Integrated Arrival and Departure Management for Urban Air Mobility Vertiport Operations in the New York City Airspace

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***Abstract*—This paper introduces the Vertiport Human-Automation Teaming Toolbox (V-HATT), a novel framework developed for managing Urban Air Mobility (UAM) in terminal airspace and vertiports. V-HATT is designed to integrate the efforts of human vertiport operator (VO) with an automation system for scheduling and real-time operational control, creating a cohesive system for UAM traffic management. Using the Helo Holdings, Inc. (HHI) Heliport as a case study, we demonstrate how the V-HATT framework effectively manages incoming and outgoing traffic in a busy urban airspace like New York City. The framework employs mixed-integer linear programming (MILP) algorithms to schedule optimal arrival and departure sequences, focusing on minimizing in-air and ground delays while accounting for throughput and aircraft-specific constraints. This integrated approach promises significant improvements in UAM efficiency, safety, and reliability, contributing to the sustainable expansion of urban air transportation systems.**

***Index Terms*—Urban Air Mobility (UAM), Vertiport Operations, Human-Automation Collaboration**

NOMENCLATURE

$\mathcal{F}$	Set of flights.
$\mathcal{I}$	Set of FATOs in the vertiport.
$\mathcal{N}_i$	Set of open time slot for FATO i.
$\omega_{f,n}$	Binary variable indicating if f arrives at time slot n.
t_f	Scheduled time of arrival/departure for flight f.
$\hat{t}_f$	Requested time of arrival/departure for flight f.
d_f^{min}	Flying duration difference of using regular cruise speed and maximum speed for flight f.
d_f^{max}	Maximum in-air delay for flight f.
δ	Time length of each time slot for FATOs.
s_n	Start time point of time slot n.
v_f^c	Regular cruise speed for flight f.
v_f^{max}	Maximum speed for flight f.
l_f	Route distance from the boundary of terminal airspace to the vertiport for flight f.

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I. INTRODUCTION

A. Motivation

Vertiports, alongside terminal airspace, stand central to the envisioned success of urban air mobility (UAM), offering pivotal transportation solutions for both passengers and cargo within city airspaces. However, with escalating traffic densities in these limited zones, there's a risk of traffic demand outstripping vertiport capacity. This imbalance may give rise to conflicts in terminal areas and spark concerns over operational safety and energy efficiency. Addressing this predicament, we have prototyped the Vertiport Human-Automation Teaming Toolbox (V-HATT) [1], [2]. This tool enables the simulated execution of vertiport airside operations, all under the oversight of human VO. Given the FAA's stipulated operational constraints [3] for the regulation of traffic and conflict resolution in and around vertiports, V-HATT demonstrates a degree of automation required to manage large volumes of UAM to meet those constraints under various operating conditions.

In this paper, our primary objective is to unfold the automated arrival and departure management facets embedded within V-HATT. This design permits a synergistic collaboration between the automation system and human vertiport operators (VOs), ensuring harmonized scheduling management within terminal airspace.

B. Related Work

Recent advancements in Urban Air Mobility (UAM) have necessitated the development of vertiport design guidelines by both governmental and industry bodies. Notably, the Federal Aviation Administration (FAA) issued interim guidelines on vertiport design to accommodate VTOL capabilities [4]. Similarly, the Australian Civil Aviation Safety Authority (CASA) has detailed vertiport design considerations, including physical characteristics, obstacle limitations, and visual aids [5]. The

European Union Aviation Safety Agency (EASA) has also contributed by outlining prototype technical specifications for the operation of Visual Flight Rules (VFR) vertiports with manned VTOL-capable aircraft in the enhanced category [6]. While these guidelines collectively address various aspects of vertiport design, there is a recognized gap in their coverage of Human-Machine Interface (HMI) considerations. Specifically, there is a lack of comprehensive guidance on vertiport human management within highly automated systems, indicating an area that requires further attention and development.

NASA's High Density Vertiplex (HDV) project simulated multiple aircraft operations beyond visual line of sight (BVLOS) around vertiports, utilizing a distributed graphics processing unit (GPU) system initially developed for Uncrewed Aircraft System (UAS) Traffic Management (UTM) to study autonomous separation in localized airspace [7]. Additionally, a NASA survey identified crucial design requirements for Human-Machine Interface (HMI) workstations, highlighting the need for clear differentiation between flight plan data for VO versus that for provider of services for UAM (PSU) and vehicles at vertiports [8].

In academia, terminal airspace management for UAM has been the focus of extensive study, showcasing a range of methodologies and objectives. One approach utilized voxelization techniques and the concept of obstacle-free volume (OFV) to analyze feasible approach and departure directions for UAM [9]. Another contribution to the field involved examining the throughput of vertiports, where a rolling-horizon scheduling algorithm with enhanced route selection capabilities was proposed [10]. Additionally, a noteworthy study introduced a scenario accommodating mixed fleets of eVTOL aircraft, both winged and wingless [11]. This research proposed a heuristic strategy, termed 'insertion and local search', aimed at minimizing the operational makespan for these diverse fleets, demonstrating the potential for innovative scheduling techniques in UAM.

C. Contributions

The contributions of this study include:

1) **Framework for UAM terminal airspace and vertiport management.** A novel V-HATT framework is introduced for the management of terminal airspace and vertiport operations. This comprehensive framework encompasses long-term planning for designing airspace corridors, holding patterns, and vertiport surface layout, short-term scheduling for optimal arrival and departure sequencing, and a real-time operational phase that synergizes the inputs from both automation systems and human VOs.
2) **Design of terminal airspace and vertiport layout for New York City.** The Helo Holdings, Inc. (HHI) heliport is selected as the vertiport to offer UAM services in New York City. Terminal airspace above Jersey City is designed to effectively separate inbound and outbound traffic, with regulated metering gates and a designated holding pattern to manage aircraft. The vertiport's layout includes final approach and takeoff areas (FATOs), touchdown and liftoff areas (TLOFs), parking gates, and taxiways, optimized for UAM operations.
3) **Vertiport management interface (VMI) for human VO.** The V-HATT aims to harmonize the efforts of humans and the automation system in vertiport management. To this end, a VMI is developed as a dynamic and real-time tool for VOs, facilitating effective traffic monitoring and management, augmented by the automation system's capabilities.
4) **Automation system for optimized arrival and departure timing.** An automation system utilizing mixed-integer linear programming (MILP) is proposed to alleviate VO's workload and optimize the sequencing of aircraft. The arrival management algorithm computes the scheduled time of arrival (STA) for incoming flights, aiming to minimize in-air delays while considering vertiport throughput and aircraft-specific constraints such as remaining energy levels. For departures, the system strategically calculates the scheduled time of departure (STD) to minimize ground delays. The automation system also provides advisories on speeds and holding times to ensure compliance with assigned STAs.

II. Problem Description

A. Framework of the V-HATT

Figure 1 showcases the V-HATT framework, emphasizing terminal airspace and surface management within the UAM ecosystem. The management process encompasses three distinct phases:

1) **Planning phase.** This long-term, monthly planning phase establishes operational scenarios. It involves designing terminal airspace configurations around vertiports, including approach and departure routes, holding pattern locations, and metering gates within structured airspace. Additionally, it requires planning the vertiport surface layout, such as the number and positioning of FATOs, TLOFs, parking gates, and taxiways. In scenarios of high-density traffic, employing demand capacity balancing (DCB) for strategic conflict management, as suggested by [12] and [13], is crucial. Thus, this phase also involves assessing the capacity limitations of the high-performance layer (HPL) of airspace through simulation.
2) **Schedule phase.** Focused on short-term (hourly) automation, this phase schedules the departure and arrival queues within UAM, considering surface resource constraints. It comprises independent arrival and departure management modules that coordinate with surface resource management. The system calculates optimal arrival times, assigns FATOs to incoming aircraft, and determines optimal departure times to minimize ground delays. Upon scheduling, this information updates the surface resource management module, which oversees

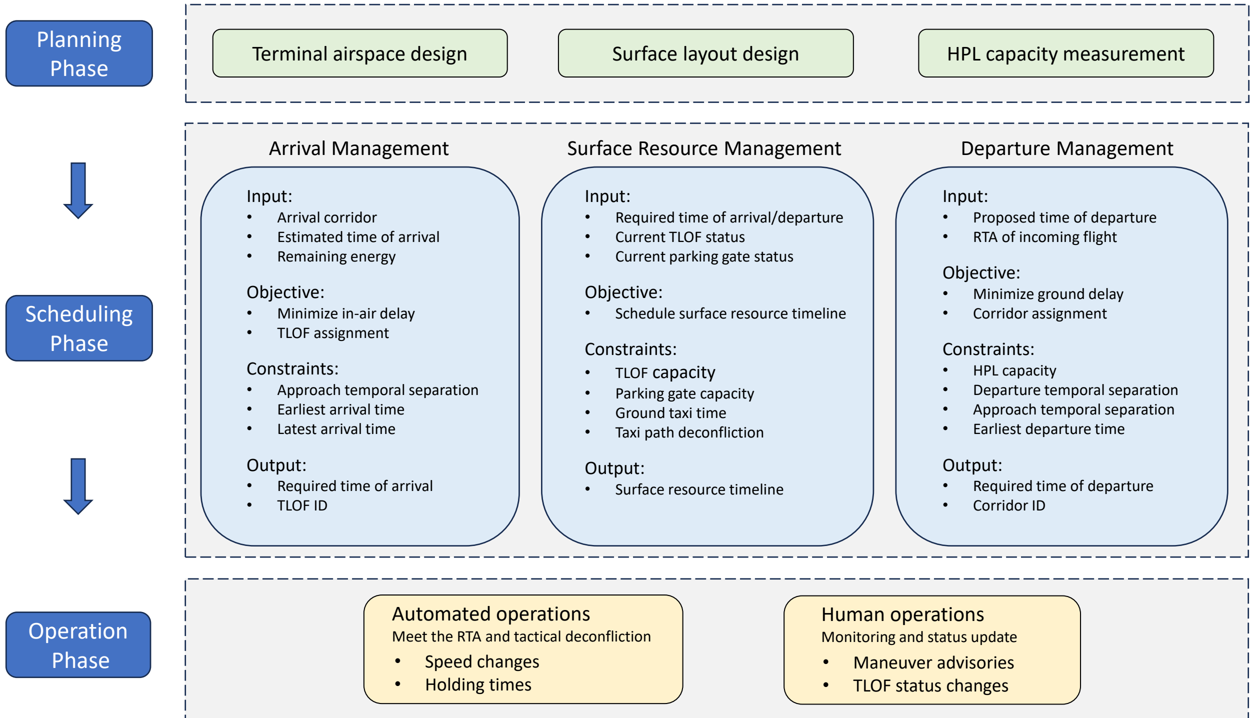


Fig. 1: The framework of Vertiport Human-Automation Teaming Toolbox (V-HATT).

TLOFs, parking gates capacity, and taxi path conflict detection.

3) **Operation phase.** This phase delivers real-time maneuver advisories, integrating inputs from both the automation system and VO. For automated operations, the goal is to achieve the scheduler's calculated optimal STA by adjusting cruise speed and holding times, including tactical deconfliction measures like speed adjustments to prevent collisions. Human operators are essential for overseeing scheduled timelines, monitoring system operations, and updating vertiport resource statuses as needed. They are equipped to issue maneuver advisories, adjust FATOs and TLOFs statuses, and authorize arrivals, departures, and taxi movements.

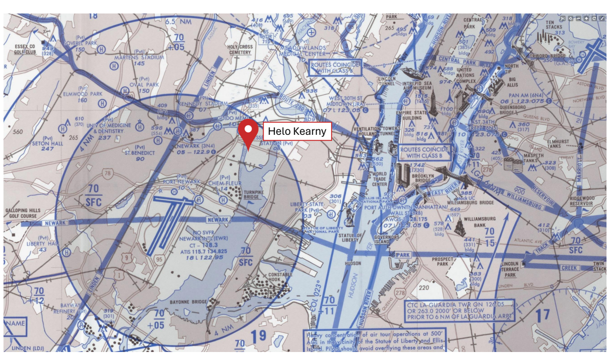


Fig. 2: Aeronautical chart [14] showing Kearney heliport.

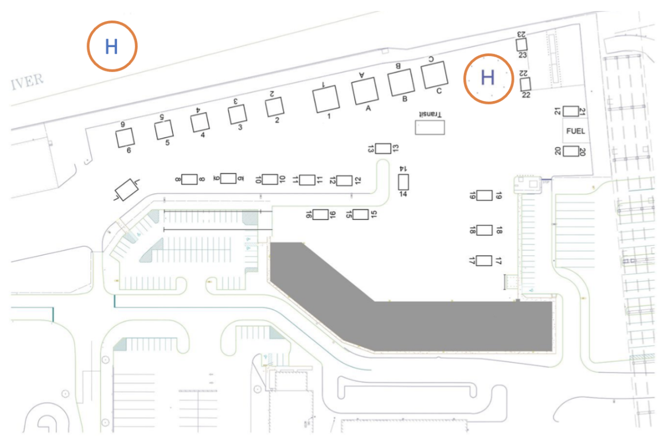


Fig. 3: Layout of the HHI vertiport. The two orange circles denote the FATO, adjacent to these are squares labeled A-C and 1-6, identified as TLOFs. The remaining rectangular areas function as parking gates.

B. Vertiport Layout

As shown in figure 2, the HHI heliport, a privately owned facility located in Kearney, NJ, serves as a model for vertiport use case formulation. Positioned northeast of Newark International Airport (EWR) and directly beneath aircraft arrival and departure paths, this heliport is situated 1.8 miles within the EWR Class B airspace. Consequently, below 500 feet, UAM pilots must use the common traffic advisory frequency (CTAF) to communicate position and flight intent with EWR terminal

Fig. 4: Terminal airspace visualization via the VMI.

and tower controllers to secure clearance for their operations.

Figure 3 illustrates the layout of HHI's landing area. During the final approach phase, aircraft are directed toward the FATOs before making contact with the TLOFs. After landing, the aircraft taxi to a designated parking gate for recharging, refueling, maintenance operations, moving passengers, and loading and unloading cargo. In contrast, the departure process allows for aircraft to directly initiate takeoff from TLOFs, subsequently integrating into established exit routes.

C. Terminal Airspace VMI

To facilitate the monitoring and management of aircraft within terminal airspace and the vertiport environment by the human VO, a VMI was developed.

Figure 4 depicts the terminal airspace page, dynamically displaying all categories of air traffic, including commercial aircraft, general aviation aircraft, helicopters, and eVTOLs, over the map. The HHI vertiport is marked by a blue point, while two red lines delineate corridors designed explicitly for helicopter and eVTOL ingress and egress. Notably, each corridor incorporates two parallel paths, separated by approximately 200 feet, to distinctively manage arrival and departure traffic. An oval pattern above the Hackensack River functions as a holding area, designed to absorb in-air delays during periods of high traffic density, with red dashed lines indicating the pathways most often used for entering and exiting this pattern.

Within the Class B airspace surrounding the HHI heliport, aircraft operations are conducted below 300 feet, ensuring separation from the higher-altitude arrival and departure paths of commercial traffic at EWR. Over the Hudson and East Rivers, helicopter altitudes may vary by as much as 100 feet. To facilitate safe navigation, pilots utilize the CTAF for broadcasting their positions and flight intentions.

Moreover, the VMI provides critical supplementary information, such as current weather conditions, enabling VOs to make informed decisions regarding the operational status of the vertiport, such as closures during adverse weather or the selective use of FATOs based on wind direction. Additionally, the interface displays detailed aircraft information, including type, call sign, ETA, and allocated arrival and departure FATOs, thus enhancing the efficiency and safety of the airspace and vertiport management.

D. Vertiport Scheduler VMI

Figure 5 showcases the scheduler interface for human VOs. This interface provides a dual-paneled view encompassing arrivals and departures, alongside a ribbon view for temporal slot management. The arrivals view panel presents a table that lists incoming aircraft with several key pieces of infor-

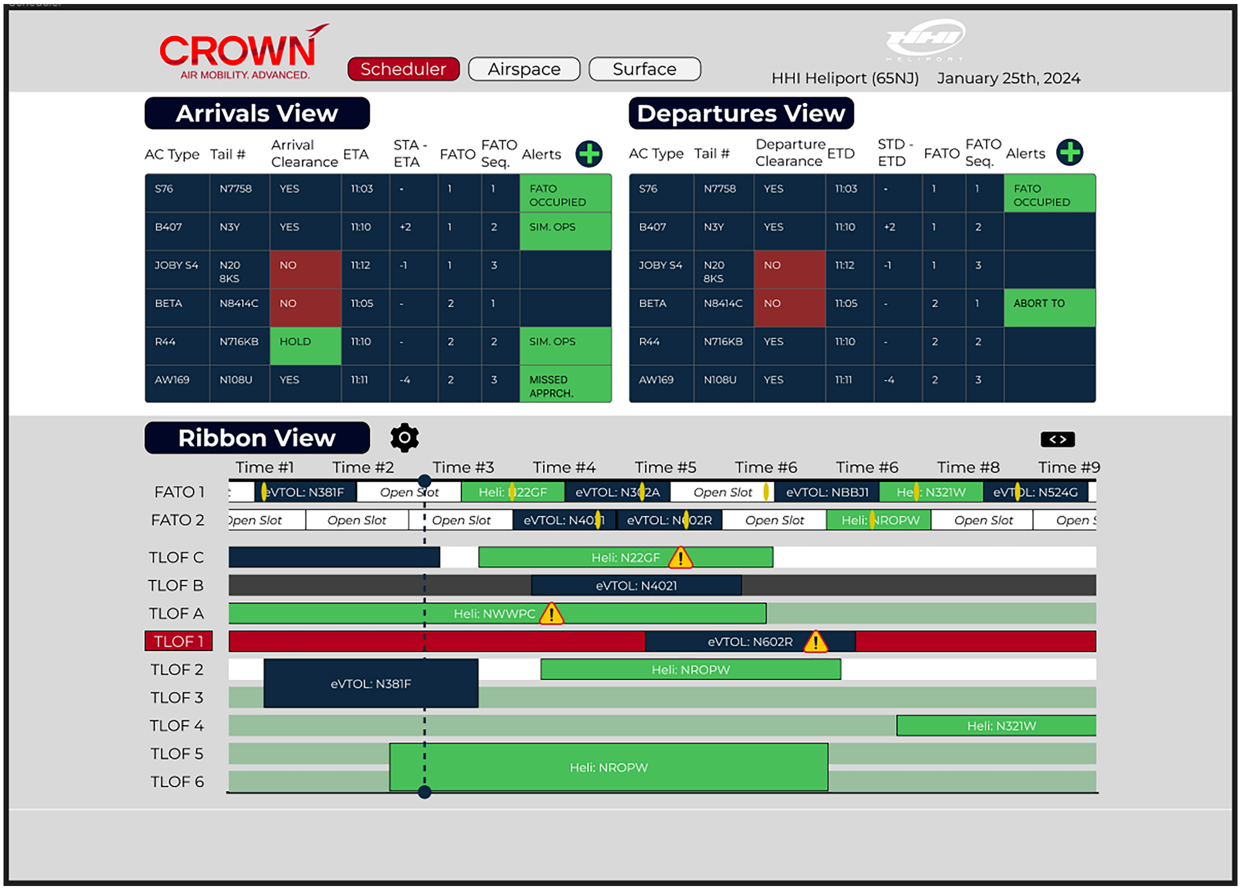


Fig. 5: View of the scheduler from VMI.

mation, including aircraft type, tail number, whether arrival clearance has been granted, time of arrival, assigned FATOs, and alert notes such as "FATO OCCUPIED" or "MISSED APPROACH". The corresponding departures view on the right mirrors this structure for outgoing flights, listing aircraft information, departure time, and alert notes.

The ribbon view in Figure 5 is a timeline-oriented display that spans several time slots. It graphically illustrates FATOs and TLOFs occupancy status. The FATO and TLOF are presented as a horizontal bar, segmented into time intervals. Green or dark blue markings with the appropriate call sign indicate time intervals occupied by aircraft, while white markings indicate available intervals. This display offers a fast, comprehensive view of resource allocation over time, with color-coded warnings, such as orange triangles, alerting to any potential issues or advisories.

In this system, we empower human VOs with the necessary tools to enact adjustments in response to unforeseen events. For instance, should an aircraft fail to meet its scheduled arrival time, the VO is tasked with manually allocating a new time slot and subsequently utilizing the automation system to adjust the schedule of subsequent flights accordingly. The interface thus serves as a dynamic and real-time organizational tool, equipping VOs with the capability to efficiently manage terminal and vertiport traffic flows, bolstered by the underlying automation system.

III. Problem Formulation

A. Arrival Management

After receiving approval from the VO, arriving aircraft initiate the final landing sequence within the terminal airspace surrounding the vertiport. Each aircraft is allocated a STA along with a suggested cruise speed or holding duration to ensure timely arrival, in addition to being designated a specific FATO for landing.

As previously mentioned, the arrival management module calculates the optimal arrival times for incoming aircraft and organizes the arrival sequence. This process takes into account the FATO's availability, the aircraft's dynamics (such as minimum and maximum speeds), and priority levels for arrivals. To determine the most efficient arrival schedule, we employ a MILP approach.

In this optimization framework, we introduce two decision variables: a continuous variable t_f representing the scheduled arrival time for flight f, and a binary variable $\omega_{f,n}$ that designates the reservation of FATO's time slot n. The mathematical formulation is as follows:

$$\min_{\boldsymbol{t}\in\mathbb{R}^+,\boldsymbol{\omega}\in\mathbb{B}} \sum_{f\in\mathcal{F}} |t_f - \hat{t}_f| \quad (1)$$

$$\text{s.t.} \quad t_f \geq \hat{t}_f + d_f^{min}, \qquad \forall f \in \mathcal{F} \quad (2)$$

$$t_f \leq \hat{t}_f + d_f^{max}, \qquad \forall f \in \mathcal{F} \quad (3)$$

$$\sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}_i} \omega_{f,n,i} = 1, \qquad \forall f \in \mathcal{F} \quad (4)$$

$$t_f - s_n \geq M \cdot (\omega_{f,n} - 1), \quad (5)$$
$$\forall f \in \mathcal{F}, i \in \mathcal{I}, n \in \mathcal{N}_i$$

$$t_f - s_n \leq \delta + M \cdot (1 - \omega_{f,n}), \quad (6)$$
$$\forall f \in \mathcal{F}, i \in \mathcal{I}, n \in \mathcal{N}_i$$

$$\sum_{f\in\mathcal{F}} \omega_{f,n} \leq 1, \qquad \forall i \in \mathcal{I}, n \in \mathcal{N}_i \quad (7)$$

The goal of this scheduling approach is to minimally adjust to ensure a safe, efficient, and fair arrival sequence. Therefore, the objective is to minimize the deviation between the scheduled STA t_f and the initially requested ETA $\hat{t}_f$, as depicted in equation (1). This nonlinear absolute value expression is linearized with two supplementary constraints:

$$\min_{\boldsymbol{t}_f,\boldsymbol{e}\in\mathbb{R}^+,\boldsymbol{\omega}\in\mathbb{B}} \sum_{f\in\mathcal{F}} e \quad (8)$$

$$\text{s.t.} \quad e \geq t_f - \hat{t}_f, \qquad \forall f \in \mathcal{F} \quad (9)$$

$$e \geq \hat{t}_f - t_f, \qquad \forall f \in \mathcal{F} \quad (10)$$

Constraint (2) specifies the earliest possible arrival time for flight f by considering its regular cruise speed v_f^c and maximum speed v_f^{max} over a given distance l_f. The term $d_f^{\min}$ denotes the difference in flying duration when utilizing cruise speed versus maximum speed, calculated as:

$$d_f^{min} = \frac{l_f}{v_f^{max}} - \frac{l_f}{v_f^c}$$

This ensures that the scheduler assigns feasible STAs by accounting for the dynamic characteristics of the flight.

Constraint (3) defines the latest permissible arrival time for flight f, incorporating the maximum allowable in-air delay $d_f^{\max}$, which accounts for the longest possible airborne duration given the remaining energy and landing priority. This ensures priority for aircraft with low energy reserves or in emergencies, optimizing the sequence of arrivals.

Constraint (4) ensures that each aircraft can reserve only one time slot across all FATOs $i \in \mathcal{I}$ and their available slots $n \in \mathcal{N}_i$, with $\omega_{f,n} = 1$ indicating that flight f is allocated to arrive at the i-th FATO within time slot n.

Constraints (5-6) determine the allocation of scheduled arrival times t_f to specific time slots. If t_f relative to the start of time slot n, s_n, falls within the interval $[0, \delta]$, then $\omega_{f,n}$ is activated as 1. The parameter δ represents the duration of each time slot, set to 150 seconds to accommodate approach or departure uncertainties and mitigate downstream impacts on subsequent aircraft.

Finally, constraint (7) ensures that each time slot at the FATOs is reserved no more than once, maintaining orderly and efficient slot allocation.

B. Departure Management

Upon finalizing the arrival sequence, the system proceeds to update the availability of FATO's open time slots, subsequently organizing the departure queue. The prioritization of arrivals over departures is predicated on the principle that in-air aircraft inherently necessitate precedence for FATO usage. It is pertinent to highlight that despite the capability of aircraft to execute immediate takeoffs via TLOFs, the allocation of a specific time slot on FATOs is imperative to circumvent potential conflicts between arriving and departing flights.

In managing the departure sequence, the objective to minimize ground delay is important, leading to the development of a congruent MILP formulation detailed as follows:

$$\min_{\boldsymbol{t}\in\mathbb{R}^+,\boldsymbol{\omega}\in\mathbb{B}} \sum_{f\in\mathcal{F}} t_f - \hat{t}_f \quad (11)$$

$$\text{s.t.} \quad t_f \geq \hat{t}_f, \qquad \forall f \in \mathcal{F} \quad (12)$$

$$\sum_{i\in\mathcal{I}} \sum_{n\in\mathcal{N}_i} \omega_{f,n,i} = 1, \qquad \forall f \in \mathcal{F} \quad (13)$$

$$t_f - s_n \geq M \cdot (\omega_{f,n,i} - 1), \quad (14)$$
$$\forall f \in \mathcal{F}, i \in \mathcal{I}, n \in \mathcal{N}_i$$

$$t_f - s_n \leq \delta + M \cdot (1 - \omega_{f,n,i}), \quad (15)$$
$$\forall f \in \mathcal{F}, i \in \mathcal{I}, n \in \mathcal{N}_i$$

$$\sum_{f\in\mathcal{F}} \omega_{f,n,i} \leq 1, \qquad \forall i \in \mathcal{I}, n \in \mathcal{N}_i \quad (16)$$

The goal, as specified by the objective function (11), is to minimize the cumulative ground delay, represented by the sum of the differences between the scheduled departure time t_f and the initially requested departure time $\hat{t}_f$. Constraint (12) ensures that no departure is scheduled before the requested time, thereby allowing sufficient duration for aircraft recharging and passenger transitions. The constraints from (13) to (16) mirror those in the arrival management framework, facilitating the assignment of FATO's open time slots for departures.

C. Speed Control and Airborne Holding Strategy

In the scheduling phase, STA and STD are assigned to each aircraft. During the operational phase, the automation system provides maneuver advisories to ensure that aircraft can adhere to their STA and STD. For departing aircraft, adhering to the scheduled FATO time slot is straightforward, requiring no further restrictions. However, for arriving aircraft, considering the distance from the terminal airspace boundary to the vertiport, it becomes necessary to determine optimal speeds and potential holding times. If an aircraft is capable of maintaining a speed greater than the minimum to achieve its STA, the desired speed v_f^d can be calculated as follows:

$$t_f - \hat{t}_f = \frac{l_f}{v_f^d} - \frac{l_f}{v_f^c}, \tag{17}$$

$$\Rightarrow v_f^d = \frac{l_f \cdot v_f^c}{l_f + v_f^c \cdot (t_f - \hat{t}_f)} \tag{18}$$

For instances where the required airborne delay exceeds a threshold, commanding the aircraft to enter a holding pattern becomes necessary, with the holding duration h_f calculated by:

$$t_f - \hat{t}_f = \left(\frac{l_f}{v_f^{\min}} + h_f \right) - \frac{l_f}{v_f^c}, \tag{19}$$

$$\Rightarrow h_f = t_f - \hat{t}_f + \frac{l_f}{v_f^c} - \frac{l_f}{v_f^{\min}} \tag{20}$$

Algorithm 1 delineates the process for determining aircraft speed and implementing airborne holding:

Algorithm 1: Algorithm for Aircraft Speed Control and Airborne Holding

foreach *aircraft* f **do**
  Calculate arrival time discrepancy $g_f = t_f - \hat{t}_f$
  Determine desired speed $v_f^d = \frac{l_f \cdot v_f^c}{l_f + g_f \cdot v_f^c}$
  if $v_f^d \geq v_f^{\min}$ **then**
    Set speed $v_f \leftarrow v_f^d$
    Set holding time $h_f \leftarrow 0$
    Maintain original route at speed v_f
  else
    Adjust speed to minimum $v_f \leftarrow v_f^{\min}$
    Calculate holding time $h_f \leftarrow g_f + \frac{l_f}{v_f^c} - \frac{l_f}{v_f^{\min}}$
    Reroute aircraft to holding pattern for h_f

Notably, for aircraft like eVTOLs capable of hovering, the minimum speed might effectively be zero. Nonetheless, due to substantial energy demands, sustained hovering is typically reserved for landing and take-off phases. Consequently, a minimum speed threshold (e.g., 50 knots) is established to prevent unnecessary energy expenditure, simulating fixed-wing aircraft flight dynamics en route.

IV. Numerical Experiments

A. Experiments Scenarios

To comprehensively assess the efficacy of the proposed arrival and departure management modules, we designed a series of experiment scenarios that incorporate varying levels of flight demand. Employing the Monte Carlo method, we conducted extensive numerical simulations to evaluate the modules' time efficiency metrics under these diverse conditions.

To mirror real-world operational challenges and test our methodologies under stressful conditions, we delineated two distinct traffic demand scenarios: nominal demand and peak demand. The nominal demand scenario assumes steady arrival and departure requests across the time horizon, thereby simulating a nominal operational tempo. Conversely, the peak demand scenario is engineered to replicate instances of sudden, acute escalations in traffic demand. To generate flight schedules that accurately reflect these scenarios, we opted for the beta distribution. This choice was motivated by the distribution's flexibility, its shape parameters α and β allow for the modeling of varied traffic demand patterns. Detailed specifications of the parameters employed to construct these demand profiles are presented in Table I, while Figure 6 visually contrasts the arrival and departure demands across different scenarios.

TABLE I: Parameters of the Beta Distribution

Flight	Parameter	Scenario	
		Peak	Nominal
Arrival	α	9	2
	β	18	1.5
Departure	α	2	1.5
	β	10	2

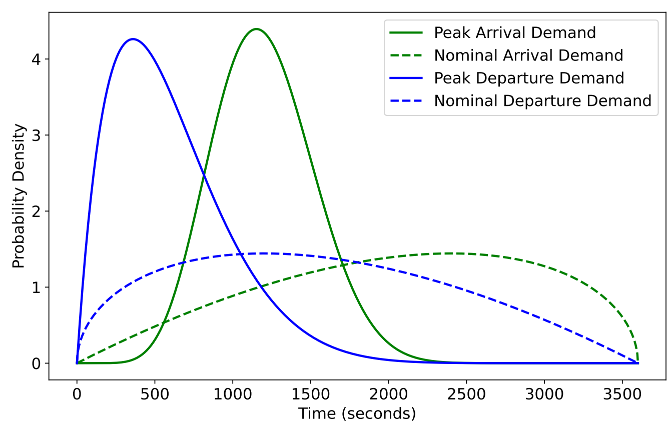
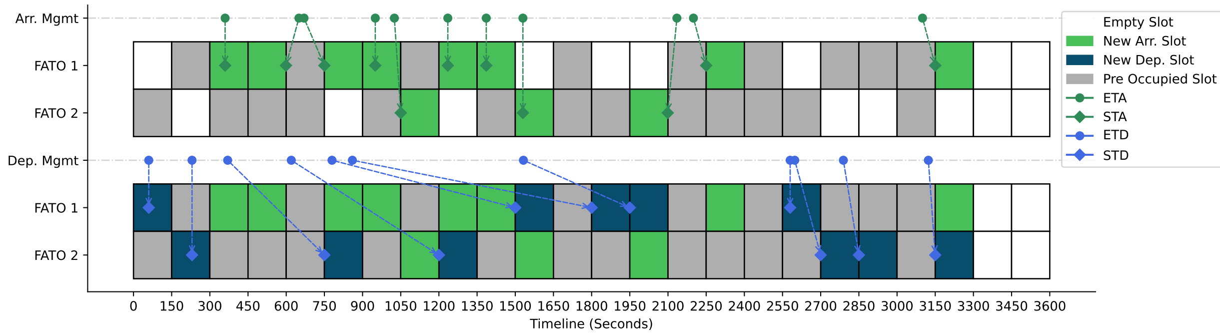


Fig. 6: Arrival and departure demand on peak and nominal scenarios based on beta distribution.

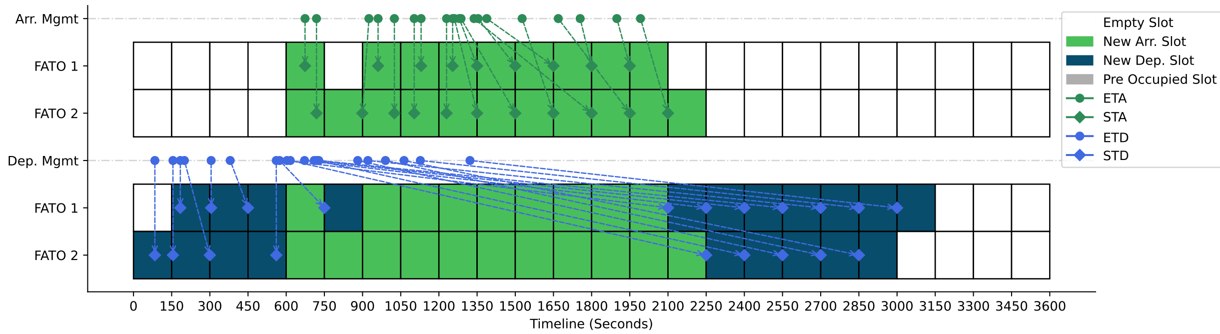
The validation of our algorithms was facilitated by a computing platform, specifically an AMD Ryzen 9 3950X 16-core CPU with 64GB RAM. The resolution of programming challenges was handled through Gurobi 10.0.2, a state-of-the-art optimization solver.

B. Visualization of Arrival and Departure Schedules

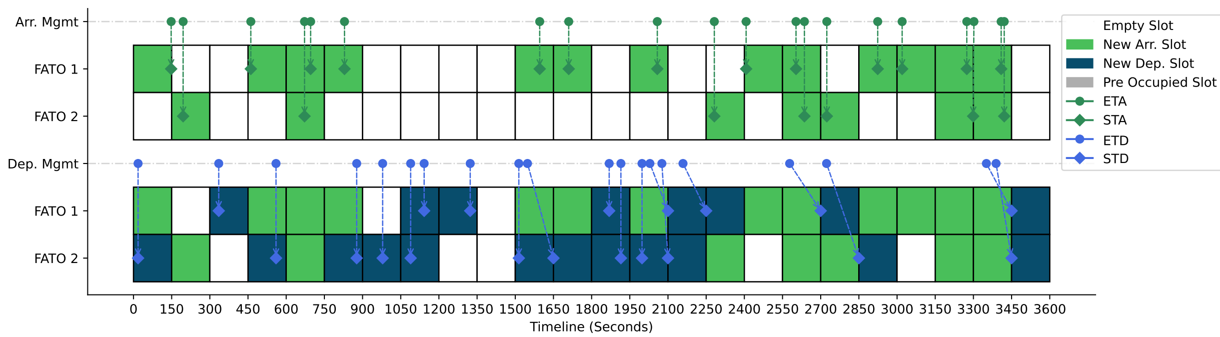
To elucidate the scheduling phase, we employed visualizations encompassing three distinct scenarios: schedules incorporating pre-occupied time slots, peak demand schedules, and nominal demand schedules. As depicted in Figure 7, each visualization comprises two bars symbolizing the status of time slots after arrival and departure management. Within these bars, each row signifies the time slots allocated to one of the two FATOs at the HHI vertiport, with each time slot spanning 150 seconds. Color coding is utilized to denote the



(a) Schedule with the pre-occupied time slots.



(b) Schedule on peak demand.



(c) Schedule on nominal demand.

Fig. 7: Visualization of arrival and departure management.

status of each time slot: white indicates availability for arrivals or departures, green signifies reservations for arrivals, blue for departures, and grey represents pre-occupied slots—either carried over from previous scheduling periods or temporarily closed due to exceptional circumstances. Moreover, the visualization integrates dots to represent original arrival and departure demands, thereby illustrating the efficacy of the scheduling algorithm. This visual format is designed for display on the scheduler VMI, facilitating easy monitoring and adjustment by the VO.

The scheduling phase prioritizes arrival sequencing before addressing departures, a strategy driven by the significantly higher costs associated with in-air holding compared to ground delays. This prioritization is evident in Figure 7, where the adjustments in arrival times are notably less drastic than those for departures, particularly under peak demand conditions. In such scenarios, the latter portion of the fleet may incur ground delays to ensure minimal in-air adjustments for incoming flights.

Despite the automation system's capabilities in optimizing flight scheduling, certain scenarios necessitate manual intervention by the VO. The system's optimal time slot assignments must contend with the variable performance of pilots and unforeseeable events like missed approaches or delays in take-off. Although the design of the 150-second time slots aims to provide a sufficient buffer for pilot variability, overlapping arrivals and departures may still occur. In these instances, the VO must closely monitor schedule execution and make requisite adjustments to accommodate incoming aircraft.

C. Time Efficiency Analysis.

In this study, we employed Monte Carlo simulations to examine the outcomes across various demand scenarios—low (10 arrivals and 10 departures per hour) and high (20 arrivals and 20 departures per hour) demands, under both even and peak conditions. This analysis aimed to elucidate the efficacy of our system in orchestrating arrival and departure schedules among fluctuating traffic volumes. We conducted 30 simulation runs for each scenario, with results depicted in Table II.

TABLE II: Simulation results

Scenario	Nominal	Nominal	Peak	Peak
Demand	**Low**	**High**	**Low**	**High**
Ave. in-air delay (sec.)	0.2	2.4	4.0	130.9
Ave. early arrival time (sec.)	0.1	0.7	1.1	1.4
Ave. ground delay (sec.)	17.8	281.2	128.0	1116.9
Max in-air delay (sec.)	21.0	236.0	142.0	1018.0
Max ground delay (sec.)	394.0	1219.0	937.0	2079.0
Arrival reschedules rate	2.3%	9.8%	13.0%	69.6%
Departure reschedules rate	14.6%	71.2%	48.7%	79.8%

The simulations unearthed several critical insights into the system's operational dynamics:

1) **In-Air and Ground Delays:** A visible escalation in both in-air and ground delays was observed as we transitioned from low to high demand, and from nominal to peak scenarios. This pattern highlights the challenges faced by the system in maintaining traffic flow efficiency under intensified demands, especially during peak periods. The analysis of peak demand scenarios illuminates the system's vulnerability to extreme conditions, revealing a significant escalation in delays—airborne delays peaking at 1018 seconds and ground delays at 2079 seconds. This extended airborne delay not only augments aircraft energy consumption but also heightens the risk of mid-air collisions due to overcrowded holding patterns. Concurrently, prolonged ground delays result in excessive occupancy of parking gates, thereby constraining the system's capacity to accommodate incoming flights and further exacerbating airborne delays. Such conditions pose challenges to the management of arrivals, surface operations, and departures, underscoring the need for integrated strategies to mitigate these impacts.
2) **Early Arrivals:** We define early arrival as instances where pilots increase their speed to arrive ahead of their scheduled time, and the level depends on the gap between max speed and cruise speed, as well as the distance to the destination. Although these adjustments are relatively minor compared to in-air delays, they play a pivotal role in augmenting the overall efficiency of vertiport utilization.
3) **Rescheduling Rates:** This metric, indicative of the frequency with which flights undergo modifications to their requested arrival and departure times, serves as a gauge for the automation system's proactive engagement and its efficacy in alleviating the operational workload on human VOs. The observed escalation in rescheduling rates with increasing traffic volumes underscores the necessity to develop this human-machine teaming toolbox to solve scheduling challenges for future high-density urban airspace.

While the system demonstrates commendable efficiency in managing traffic under low and nominal demand conditions, it encounters challenges in high and peak demand scenarios. These challenges, marked by significant delays and a heightened necessity for schedule adjustments, underscore the imperative for advanced traffic management strategies. Implementing strategies such as demand-capacity balancing could be pivotal in managing the influx of aircraft in terminal airspace during sudden demand spikes, thereby ensuring smoother operations.

D. Computational Time.

In this experiment, we analyzed the computational efficiency of our proposed method to determine its capability to address varying scales of the problem at hand. Specifically, we varied the scheduling horizon from 0.5 to 6 hours, correlating to an increase in the number of flights from 10 to 120. The outcomes, detailed in Table III, demonstrate a linear relationship between the problem size and the computational time. Notably, our system is capable of scheduling up to 120 aircraft within one minute. These findings underscore the robust efficiency of our proposed MILP approach.

TABLE III: Computational Time on Different Scales

Schedule Horizon (hours)	Number of Flights	Computational (Seconds)	
		Mean	**Std**
0.5	10	0.46	0.05
1.0	20	1.63	0.18
2.0	40	6.18	0.68
3.0	60	13.61	1.50
6.0	120	53.33	6.01

V. CONCLUSION

In this work, we presented the implementation of the V-HATT framework, including the design of terminal airspace and vertiport layouts in New York City for UAM, the procedural strategies for approach and departure, and the strategic methods for efficient terminal airspace and vertiport management. Central to our study was the development of an automated system within the V-HATT framework, leveraging a MILP-based strategic method for optimizing arrival and departure timings, coupled with a tactical algorithm for in-air speed and holding time adjustments. We further elucidated the role of VMIs, which facilitate crucial human VOs oversight for schedule verification, execution monitoring, and manual intervention in response to unforeseen events.

Our experimental visualization highlighted the effectiveness of the strategic management module in sequencing arrivals and departures, while also identifying operational challenges necessitating further VOs intervention. The analysis of time efficiency revealed the system's adaptability to variable traffic patterns, though it also highlighted the potential large delay under high-demand scenarios, suggesting the need for additional strategies to enhance operational fluidity. Moreover, our computational time analysis attested to the proposed methods' efficiency and their applicability in real-time operations.

Looking ahead, the V-HATT project aims to broaden its scope by integrating current management protocols with surface operations, including taxiway deconfliction and parking gate assignments for essential services such as battery charging and passenger loading. This expansion will be tested in a simulated environment incorporating human-in-the-loop interactions. We are optimistic that our contributions will lay a foundational framework for future UAM management systems.

References

[1] P. Krois, J. Block, P. Cobb, G. Chatterji, S. Chen, and P. Wei, "The vertiport human automation teaming toolbox (V-HATT) for the design and evaluation of urban air mobility Infrastructure," in *AIAA SCITECH 2024 Forum*, 2024, p. 1952.

[2] S. Chen, P. Wei, P. Krois, J. Block, P. Cobb, G. Chatterji, and C. Kurian, "Arrival management for high-density vertiport and terminal airspace operations," *The Journal of Air Traffic Control*, 2023.

[3] Federal Aviation Administration, *Urban Air Mobility (UAM) Concept of Operations v2.0*. U.S. Department of Transportation Federal Aviation Administration, Washington DC, 2023.

[4] ——, "Engineering brief no. 105, vertiport design," September 2022, https://www.faa.gov/airports/engineering/engineering_briefs/engineering_brief_105_vertiport_design.

[5] Australian Government Civil Aviation Safety Authority, "Guidelines for vertiport design," Draft Advisory Circular AC 139.V-01 v1.0, 2022, https://consultation.casa.gov.au/regulatory-program/draft-ac-139-v-01-v1-0/supporting_documents/Draft%20AC%20139.V01%20v1.0.PDF.

[6] European Union Aviation Safety Agency, "Vertiports: Prototype technical specifications for the design of vfr vertiports for operation with manned vtol-capable aircraft certified in the enhanced category," PTS-VPT-DSN, 2022, https://www.easa.europa.eu/en/document-library/general-publications/prototype-technical-designspecifications-vertiports.

[7] Northeast UAS Airspace Integration Research Alliance (NUAIR), "High-density automated vertiport concept of operations," NASA, NASA Technical Reports 20210010603, March 2021. [Online]. Available: https://ntrs.nasa.gov/citations/20210010603

[8] N. Mendonca, J. Murphy, M. D. Patterson, R. Alexander, G. Juarex, and C. Harper, "Advanced air mobility vertiport considerations: A list and overview," in *AIAA AVIATION 2022 Forum*, 2022, p. 4073.

[9] S. Shin and K. Lee, "Assessment of approach and departure paths for vertical takeoff and landing aircraft," *Journal of Aerospace Information Systems*, vol. 20, no. 12, pp. 917–922, 2023.

[10] I. C. Kleinbekman, M. Mitici, and P. Wei, "Rolling-horizon electric vertical takeoff and landing arrival scheduling for on-demand urban air mobility," *Journal of Aerospace Information Systems*, vol. 17, no. 3, pp. 150–159, 2020.

[11] P. Pradeep and P. Wei, "Heuristic approach for arrival management of aircraft in on-demand urban air mobility," *Journal of Aerospace Information Systems*, pp. 1–12, 2020.

[12] S. Chen, P. Wei, A. D. Evans, and M. Egorov, "Estimating airspace resource capacity for advanced air mobility operations," in *AIAA AVIATION 2022 Forum*, 2022, p. 3317.

[13] S. Chen, A. D. Evans, M. Brittain, and P. Wei, "Integrated conflict management for uam with strategic demand capacity balancing and learning-based tactical deconfliction," *IEEE Transactions on Intelligent Transportation Systems*, 2024.

[14] United States National Ocean Service, "Helicopter route chart, new york," [Washington: U.S. Dept. of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service], 1999, map. Available online: https://www.loc.gov/item/00557352/.