) could be constructed for long distances leading into high activity airports to enable UAM access, perhaps even in instrument conditions.

VIII. Conclusion

This study develops an Integer Programming (IP) approach to analytically develop deterministic vertiport capacity envelopes and assess the sensitivity of aircraft throughput to topology variations and operational parameter situations. The IP formulation and underlying network modeling approach is flexible and easily adapted to any of the four common vertiport topologies characterized in this research. The flexibility of this approach is displayed through its application to 156 different vertiports and 146 different operational parameter settings. The findings from the sensitivity study support the identification of design or operational strategies and tradeoffs to maximize the throughput of a vertiport, minimize its physical footprint, and increase its robustness to off-nominal operations.

First, the sensitivity study indicates that the ratio of gates to Touchdown and Liftoff (TLOF) pads at a vertiport is a key design factor. There is an optimal ratio that will maximize throughput for a given set of operational parameters. Having fewer gates than this ratio will reduce both throughput and operational robustness by starving the TLOF pad of aircraft. Having more gates than this ratio has little to no effect on throughput, but increases robustness and requires a larger footprint.

Second, equipping vertiports with aircraft staging stands can provide significant benefits. Each staging stand enables the vertiport to support more unbalanced arrivals or departures which is a valuable capability during peak period operations, especially where flow may be just into or out of a facility (such as during commuting rush hours or airline flight banks). Staging stands require smaller footprints than gates and may provide some throughput benefits as well.

Third, equipping vertiports with multiple TLOF pads can dramatically increase throughput if those pads can operate fully independently or support simultaneous, paired arrivals and departures. Achieving paired arrivals and departures provides nearly as large a throughput increase as independent operations, but is likely to require smaller separation minima and specialized avionics. Operational robustness may also be increased if multiple TLOF pads feed the same set of gates.

Future work may seek to explore the robustness of vertiport operations to realistic variance in operational parameters and off-nominal conditions. Assigning probabilities to such conditions and determining vertiport topologies that on average maximize throughput for minimum footprint is an initial approach. Perhaps more informative is the development of stochastic simulation capabilities for capacity envelopes.

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Appendix – Four Throughput Limiting Processes of an Airport or Vertiport

1. Ground Access Capacity

Ground access capacity refers the number of passengers that can physically access the vertiport from the surrounding area in a given period of time. This may be thought of as “community to curb” capacity, or vice-versa. The capacity of ground access is primarily dependent upon the performance of transportation systems external to the vertiport. For example, road network congestion surrounding the vertiport, subway or light rail delays, or poor walking conditions may all influence the rate at which passengers can arrive at or depart from the vertiport.

While ground access capacity has not traditionally been a throughput-limiting process for most commercial airports, various attributes of vertiports may exacerbate this potential bottleneck. For example, rooftop UAM vertiports may experience ground access limits due to limited elevator throughput. Similarly, vertiports in dense urban areas may become less accessible during rush hour periods or may have little space for dedicated pickup and drop-off areas.

Despite these differences, ground access capacity was not considered to be within the scope of the vertiport capacity envelope analysis of this paper and was not considered further. This scoping is consistent with how capacity envelopes are defined for commercial airports today.

2. Terminal Capacity

Terminal capacity refers to the number of passengers that can be processed from “curb to gate” at the vertiport. Depending upon the regulations, business model, and ConOps of UAM operators, various terminal functions may be required including check-in, baggage drop/claim, security check, weight check, safety briefing, and aircraft boarding. While terminal capacity had not historically been a rate-limiting process for commercial aviation, current security screening requirements in response to the September 11th terrorist attacks have created some instances where passengers or flight crew have been unable to be processed in the terminal in a reasonable time leading to flight delays.

UAM vertiports are likely to have highly constrained terminal space (due to low footprint availability in dense urban areas) that could lead to more acute terminal capacity bottlenecks. However, emerging biometrics, near field communications, big data analytics, and smartphone applications have shown potential to significantly relieve terminal processing time [25]. Furthermore, the most time intensive terminal process is security screening which is not currently required for UAM operations utilizing aircraft less than 12,500 lbs. Terminal capacity was therefore not considered in this analysis *except* for aircraft boarding which was considered to be an aspect of aircraft turn-time.

3. Airfield Capacity

Airfield capacity refers to the number of aircraft that can be processed at a vertiport with unconstrained arrival demand and passenger supply. Airfield capacity is dependent upon the number and performance of TLOF pads, taxiways, staging stands, and gates. Furthermore, airfield capacity is also dependent upon a number of operational parameters including taxi times, aircraft turnaround times, and approach/departure procedure times. Airfield capacity is also

influenced by air traffic control aspects due to the strong role that wake vortex and radar separation standards have upon final approach and initial departure operations from the TLOF pad.

Airfield capacity is the primary process that constrains airport throughput in today's air transportation system. Airport throughput is commonly limited during peak periods or instrument conditions by separation requirements on the runways. Similarly, congested or long taxiways, insufficient gate capacity, or limited deicing services are also causes of some delays and throughput limitations at many congested airports.

Airfield capacity is anticipated to be one of the leading throughput bottlenecks at UAM vertiports. The proposed number of operations is beyond those handled at any heliport or airport today and it is unclear how TLOFs, taxiways, gates, and approach and departure procedures, among other vertiport components, will be configured and managed to relieve airfield congestion. Airfield capacity was therefore the principal concern of the study conducted in this paper.

4. Airspace Capacity

This paper considers the airspace capacity of a vertiport to refer to the number of aircraft that can be delivered to (or accepted from) the vertiport's final approach segment (or initial departure procedure) from the surrounding terminal or en-route airspace. Weather conditions, controller workload, and separation standards may influence the rate at which aircraft can enter or exit these procedures into the surrounding airspace. Although a less common cause of airport throughput limitations than airfield capacity, airspace capacity has been shown to disrupt flow to/from airport runways in the presence of various perturbations and so called "starve" the runways [26]. Furthermore, the airspace capacity of UAM vertiports may experience more frequent constraints than commercial airports due to Temporary Flight Restrictions (TFRs) or noise abatement restrictions.

Airspace capacity, especially in controlled airspace, has been identified as one of the primary operational constraints for UAM systems [1,2,27]. The density and sheer volume of anticipated UAM traffic, as well as the low flight altitudes and advanced automation of the aircraft are anticipated to cause controller and pilot workload, flight safety, and communication/navigation/surveillance challenges constituting an Air Traffic Control (ATC) constraint on UAM operations. Due to the recognition of airspace capacity as a significant operational challenge and throughput limiting element of UAM in its own right, this research shall not consider airspace capacity limitations as part of vertiport capacity. This is consistent with current FAA practices for commercial airport capacity envelopes which are defined with unconstrained arrival availability and departure acceptance.