# Exploration of On-Demand Urban Air Mobility: Network Design, Operation Scheduling and Uncertainty Considerations

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*Abstract*— **Traffic congestion has been one of the leading sustainability issues in transportation around the world. The emerging concept urban air mobility (UAM) is expected to provide a new solution by making use of the three-dimensional airspace to transport passengers and goods in urban areas. Among different constraints and challenges for promotion and commercialization of UAM, we will focus on optimal infrastructures location identification, facility capacities and aircraft fleet size and analyze corresponding transportation system performance as well as impact from uncertainties.**

***Keywords-Multimodal transportation; eVTOL; Skyport; Travel mode choice; Sequencing and scheduling; Robust Optimization***

## I. INTRODUCTION

Urban air mobility (UAM), defined as safe and efficient air traffic operations in metropolitan areas for manned and unmanned aircraft systems, is expected to provide an alternative transportation mode with greatly improved mobility by making use of the three dimensional low altitude airspace. This concept is based upon a new type of electric aircraft, which is enabled to take off and land vertically, a.k.a eVTOL with advanced autonomous and distributed electric propulsion technologies.

A significant number of studies by NASA, Department of Transportation, and local authorities have found that UAM will provide a compelling case to constitute a new form of transportation, reduce congestion, and overcome the geographic constraints of ground mobility modes [1]. For example, Antcliff et al. (2016) have demonstrated that UAM service has the potential to reduce travelers' daily long distance door-to-door commute time to around one third of that for ground transportation taking Silicon Valley areas as a case study [2]. Therefore, numerous efforts have been made to push the advancement of UAM service. NASA and FAA have been leading the market feasibility study and promotion of UAM [3]. More than 70 manufacturers worldwide, including Boeing, Airbus and Bell Helicopters, have been devoted to better design of eVTOL aircrafts and over $1 billion investment has been made as of September 2018 [4]. Besides, high profile events have been organized around the world in 2018 to discuss challenges and solutions for UAM applications, such as Uber Elevate and LA City's mayor gathering [4].

Despite all those efforts from all participants, full-scale operation of UAM still needs to conquer several critical challenges, including aircraft certification, battery technology, vehicle efficiency, vehicle performance and reliability, air traffic control, aircraft noise, safety, cost and affordability, emissions and sufficient infrastructure in cities [5]. The solutions to regulation can come from cooperation between federal and local authorities. Research on automation and DEP technology will help with vehicle performance and safety level improvement, noise control and community acceptance. This dissertation will contribute to promotion of UAM large-scale service from network design and operation scheduling perspectives by answering the following questions: (1) Where should be the optimal locations for infrastructures? (2) What will be the potential UAM service demand and corresponding transportation system performance? (3) How should we design infrastructure capacity, including capacity to take eVTOL aircrafts as well as to capacity of charging facilities? (4) How many eVTOL do we need to fulfill the UAM service? (5) What will be the impact of uncertainties on network design and operation scheduling?

Mathematical models will be developed and estimated to answer the above questions. Tampa Bay Area of Florida (including four counties) in US will be taken as the case study to demonstrate the effectiveness of the proposed modeling framework.

## II. RESEARCH OVERVIEW

The main objective of this research is to build up mathematical models to design the supporting infrastructure system and operation strategies for large-scale on-demand UAM service.

The five proposed questions will be answered from three parts. The first part will focus on the UAM network design, which includes optimal vertiport location identification and UAM user allocation to the vertiport. The second one will focus on eVTOL operation and user serving scheduling based on vertiport location and UAM service demand input from the first part. The third part will look into how potential uncertainties can influence our modeling structure and corresponding network design and operation scheduling results.

### A. UAM Network Design

For non-optimization methods, previous research has focused on accommodating to existing physical restrictions or using travel demand as the only standard for optimal vertiport placement. For optimization methods, few have incorporated the operation features of UAM service for its network design. In our research, we will apply the modeling structure of the traditional hub-and spoke system for UAM network design while integrating the operation features of UAM service and user travel mode choice behaviors. The output of the proposed model is able to provide us optimal locations for vertiport among a set of candidates, service demand at each selected vertiport and optimal travel route for each UAM user. In addition, we are also able to provide how different parameter settings may influence the UAM adoption and transportation system performance.

### B. Operation Scheduling

There is lack of research which focus on scheduling of eVTOL aircrafts at vertiport to satisfy their charging needs and for the whole UAM network to serve UAM users. In our research, we will develop two models to achieve the two goals. The first model will study the optimal charging scheduling for arrival eVTOL aircraft at each vertiport with the objective to maximize the service quality. Then another model will be developed to research on eVTOL scheduling to satisfy the UAM service demand at network level while the charging scheduling model will be taken as the sub-model. Optimal locations of vertiports and user demand in the system from the output of the network design will be adopted as the input for our operation scheduling process. The output of the charging scheduling model will be the optimal charging schedules as well as user service schedule vertiport with respect to minimum waiting time for users. The output for the second model will be the optimal charging capacity at each vertiport and eVTOL fleet size in the network with respect to maximum profit of service providers.

### C. Robust Network Design and Operation Scheduling

There has been no research working on network design and operation scheduling for UAM service that consider potential uncertainties in the service process. Nevertheless, potential demand and service time during each element of multimodal UAM service can all suffer from uncertainties. In our research, appropriate robust models will be developed corresponding to the deterministic models proposed above and corresponding optimization results will be compared with the deterministic model.

## III. UAM Network Design

In traditional hub-spoke system, airports are represented by nodes and transportation between two airports are represented by links. Traffic between any two airports is not transported directly for all pairs of nodes, but transferred via designated transshipment nodes called hubs. For multimodal UAM service, let N denote a set of nodes representing origins (O) and destinations (D) of travelers' daily trips in urban or suburban areas, M denote the set of candidate locations for vertiports and P denote set of OD pairs. Travelers can travel directly by pure ground transportation between any pair of OD, or using multimodal UAM service. In the latter case, travelers need to get to a vertiport near their origins first, then take eVTOL aircraft to another vertiport, and reach their destination from the second vertiport, where vertiports are equivalent to hubs.

The decision variables of the UAM network design problems are $y_{k,}\forall k \in M$, $x^p$, $\forall p \in P$ and $x^p_{kd}, k, d \in M, \forall p \in P$. All of these decision variables are binary variables, $y_{k,}$ take value of 1 if location $k$ $(k \in M)$ is selected as a vertiport, $x^p$ take value of 1 if trip $p$ is through pure ground transportation, and $x^p_{kd}$ takes value of 1 if trip $p$ is through multimodal UAM service that goes through two vertiports $k$ and $d$ with the order of $k$ to $d$. Let $u$ denote the number of vertiports to be built, $c^p$ and $t^p$ represent the travel cost and time between origin and destination using pure ground transportation respectively, $c^p_{kd}$ $and$ $t^p_{kd}$ denote the total UAM service cost and service time respectively, and $vot^p$ represent value of time for travelers with trip OD $p$.

The mathematical model for on-demand UAM service network design can be expressed as follows:

$$min \sum_{p \in P} w^p \left\{ (t^p \times x^p) + \sum_k \sum_{d \neq k} \left( t^p_{kd} \times x^p_{kd} \right) \right\}$$

$$\sum_k y_k = u, \quad \forall k \in M \tag{1}$$

$$x^p + \sum_k \sum_{d \neq k} x^p_{kd} = 1, \ \forall \ p \in P \tag{2}$$

$$\sum_{d \in M, d \neq k} x^p_{kd} + \sum_{d \in M, d \neq k} x^p_{dk} \leq y_k, \ \forall k \in M, \forall \ p \in P \tag{3}$$

$$d_{kd} \geq buffer_a \times x^p_{kd}, \ \forall k, d \in M, \ k \neq d, p \in P \tag{4}$$

$$\left( c^p_{kd} - c^p \right) \times x^p_{kd} \leq vot^p \times \left( t^p - t^p_{kd} \right), \forall k, d \in M, p \in P \tag{5}$$

$$y_k \in \{0,1\}s, \ x^p_{kd} \in \{0,1\}, \ \ k, d \in M, p \in P$$

The objective function is to minimize the system travel time including the travel time for pure ground transportation and that for multimodal UAM service. The first three constraints represent based on hub-and-spoke modeling structure, which limit the number of vertiports and restrict each UAM trip transferred through selected vertiports. Constraint (4) restricts the minimum cruise distance between two vertiports to ensure eVTOL operation efficiency. And constraint (5) represent that users will only adopt UAM service if value of saved travel time is larger than the additional cost.

## IV. EVTOL CHARGING SCHEDULING AT VERTIPORT

Given eVTOL aircrafts and UAM users' arrival time as well as the SoC for each arrival eVTOL, the eVTOL charging scheduling model is to provide optimal sequencing and scheduling procedures for eVTOL aircrafts to get charged at vertiports while minimizing the total waiting time of UAM users.

### *A. Notations*

| | |
|---|---|
| *Sets:* | |
| $\boldsymbol{J}$ | Set of eVTOL aircrafts, indexed $j = 1, \dots, n$ |
| $\boldsymbol{\mu}$ | Set of charging facilities, indexed $i = 1, \dots, m$ |
| $\boldsymbol{\tau}$ | Set of time periods, indexed $t = 1, \dots l$ |
| $\boldsymbol{K}$ | Set of passengers, index $k = 1, \dots, w$ |
| Parameters: | |
| $\boldsymbol{SoC_j}$ | State of charge for eVTOL $j$ |
| $\boldsymbol{r_j}$ | Release time for eVTOL $j$ to get charged (i.e. arrive time plus a buffer time) |
| $\boldsymbol{d_k}$ | Arrival time for passenger $k$ |
| $\boldsymbol{p_j}$ | Charging time for eVTOL $j$ |
| $\boldsymbol{w_{kq}}$ | 1 if passengers $k, q$ share the same destination, 0 otherwise. |
| $\boldsymbol{SoC_{min}}$ | Minimum state of charge for each eVTOL after recharge. |
| $\boldsymbol{c}$ | Capacity of the battery. |
| $\boldsymbol{q}$ | Charge rate of charging facility. |
| $\boldsymbol{l}$ | Upper bound for makespan (total time required to charge all eVTOL). |
| $\boldsymbol{M}$ | A large number (i.e., "big-M"), $M \geq l, l \geq \sum_j p_j + \max_j\{r_j\}$ |
| *Auxiliary variables:* | |
| $\boldsymbol{C_j}$ | Completion time for eVTOL $j$ |
| $\boldsymbol{T_{jk}}$ | Tardiness for customer $k$ taking eVTOL $j$, i.e. takeoff time of eVTOL minus arrival time of passenger. |
| $\boldsymbol{F_j}$ | Time when eVTOL takeoff |
| *Decision Variables:* | |
| $\boldsymbol{x_{ij}^t}$ | Binary variable and takes value of 1 if eVTOL $j$ starts charging at facility $i$ from period $t$, 0 otherwise. |
| $\boldsymbol{y_{jk}}$ | Binary variable and takes value of 1 if eVTOL $j$ is to serve customer $k$. |

### *B. Modeling Approach*

The modeling structure of the scheduling problem in this study can be decomposed into two sub-models, eVTOL charging scheduling model and passenger serving scheduling model. First of all, we discretize the studied time horizon into a set of time periods. For the eVTOL charging scheduling model, one eVTOL can start to get charged at one of those time periods at one charging station, which can be described by constraint (2). In addition, for each charging facility, at any period of time, only one eVTOL can be in charging process as represented by constraint (3). Besides, eVTOL can only start to get charged after release time, which is restricted by constraint (4).

$$\sum_{i\in\mu}\sum_{t=1}^{l-p_j+1} x_{ij}^t = 1, j \in J \quad (2)$$

$$\sum_{j\in J}\sum_{s=\max(1,t-p_j+1)}^{t} x_{ij}^s \leq 1, i \in \mu, t \in \tau \quad (3)$$

$$\sum_{i\in\mu}\sum_{t=1}^{r_j} x_{ij}^t = 0, j \in J \quad (4)$$

For passenger scheduling model, each passenger can only be served by exactly one eVTOL while each eVTOL can take at most four passengers, which are represented by constraints (5) and (6). It should be noted that passengers can be served by the same eVTOL only when they share the same destination vertiport, which is restricted by constraint (7).

$$\sum_{j\in J} y_{jk} = 1, k \in K \quad (5)$$

$$\sum_{k\in K} y_{jk} \leq 4, j \in J \quad (6)$$

$$y_{jk} + y_{jq} - 1 \leq w_{kq}, j \in J, q, k \in K, q \neq k \quad (7)$$

To compute tardiness for each of the passengers, we need first to obtain the takeoff time of eVTOL serving that passenger. The takeoff time should be greater than the charging completion time of eVTOL and greater than the arrival time of any passenger served by that eVTOL, which are expressed as constraint (8) and (9) respectively. The completion time of any eVTOL can be represented by inequality (10) and therefore the tardiness of each passenger can be represented by inequality (11) and restricted by predefined level of service.

$$F_j \geq C_j, j \in J \tag{8}$$

$$F_j \geq d_k y_{jk}, j \in J, k \in K \tag{9}$$

$$C_j \geq \sum_{i \in \mu} \sum_{t=1}^{l-p_j+1} (t + p_j - 1) x_{ij}^t, j \in J \tag{10}$$

$$T_{jk} \geq F_j - d_k - M(1 - y_{jk}), j \in J, k \in K \tag{11}$$

$$T_{jk} \leq LoS, j \in j\ k \in K \tag{12}$$

Our objective function is to minimize the total tardiness or total waiting time for all passengers, which can be expressed as:

$$Min \sum_k \sum_j T_{jk}$$

## V. Initial Results

### A. UAM Network Design

The data source for the numeric study is the travel demand data simulated for a typical weekday from Tampa Bay Regional Planning Model (TBRPM). The mixed integer program was solved using C++ and CPLEX 12.8.0 solver on a 3.60GHz Dell computer with 16 GB RAM under 64-bit Windows 10 operating environment. It took 231 seconds (less than 4 minutes) to obtain the optimal values. The identified vertiport locations and demand distributions are presented in Fig. 1.

In summary, 7019 users among 99207 users select UAM service, which results in system (including both UAM service and pure ground transportation) travel time of 85471.9 hours and travel cost of $2,514,700 (94285.3 hours and $2,447,530 for system with pure ground transportation). The demand is unevenly distributed across these vertiports with the highest demand of 1016 and the lowest 118.

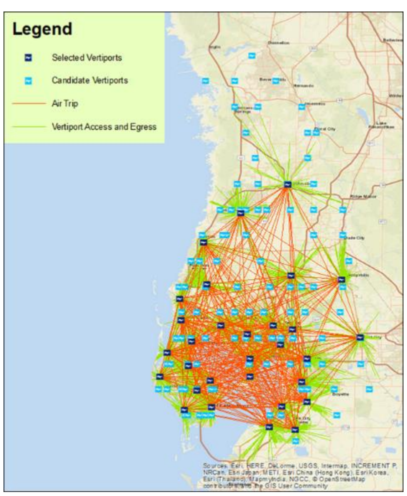


Figure 1. Identified optimal vertiport locations and user allocation

### B. EVTOL Charging Scheduling

From the network design model in the previous section, we are able to obtain the number of arrivals for each UAM user and eVTOL at each vertiport as well as their arrival times. In this research, we are going to use the busier vertiport identified in the numerical study as our case study in this section. Table 1 presented some optimization results for different scheduling horizons.

TABLE I. Model Estimation results for charging scheduling

| Schedule horizon (min) | Charging Facility | user arrivals | Solution time (s) | Objective value (min) |
|---|---|---|---|---|
| 5 | 3 | 14 | 10 | 52 |
| 10 | 3 | 18 | 15 | 47 |
| 15 | 3 | 21 | 175 | 54 |
| 20 | 3 | 27 | 163 | 46 |
| 25 | 3 | 28 | 174 | 48 |
| 30 | 3 | 33 | 160 | 44 |

## VI. Conclusion

This study explores the area of on-demand urban air mobility with focus on network design and operation scheduling. The proposed modeling framework is able to identify optimal infrastructure locations, influence of UAM on system performance and its potential adoptions, facility capacity requirement, optimal fleet size design and impact of uncertainties given the travel demand pattern in the study area. The results will be significant in promotion of UAM service and further understanding of UAM. Policy makers and city planners will gain more insights about infrastructure placement and mobility variation for different regions and service providers will be more interested in the implications revealed on pricing and operation strategies.

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