Heuristic Approach for Arrival Sequencing and Scheduling for eVTOL Aircraft in On-Demand Urban Air Mobility

Priyank Pradeep
Aerospace Engineering
Iowa State University
Ames, IA, USA
ppradeep@iastate.edu

Peng Wei
Aerospace Engineering
Iowa State University
Ames, IA, USA
pwei@iastate.edu

***Abstract*—The electric vertical takeoff and landing (eVTOL) aircraft sequencing and scheduling problem have been formulated in urban air mobility (UAM) context for a mixed fleet (winged/wingless) of eVTOLs expected to land on a vertiport with single landing pad. The objective of the problem is to minimize the makespan (landing completion time) of a given set of eVTOLs, which is equivalent to maximizing the arrival throughput. The landing order (sequence) and makespan of the mixed fleet is optimized using a heuristic approach called insertion and local search (ILS) combined with two different scheduling methods i) mixed-integer linear programming (MILP) or ii) time-advance (TA) algorithm. Finally, sensitivity analysis is performed to see the impact of number of eVTOLs expected to land on computational times of both the algorithms. Through numerical simulations and sensitivity analysis, our algorithms demonstrated real-time scheduling capabilities for on-demand UAM arrivals, which can be used as a potential future service for UAM vertiports and terminal airspace.**

***Keywords*—Electric Vertical Takeoff and Landing (eVTOL), Insertion and Local Search (ILS), Mixed Integer Linear Programming (MILP), Required Time of Arrival (RTA), Urban Air Mobility (UAM).**

I. INTRODUCTION

Commuting time has an adverse impact on physical activity and cardiorespiratory fitness (CRF) of human beings [1]. In 2014, road-traffic congestion resulted in a wastage of 6.9 billion person-hours and 3.1 billion gallons of excess fuel consumed in the USA alone [2]. On-demand passenger electric vertical takeoff and landing (eVTOL) aircraft are perceived as the key enabler for urban air mobility (UAM) to cut down on daily commute time for people and reduce carbon footprint by utilizing three-dimensional airspace efficiently with zero operational emission [3]–[5].

Recently, technological advances have made it possible to build and flight test eVTOL aircraft to make them a reality in the near future. Over a dozen companies, e.g., Airbus, Aurora, Bell, EHang, Embraer, Jobby Aviation, Lilium, Pipistrel, Volocopter, and Zee.Aero, with many different design approaches, are passionately working to ensure safe and energy efficient eVTOL aircraft become an integral part of a daily commute [3]–[6]. The eVTOL aircraft designs vary from multirotor (EHang 184, Volocopter) to tilt-rotor/tandem tilt-wing (Joby S2, Airbus Vahana, Zee.Aero). However, all of them have one thing in common, i.e., use of distributed electric propulsion (DEP) technology and a redundant battery bus architecture to avoid the problem of catastrophic engine failure by having full propulsion system redundancy [3].

II. BACKGROUND AND MOTIVATION

A. Background

The envisioned concept of UAM involves a network of eVTOL aircraft that will enable rapid and reliable transportation between suburbs and downtown of cities and within cities (intra-city) [3], [7]. Similar to Unmanned Aircraft System Traffic Management (UTM), the air traffic services for UAM need to safely and efficiently manage eVTOL aircraft without burdening Air Traffic Control (ATC) or impacting traditional aviation operations [7], [8]. However, unlike the small UAV that can take off and land almost anywhere in the UTM framework, eVTOL aircraft of UAM operation need to take off from and land at vertiports.

From our previous research on trajectory optimization of eVTOLs, we learned that arrival air traffic flow needs to be separated for wingless (multirotor) eVTOL aircraft from winged (tilt-rotor/tandem tilt-wing) eVTOL aircraft because of difference in cruise speeds [4], [5]. For example, the cruise speed of multirotor eVTOL aircraft EHang 184 is 27.78 m/s, whereas the minimum maneuver speed of Airbus Vahana (tandem tilt-wing eVTOL) is 45.5 m/s [6], [9], [10]. Hence, it would be a big challenge for eVTOL arrival sequencing and scheduling service provider to safely and efficiently maintain minimum separation between the wingless and winged eVTOLs especially when winged eVTOL is trailing the wingless on the same airway in UAM. Therefore, we propose an airspace design concept to separate wingless eVTOL arrival air traffic from winged until merging at the metering fix because of the aforementioned reason.

B. Motivation

Before the large-scale fully autonomous UAM operations become true, the first bottleneck of UAM traffic throughput is expected to appear at the vertiport (or skyport) terminal airspace. In UAM operations, we anticipate that the arrival phase (compared with departure) will be one of the most safety-critical phases of flight. This is because of the following reasons: (1) arrival traffic will be restricted by the capacity of vertiports, and air traffic is, in general, dynamic and complex in terminal airspace; (2) flight endurance of eVTOL aircraft will be limited by the specific energy (the amount of energy per unit weight provided by the battery) and state-of-charge (SOC) of lithium-ion polymer (Li-Po) batteries [3], [4]. Therefore, UAM operations will require safe and efficient services similar to ATC services in National Airspace System (NAS) for commercial aircraft [3], [7]. However, matured UAM operations will require introducing orders-of-magnitude more eVTOL aircraft in given airspace then that can be accommodated by the current air traffic control (ATC) system [7].

Our research on solving the arrival sequencing and scheduling for eVTOL aircraft in UAM is inspired by deterministic modeling of arrival sequencing and scheduling problem in the terminal area for commercial air traffic [11]–[16]. First-come-first-served (FCFS), is the most straightforward arrival sequencing and scheduling method as it schedules the aircraft in the order of their estimated time of arrival (ETA) to the metering points (gates and runway threshold) [13]. The FCFS sequencing order provides a sense of fairness and is easy to implement for the ATC. However, it can not achieve optimal runway throughput in UAM because of very different nominal cruise speeds of various eVTOL aircraft. Therefore, mixed fleet of eVTOLs (winged/wingless) and the low specific energy of Li-Po batteries provides an incentive to deviate from the FCFS order and find the most efficient sequence (landing order) with optimal spacing between the eVTOL aircraft to maximize vertiport throughput for UAM arrival operations.

Finding an optimal arrival sequencing order is a non-deterministic polynomial time (NP) hard problem [15], [16], [20]–[22]. Hence, instead of finding an exact solution for sequencing order, many researchers have investigated heuristic and metaheuristic optimization algorithms for commercial air traffic [15], [16], [20]–[22]. Furthermore, due to the anticipated dynamic environment of on-demand UAM operations, it might not be possible to compute the optimal arrival sequence of eVTOLs that deviates significantly from the FCFS order in real time. However, we anticipate that arrival sequencing and scheduling service provider for UAM will have the computing capability to explore other sequences by shifting eVTOL landing slots by a small number from its FCFS order like the commercial aircraft in the terminal area [15], [16], [21], [23]. This paper aims to solve eVTOL arrival sequencing and scheduling problem in UAM using insertion and local search (ILS) heuristic approach [15].

In commercial air traffic world, one possible approach to decrease the average delay incurred by aircraft and maximize the runway throughput is to accelerate from their ideal speeds. This strategy is known as time advance (TA) [13], [16]. Similarly, to maximize the throughput at a vertiport, given the anticipated randomness in on-demand traffic in UAM and different cruise speeds of various eVTOLs, time-advance (TA) strategy [13], [16] has been combined with the ILS in this paper.

III. PROBLEM STATEMENT

A. CONOPS for eVTOL aircraft arrivals

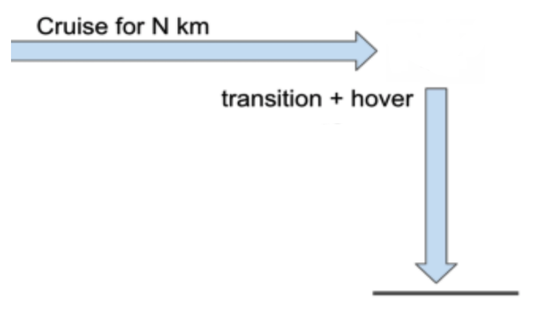

Fig. 1. Proposed CONOPS for eVTOL aircraft arrivals by Airbus Vahana [6]

In this paper, the arrival concept of operations (CONOPS) for the mixed fleet of eVTOL aircraft (wingless/winged) is assumed to be cruising at a constant altitude followed by the vertical descent to land on the vertiport with single landing pad. The vertical descent would be exceptionally safe when skyscrapers surround the vertiport. Therefore, for such vertiports, we assume the first metering fix (MF1) for arrival at cruise altitude directly above the vertiport and the second metering fix (MF2) at the vertiport itself. The ETA for each eVTOL aircraft to the MF1 is assumed to be based on the following: i) nominal cruise speed of the eVTOL aircraft, ii) airways to the first metering fix are geodesic path, iii) negligible time to decelerate to hover, and iv) no miles-in-trail enroute restrictions on the airways. The ETA for the i^{th} eVTOL aircraft to the MF2 is given by:

$$ETA(i)_{MF2} = ETA(i)_{\text{MF1}} + t_{\text{i}} \quad \forall\ i \tag{1}$$

where t_{i} is the vertical time of descent for the i^{th} eVTOL aircraft. Since the MF1 is also a merging point for eVTOL air traffic in UAM, therefore, the ETAs of eVTOL aircraft to the MF1 is used to define the FCFS order.

B. Objective of the problem

The goal of a scheduler is to assign each aircraft in the arrival traffic a required time of arrival (RTA) to the metering fix. However, for safety the RTA(i) for the i^{th} eVTOL aircraft should lie between it's earliest time of arrival (E(i)) and latest time of arrival (L(i)) to the metering fix.

We anticipate that the arrival sequencing and scheduling

Fig. 2. Vertiport with single landing pad [2]

service providers for eVTOL aircraft would like to land the sequence of eVTOLs as soon as possible, given the limitations with Li-Po batteries and safety concerns associated with air traffic congestion in the terminal area. The optimization problem of minimizing the makspan i.e. the RTA of the last eVTOL (in the mixed fleet) to the MF1 is equivalent to maximizing vertiport throughput [15], [16]. Hence, the objective of this research is to find the eVTOL aircraft landing order heuristically for a given set of mixed fleet of eVTOLs such that the makespan of the eVTOLs (n) expected to land is minimized. Therefore, the decision variables are the set of (RTA)s to the MF1 and the objective of the problem is to minimize the RTA of the last eVTOL aircraft to the MF1:

$$min.\ RTA(n)_{\text{MF1}} \tag{2}$$

C. Window constraints on arrival scheduling

As stated above the following window constraints are imposed on the $RTA(i)_{\text{MF1}}$ of each eVTOL aircraft, where i denotes the i^{th} aircraft in the arrival traffic sequence:

$$E(i)_{MF1} \leq RTA(i)_{\text{MF1}} \leq L(i)_{MF1} \quad \forall\ i \tag{3}$$

Given the $ETA(i)_{\text{MF1}}$: (a) the earliest time of arrival to the MF1 $(E(i)_{\text{MF1}})$ is calculated based on the maximum speed of the eVTOL aircraft i; and (b) the latest time of arrival $(L(i)_{\text{MF1}})$ is calculated based on the mission and state-of-charge (SOC) of the Li-Po battery pack of the eVTOL aircraft i, however, in the current research it is randomly assigned a value between 900 to 1200 seconds above the $ETA(i)_{MF1}$ for each eVTOL aircraft. In the future, we will incorporate Li-Po battery model [18], [19] to estimate the latest times of arrival of eVTOLs more realistically.

D. Minimum time separation

As UAM would involve low altitude operations [2], [6], [9] and the focus of this paper is on the vertiport with single landing pad. Therefore, we imposed a safety requirement that the trailing eVTOL aircraft shall not descend unless the leading has landed on the vertiport. Hence, the minimum time separation (t_{ij}) between the trailing eVTOL aircraft j and the leading eVTOL aircraft i is dependent on the vertical time of descent (t_i) of the leading eVTOL aircraft (i) and is independent of the trailing eVTOL aircraft (j).

$$t_{ij} = t_i \quad \forall\ i < j \tag{4}$$

Therefore, the following constraints have been imposed on the eVTOL sequencing and scheduling problem:

$$t_i \leq RTA(j)_{MF1} - RTA(i)_{\text{MF1}} \quad \forall\ i < j \tag{5}$$

In this paper, the vertical descent is assumed to be from the cruise altitude of 500 m above sea-level to vertiport at sea-level. The vertical time of descent (t_i) for winged and wingless eVTOLs is computed using the multiphase optimal control framework (minimum energy path) from our previous research on trajectory optimization of Airbus Vahana and EHang 184 respectively [4], [5]. The multiphase optimal control problem is transcribed using GPOPS-II, and then IPOPT has been used as the solver to solve the problem transcribed to nonlinear programming by GPOPS-II [24], [25].

TABLE I
Minimum time separations (sec) at the MF1

Leading eVTOL \ Trailing eVTOL	Winged	Wingless
Winged	151	151
Wingless	173	173

IV. PROPOSED ALGORITHM

A. Insertion and local search heuristics

The insertion and local search (ILS) heuristic algorithm developed in this paper for arrival sequencing and scheduling of eVTOL aircraft expected to land on a vertiport with single landing pad, is based on the ILS algorithm described for single runway scheduling of commercial air traffic by Malik and Jung [15].

The heuristic starts with the initial guess for eVTOL aircraft arrival sequence as the FCFS to the MF1. The iteration begins for fixing the 1^{st} position in the arrival sequence and then it continues till fixing the $(n-k+1)^{th}$ position, where n is the total number of eVTOL aircraft expected to land on the vertiport and k is the number of eVTOL aircraft involved in each iteration for local neighborhood search (local optimization). For example, the i^{th} iteration for fixing the i^{th} position in the arrival sequence involves local neighborhood search starting from the i^{th} position in the sequence till the $(i+k-1)^{th}$ position. Hence, at each iteration $k*(k-1)$ sequences (permutations) of eVTOL aircraft are possible. Therefore, local optimization is carried out $k*(k-1)$ times to pick the preferred local sequence and fix the i^{th} position with the best eVTOL aircraft. During the local neighborhood search, the preferred sequence is the one with the least objective value among all the objective values in the $k*(k-1)$ sequences. Hence, after the i^{th} iteration, the eVTOL aircraft positions from 1^{st} till i^{th} are considered fixed whereas the positions from $(i+1)^{th}$ till n^{th} are considered free. However, at the end of fixing the $(n-k+1)^{th}$ position, the eVTOL aircraft positions at $n+2-k, ..., n$ are fixed based on the preferred sequence for $(n-k+1)^{th}$ position in the arrival sequence as shown in Fig. 3.

Consider a feasible sequence (H) consisting of n eVTOL aircraft $(a_1, a_2, a_3, ...a_n)$. For example, when $k = 3$, six different sequences (H_i^1, H_i^2, H_i^3, H_i^4, H_i^5, H_i^6) are possible during the i^{th} iteration by juggling eVTOL aircraft located at free neighborhood positions: $i, i+1$ and $i+2$ [15]. Fig. 4, shows a few iteration steps of the ILS algorithm for $k = 3$ and fleet of 10 eVTOL aircraft expected to land, starting with the FCFS order. The green highlight indicates the preferred sequence of k free eVTOL aircraft during the i^{th} iteration that fixes the eVTOL aircraft for the i^{th} position in the sequence. The preferred sequence is the one with the least optimal objective value among all the six possibilities during the local neighborhood search. Finally, the i^{th} position (blue box in Fig. 4) in the arrival sequence is fixed using the eVTOL aircraft at the i^{th} position in the preferred sequence during the iteration.

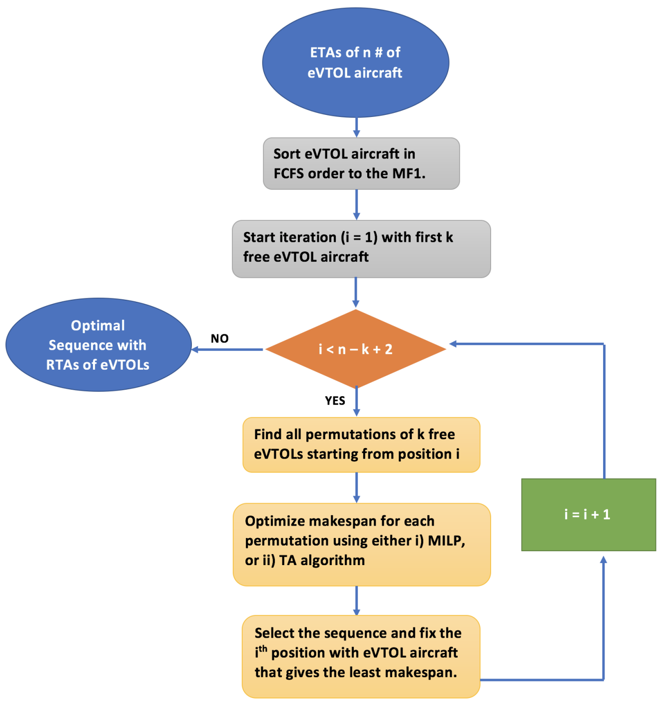

Fig. 3. Block diagram of arrival sequencing and scheduling

As stated in the previous section, the objective function of the eVTOL aircraft arrival sequencing and scheduling problem is to minimize the RTA to the MF1 of the last eVTOL aircraft in the arrival sequence. The optimal objective value for each sequence in a given iteration is computed using either the open source MILP solver Gurobi Optimizer [26] or in-house developed time advance (TA) algorithm [13], [16].

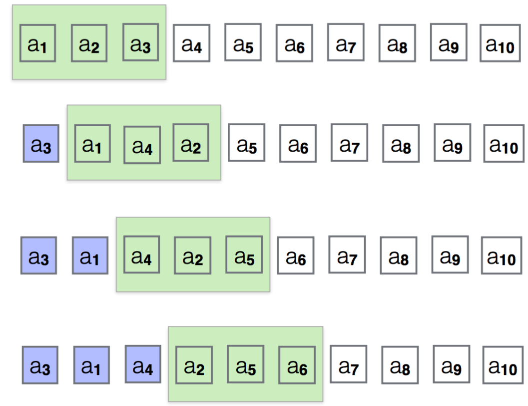

Fig. 4. Example of ILS algorithm for eVTOL arrival sequencing and scheduling [15]

B. TA algorithm

The main idea behind the TA algorithm is to speed-up an eVTOL whenever the separation from the leading eVTOL is larger than the minimum time separation (t_{ij}). Therefore, the $RTA(j)_{MF1}$ for the j^{th} eVTOL aircraft trailing behind the i^{th} eVTOL aircraft is given by:

$$RTA(j)_{MF1} = max\{E(j)_{MF1}, RTA(i)_{MF1} + t_{ij}\} \ \forall \ i < j \tag{6}$$

The above equation is based on the assumption that time to transition to hover is negligible. However, for the feasibility of the solution, the (RTA)s of all eVTOL aircraft to the MF1 should be less than their corresponding latest times of arrival to the MF1.

V. NUMERICAL SIMULATIONS AND RESULTS

A. Numerical Simulations

We anticipate arrival air traffic to a vertiport would be at random time distribution because of the on-demand nature of UAM but at an average rate when viewed as a group for a set of eVTOLs expected to land on a vertiport. Therefore, we simulated the estimated times of arrival (ETA)s of eVTOL aircraft using Poisson arrival process [27] using Python 3.6 (high-level programming language) [28] on MacBook Pro with 2.8 GHz Intel Core i7 processor. In this research, we simulated two types of eVTOL air traffic, i.e., winged and wingless, both arriving via different airways and merging at the MF1.

The earliest time of arrival of each eVTOL to the MF1 is calculated by ignoring transition and hover time. Therefore, the earliest time of arrival $(E(i))$ of the i^{th} eVTOL aircraft to the MF1 is set to be as follows:

$$E(i)_{MF1} = \frac{V_{cruise}}{VMO} * ETA(i)_{MF1} \quad \forall \ i \tag{7}$$

where V_{cruise} is the nominal cruise speed and VMO is the maximum cruise speed of the eVTOL aircraft.

The latest time of arrival ($L(i)$) of the i^{th} eVTOL aircraft to the MF1 is set to be as follows:

$$L(i)_{MF1} = ETA(i)_{MF1} + U(t) \quad \forall\, i \tag{8}$$

where $U(t)$ is a random function which uniformly samples a value between 900 and 1200 seconds. In this paper, we used function $U(t)$ to simulate the effect of remaining SOC of the Li-Po battery pack on the ETA of an eVTOL.

The winged eVTOL aircraft in the air traffic are simulated per the performance characteristics of Airbus Vahana [5], [6] whereas wingless eVTOL aircraft are simulated per the performance characteristics of EHang 184 [4], [9] as shown in Table II.

TABLE II
Performance data of eVTOL aircraft

eVTOL Type	**Nominal Cruise Speed** (m/s)	**VMO** (m/s)
Winged	45.5	80
Wingless	27.77	33.33

In this research, we assumed mixed fleet of 10 eVTOL aircraft expected to land in 1800 seconds on a vertiport with single landing pad.

B. Results

The proposed heuristic methods (ILS-MILP and ILS-TA) to minimize the makespan of a given set of eVTOLs are written in Python 3.6 and run on MacBook Pro with 2.8 GHz Intel Core i7 processor. The algorithms are tested using the case studies as described in this section.

1) Case study I - fleet mix ratio (5/5): In this case study, the ETAs of 5 winged and 5 wingless eVTOL aircraft are generated separately using Poisson arrival process assuming a total time interval of 1800 seconds for each fleet.

From Table III and Table IV, we can observe that for the simulated mixed fleet of eVTOLs and their respective (ETA)s to the MF1, both the methods (ILS-MILP and ILS- TA) minimized the makespan (RTA of the last eVTOL to the MF1) to the same value (1517.68 seconds). The minimization of the makespan was achieved by speeding-up eVTOLs whenever possible without violating any constraints. Also, it can be seen that for this simulation the preferred landing order (sequence) is FCFS. However, ILS-MILP method computed the optimal landing order and RTAs in 0.729 seconds whereas ILS-TA method computed the optimal results in 0.012 seconds.

2) Case study II - fleet mix ratio (7/3): In this case study, the ETAs of 7 winged and 3 wingless eVTOL aircraft are generated separately using Poisson arrival process assuming a total time interval of 1800 seconds for each fleet.

From Table V and Table VI, we can observe that for the simulated mixed fleet of eVTOLs and their respective (ETA)s, both the methods (ILS-MILP and ILS-TA) minimized the makespan (RTA of the last eVTOL to the MF1) to the same value (1604.48 seconds) by changing the landing order and by speeding-up eVTOLs whenever possible without violating any constraints. The multiple shuffles in landing order show landing priority given to winged eVTOLs compared to wingless eVTOLs for minimization of the makespan because of the faster cruise speed of the former. For example, the initial landing order (6) of the wingless eVTOL is changed to 9 after the optimization. Again, ILS-MILP method computed the optimal landing order and (RTA)s in more time (0.702 seconds) compared to ILS-TA method (0.013 seconds).

TABLE III
Case study 1: Simulation of eVTOLs and their ETAs

FCFS	**eVTOL Type**	**ETA (Sec)**
1	Winged	77.88
2	Wingless	82.82
3	Wingless	119.38
4	Wingless	157.40
5	Wingless	183.93
6	Wingless	245.64
7	Winged	1361.62
8	Winged	1493.70
9	Winged	1759.36
10	Winged	1820.91

TABLE IV
Case study 1: Results of ILS-MILP and ILS-TA

Sequence (MILP)	**RTA (Sec)**	**Sequence (TA)**	**RTA (Sec)**
1	48.68	1	48.68
2	199.68	2	199.68
3	372.68	3	372.68
4	545.68	4	545.68
5	718.68	5	718.68
6	891.68	6	891.68
7	1064.68	7	1064.68
8	1215.68	8	1215.68
9	1366.68	9	1366.68
10	1517.68	10	1517.68

TABLE V
Case study 2: Simulation of eVTOLs and their ETAs

FCFS	**eVTOL Type**	**ETA (Sec)**
1	Winged	100.31
2	Wingless	339.28
3	Winged	358.97
4	Wingless	657.59
5	Winged	1056.93
6	Wingless	1392.26
7	Winged	1565.58
8	Winged	1622.93
9	Winged	1685.24
10	Winged	1921.41

3) Case study III - fleet mix ratio (3/7): From Table VII and Table VIII, we can observe that for the simulated mixed

TABLE VI
Case study 2: Results of ILS-MILP and ILS-TA

Sequence (MILP)	RTA (Sec)	Sequence (TA)	RTA (Sec)
1	62.69	1	62.69
2	282.72	2	282.72
3	455.72	3	455.72
4	606.72	4	606.72
5	779.72	5	779.72
7	978.48	7	978.48
8	1129.48	8	1129.48
9	1280.48	9	1280.48
6	1431.48	6	1431.48
10	1604.48	10	1604.48

TABLE VIII
Case study 3: Results of ILS-MILP and ILS-TA

Sequence (MILP)	RTA (Sec)	Sequence (TA)	RTA (Sec)
1	124.08	1	124.08
2	395.43	2	395.43
3	568.43	3	568.43
4	741.43	4	741.43
5	914.43	5	914.43
6	1065.43	6	1065.43
7	1238.43	7	1238.43
9	1411.43	9	1411.43
8	1562.43	8	1562.43
10	1735.43	10	1735.43

fleet of eVTOLs and their respective (RTA)s, both the methods (ILS-MILP and ILS-TA) minimized the makespan (RTA of the last eVTOL to the MF1) to the same value (1735.43 seconds) by changing the landing order and by speeding-up eVTOLs whenever possible without violating any constraints. The shuffle in landing order 8 and 9 reiterates the point that overtaking and speeding-up of winged eVTOLs is one of the key factors in minimization of the makespan. Again, the computational time (0.743 seconds) of ILS-MILP method is higher than computational time (0.014 seconds) of ILS-TA method.

TABLE VII
Case study 3: Simulation of eVTOLs and their ETAs

FCFS	eVTOL Type	ETA (Sec)
1	Wingless	148.90
2	Wingless	474.53
3	Wingless	539.73
4	Wingless	560.09
5	Winged	602.34
6	Wingless	767.72
7	Wingless	830.62
8	Wingless	960.75
9	Winged	1096.67
10	Winged	1674.03

4) Case study IV - computational time: The computational times are calculated for both the algorithms, i.e., ILS-MILP and ILS-TA for sequencing and scheduling of 10, 50, 90, 130, 170, 210, 250 eVTOLs arriving at Poisson arrival rate of 1 eVTOL per 60 seconds. Also, to check the performance of both the algorithms, a lower minimum separation requirement has been imposed on the arrival air-traffic, i.e., 60 seconds for both types of eVTOLs and the mixed fleet is assumed to contain an equal mix of winged and wingless eVTOLs. From Fig. 5, it can be seen that ILS-TA algorithm is computationally faster than ILS-MILP. However, both of them are computationally efficient (within 15 seconds) for cases with fewer than 130 arriving eVTOLs.

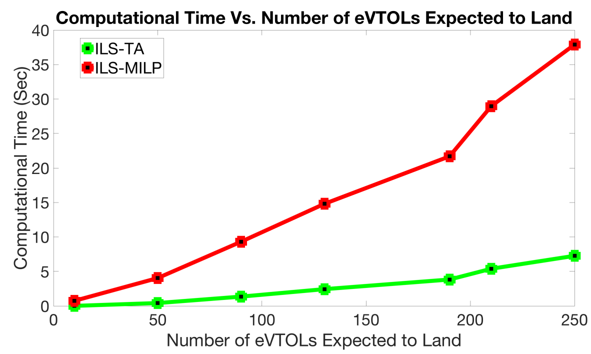

Fig. 5. Computational times of two algorithms for different number of eVTOLs

VI. CONCLUSIONS

In this paper, we formulated eVTOL aircraft sequencing and scheduling problem in urban air mobility (UAM) context for a mixed fleet (winged/wingless) of eVTOLs expected to land on a vertiport with single landing pad. The objective of the problem is to minimize the makespan of a given set of eVTOLs, which is equivalent to maximizing the arrival throughput. The landing order (sequence) and makespan of the mixed fleet are determined using a heuristic approach called insertion and local search (ILS) combined with two different scheduling methods i) mixed-integer linear programming (MILP) or ii) time-advance (TA) algorithm. The optimization results show that for minimization of the makespan it is essential to i) speed-up a trailing eVTOL whenever separation from the leading is more than minimum separation, and ii) winged eVTOLs should have designated airways separate from wingless eVTOLs so that they can overtake earlier landing slot(s) of wingless eVTOLs whenever possible. Also, ILS-TA is computationally faster than ILS-MILP and produces the same optimal results. However, both of them are computationally efficient (within 15 seconds) for cases with fewer than 130 arriving eVTOLs.

REFERENCES

[1] Hoehner, Christine M., Carolyn E. Barlow, Peg Allen, and Mario Schootman. "Commuting distance, cardiorespiratory fitness, and metabolic

risk." American journal of preventive medicine 42, no. 6 (2012): 571-578.

[2] Schrank, David, Bill Eisele, Tim Lomax, and Jim Bak. "2015 urban mobility scorecard." (2015).

[3] Holden, J., and Goel, N., Fast-Forwarding to a Future of On-Demand Urban Air Transportation, San Francisco: 2016.

[4] Pradeep, Priyank, and Peng Wei. "Energy Efficient Arrival with RTA Constraint for Urban eVTOL Operations." In 2018 AIAA Aerospace Sciences Meeting, p. 2008. 2018.

[5] Pradeep, Priyank, and Peng Wei. "Energy Optimal Speed Profile for Arrival of Tandem Tilt-Wing eVTOL Aircraft with RTA Constraint." to appear on 2018 IEEE/CSAA Guidance, Navigation and Control Conference.

[6] Lovering, Zach. Vahana Configuration Trade Study Part I. https://vahana.aero/vahana-configuration-trade-study-part-i-47729eed1cdf.

[7] Mueller, Eric R., Parmial H. Kopardekar, and Kenneth H. Goodrich. "Enabling Airspace Integration for High-Density On-Demand Mobility Operations." In 17th AIAA Aviation Technology, Integration, and Operations Conference, p. 3086. 2017.

[8] Kopardekar, Parimal, Joseph Rios, Thomas Prevot, Marcus Johnson, Jaewoo Jung, and J. Robinson. "Unmanned aircraft system traffic management (utm) concept of operations." In AIAA Aviation Forum. 2016.

[9] EHang-184, "EHANG 184 autonomous aerial vehicle specs," http://www.ehang.com/ehang184/specs/, 2018, [Online; accessed 06-March-2018].

[10] Volocopter, "Volocopter technical features," https://www.volocopter.com/en/product/, 2018, [Online; accessed 06-March-2018].

[11] Hong, Youkyung, Somang Lee, Keumjin Lee, and Youdan Kim. "Optimal Scheduling Algorithm for Air Traffic Point Merge System Using MILP." In Advances in Aerospace Guidance, Navigation and Control, pp. 407-420. Springer, Cham, 2018.

[12] Pawelek, Adrian, Ramon Dalmau Codina, Piotr Lichota, and Xavier Prats Menndez. "Arrival traffic synchronisation with Required Time of Arrivals for fuel-efficient trajectories." In Proceedings of the 17th ATIO-AIAA Aviation Technology, Integration, and Operations Conference, pp. 1-14. 2017.

[13] Neuman, Frank, and Heinz Erzberger. "Analysis of sequencing and scheduling methods for arrival traffic." (1990).

[14] Anagnostakis, Ioannis, John-Paul Clarke, Dietmar B-ograve, hme, Uwe V-ograve, and lcker. "Runway operations planning and control: Sequencing and scheduling." Journal of Aircraft 38, no. 6 (2001): 988-996.

[15] Malik, Waqar, and Yoon C. Jung. "Exact and Heuristic Algorithms for Runway Scheduling." In 16th AIAA Aviation Technology, Integration, and Operations Conference, p. 4072. 2016.

[16] Balakrishnan, Hamsa, and Bala Chandran. "Scheduling aircraft landings under constrained position shifting." In AIAA guidance, navigation, and control conference and exhibit, p. 6320. 2006.

[17] Balakrishnan, Hamsa, and Hanbong Lee. A study of tradeoffs in scheduling terminal-area operations. Proceedings of the IEEE, 2008.

[18] Chetan S. Kulkarni, Indranil Roychoudhury, and Johann Schumann. "On-board Battery Monitoring and Prognostics for Electric-Propulsion Aircraft", 2018 AIAA/IEEE Electric Aircraft Technologies Symposium, AIAA Propulsion and Energy Forum, (AIAA 2018-5034).

[19] Abdullah H. Alnaqeb, Yifei Li, Yu-Hui Lui, Priyank Pradeep, Joshua Wallin, Chao Hu, Shan Hu, and Peng Wei. "Online Prediction of Battery Discharge and Flight Mission Assessment for Electrical Rotorcraft", 2018 AIAA Aerospace Sciences Meeting, AIAA SciTech Forum, (AIAA 2018-2005)

[20] Zhan, Zhi-Hui, Jun Zhang, Yun Li, Ou Liu, S. K. Kwok, W. H. Ip, and Okyay Kaynak. "An efficient ant colony system based on receding horizon control for the aircraft arrival sequencing and scheduling problem." IEEE Transactions on Intelligent Transportation Systems 11, no. 2 (2010): 399-412.

[21] Hu, Xiao-Bing, and Wen-Hua Chen. "Genetic algorithm based on receding horizon control for arrival sequencing and scheduling." Engineering Applications of Artificial Intelligence 18, no. 5 (2005): 633-642.

[22] Psaraftis, Harilaos N. "A dynamic programming approach for sequencing groups of identical jobs." Operations Research 28, no. 6 (1980): 1347-1359.

[23] Dear, Roger George. The dynamic scheduling of aircraft in the near terminal area. Cambridge, Mass.: Flight Transportation Laboratory, Massachusetts Institute of Technology,[1976], 1976.

[24] Patterson, Michael A., and Anil V. Rao. "GPOPS-II: A MATLAB software for solving multiple-phase optimal control problems using hp-adaptive Gaussian quadrature collocation methods and sparse nonlinear programming." ACM Transactions on Mathematical Software (TOMS) 41.1 (2014): 1.

[25] Wachter, Andreas, and Lorenz T. Biegler. "On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming." Mathematical programming 106.1 (2006): 25-57.

[26] Meindl, Bernhard, and Matthias Templ. "Analysis of commercial and free and open source solvers for linear optimization problems." Eurostat and Statistics Netherlands within the project ESSnet on common tools and harmonised methodology for SDC in the ESS (2012): 20.

[27] Willemain, Thomas R., Hui Fan, and Huaiyu Ma. "Statistical analysis of intervals between projected airport arrivals." Rensselaer Polytechnic Inst., DSES Tech. Rept (2004): 38-04.

[28] Guido van Rossum and Jelke de Boer, "Interactively Testing Remote Servers Using the Python Programming Language", CWI Quarterly, Volume 4, Issue 4 (December 1991), Amsterdam, pp 283?303.