Operational Strategies and Demand Consolidation in Urban Air Mobility

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INTRODUCTION

Proposals for advanced urban air mobility services are rapidly taking shape. In this work, ee consider urban shared mobility services offered through automated electric vertical take-off and landing (eVTOL) vehicles ("flying taxis"), enabled by a new generation of eVTOL aircraft. Various concepts for service operations at urban/regional levels are presented, along with algorithms adapted for the real-time operation of shared air mobility fleets.

With the vision of eco-friendly autonomous aircraft equipped with distributed electric propulsion (DEP) and efficient batteries that allow short charging or swapping time, urban air mobility continues to generate much excitement. More than 200 concepts and partnerships have been announced for these electric vertical take-off and landing (eVTOL) aircraft (1). Compared to helicopters, eVTOLs are 4 times quieter and 10 times less expensive (2). Benefitting from this aircraft technology, the Advanced Air Mobility (AAM) (3) initiative focuses on carrying cargo and passengers between urban, local, regional, and intraregional areas, while Urban Air Mobility (UAM) market, as a subset of AAM, aims to transfer passengers and goods within metropolitan areas (3-5).

Urban Air Taxi (UAT) is envisioned as a point-to-point, (nearly) on-demand, and per-seat operation of passenger-carrying Urban Air Mobility (UAM) in its mature state. UAT does not have fixed routes or regular schedules, distinguishing it from other use cases of passenger-carrying UAM such as airport shuttle (4) or air metro (5), which are envisioned to operate on predetermined routes. UAT utilizes semi-autonomous or fully autonomous eVTOL aircraft with low noise, low operating costs, and passenger capacity of 1 to 4. The service is on-demand, but one could book their flight with advance notice. The UAT flights are shared, carrying 1 or 2 passengers on a typical flight. A high flight load factor has been identified as one of the influential components in the successful operation of UAT. This study examines the impacts of exogenous parameters, such as demand intensity, demand spread, and ground speed, in addition to design parameters, including aerial speed, maximum acceptable delay, and reservations on average load factor and rate of rejected requests.

Recognizing the dynamic and stochastic nature of the UAT fleet operation problem, we develop and implement a dynamic solution framework to examine the impacts of design parameters and exogeneous information on the success of demand consolidation using a discrete-event simulation. The outcomes shed light on the importance of design and exogenous parameters in the viability of the UAT business model and the eventual benefits to society resulting from travel time savings. The results highlight the significance of demand spread, ground speed, and maximum acceptable delay in demand consolidation.

UAT PROBLEM STATEMENT

The UAT operator provides a multimodal, (nearly) on-demand, and point-to-point service using a fleet of homogeneous UAT aircraft. The requests for UAT service arrive in real time within a short period ahead of their desired service time. When a request arrives, the origin, destination, desired pick-up and drop-off UAT pads, desired service time, and group size become known to the operator. Given the ubiquitous network of UAT pads, the origin and destination of a request coincide with the desired pick-up and drop-off UAT pads, respectively.

Each passenger group is willing to share a UAT aircraft with other passengers and is flexible about the location of their pick-up and drop-off UAT pads, which in turn enables the UAT operator to move the passengers on the ground within an acceptable distance to consolidate the customer requests and eliminate the unreasonably short empty flight legs. The itinerary of accepted requests constitutes origin, pick-up UAT pad, drop-off UAT pad, and destination. Therefore, this itinerary includes a maximum of two ground legs: one to ingress to the pick-up UAT pad and the other to egress from the drop-off UAT pad.

The UAT operator can reject a request if serving it is not profitable. However, to provide an equitable service, the UAT operator could include the loss of goodwill in its objectives. If the operator decides to serve a request, it guarantees a predetermined level of service. Therefore, the trip delay (i.e., deviation of the passenger's total trip time from their desired trip time) cannot exceed a prespecified value, which in turn, limits the wait time for the aerial service, the ingress and egress time, and the deviation from the desired flight. When considering the acceptance of a new request, the operator cannot reject the requests that have been already accepted. However, the flight legs assigned to the accepted requests, and therefore, the passenger's pick-up and drop-off UAT pads could be modified as long as the passengers have not left their origin.

DYNAMIC SOLUTION FRAMEWORK

Customer Requests

When request r arrives at time τ_r^{ARV}, its attributes are defined by the vector $\mathbb{A}_r^{REQ} = (\boldsymbol{O}_r, \boldsymbol{D}_r, \boldsymbol{S}_r^{DSRD}, \boldsymbol{E}_r^{DSRD}, q_r, \tau_r^{REQ})$, where:

τ_r^{ARV}: the time request r arrives;
$\boldsymbol{O}_r$: origin of request r;
$\boldsymbol{D}_r$: destination of request r;
$\boldsymbol{S}_r^{DSRD}$: desired pick-up UAT pad of request r;
$\boldsymbol{E}_r^{DSRD}$: desired drop-off UAT pad of request r;
q_r: group size of request r;
τ_r^{REQ}: requested time for service by request r;

In a ubiquitous network, $\boldsymbol{S}_r^{DSRD} = \boldsymbol{O}_r$ and $\boldsymbol{E}_r^{DSRD} = \boldsymbol{D}_r$ since the UAT pads are ubiquitously present in the space; however, the UAT model and operational policy presented in this study could be easily modified to address the problem in a network with a limited number of UAT pads. Additionally, Figure 1 illustrates temporal components associated with request r, where:

T_r^{ADV}: advance reservation window for request r, which is specified by the difference between the arrival time of request r and its requested time (i.e., $T_r^{ADV} = \tau_r^{REQ} - \tau_r^{ARV}$);
T_r^{DSRD}: minimum trip time corresponding to the desired flight leg of request r.
T_r^{TRIP}: total trip time of each passenger in request r, which includes ingress and egress time, aerial wait time, and aerial service time. $T_r^{TRIP} = \tau_r^{DST} - \tau_r^{REQ}$, where τ_r^{DST} is the time the passenger group of request r reaches its destination.
T_r^{DELAY}: the total delay associated with request r, defined as the deviation of the trip time of request r from the desired trip time (i.e., $T_r^{DELAY} = T_r^{TRIP} - T_r^{DSRD}$); and
ω: maximum acceptable delay.

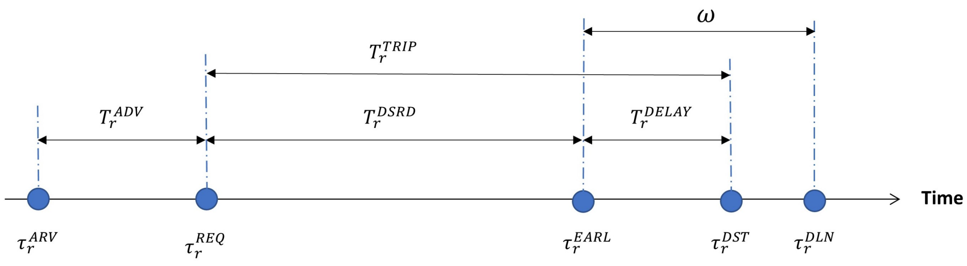

Figure 1 Temporal elements associated with request *r*

UAT Aircraft

The operator utilizes K aircraft for the aerial service. The static attributes of UAT aircraft k are represented by $\mathbb{A}_k^{eVTOL} = (Q_k, v_k^{air})$, where:
Q_k = capacity of aircraft k. With a homogenous fleet of aircraft, Q denotes the capacity of aircraft;
v_k^{AIR} = cruising speed of aircraft k. v^{AIR} denotes the cruising speed of a homogeneous fleet of aircraft.

Flight Legs

Flight legs are the constituents of a UAT aircraft itinerary. In a *ubiquitous network* of UAT pads, where UAT pads are present all over the space, the desired pick-up and drop-off UAT pads of a request form a *desired flight leg*. Additionally, to eliminate the short repositioning flight legs, *connecting flight legs* are defined within Δ^{EMPTY} of the desired pick-up and drop-off UAT pads. Subsequently, c*andidate flight legs* are the union of desired and connecting flight legs. The static attributes $\mathbb{A}_i^{LEG} = (\boldsymbol{S}_i, \boldsymbol{E}_i, \tau_i^{MIN}, \tau_i^{MAX})$ of candidate flight leg i must be available to the UAT operator. $\boldsymbol{S}_i$ is the starting point of flight i and $\boldsymbol{E}_i$ is the ending point of flight i. τ_i^{MIN} and τ_i^{MAX} are the earliest and latest time, respectively, that candidate flight leg i could start its service.

Transportation Network

The transportation network consists of ground and aerial networks. The ground network provides the travel times on the ground while the aerial network covers the information on the locations of UAT pads and, subsequently, the aerial travel times. The travel times could be deterministic or stochastic. In this paper, we assume all travel times, either on the ground or in the air, are deterministic. The ground travel times could be estimated in multiple ways, including real-world data, traffic assignments, or average speed. The UAT problem is presented as a dynamic and stochastic model. In practice, these models are often solved as a sequence of static and deterministic models (i.e., snapshot problems). In addition to the dispatching strategy, which is devised in advance, four inputs are required to solve the snapshot problem at each decision epoch: requests, flight legs, UAT aircraft, and transportation network. The states of these inputs are dynamic and, therefore, should be repeatedly updated.

DISPATCHING POLICY

As new information, such as a new request, becomes available in a dynamic model, three methods could be used to adjust the solution (7). The first approach uses policies such as first-come-first-serve (FCFS) (8). The second method is a local heuristic search, where the static problem is solved at the beginning of the planning horizon using the information available to the analyst at the time. Subsequently, with the arrival of new requests, the solution is adjusted by employing heuristic methods such as insertion heuristics, deletion heuristics, or interchange (9). The third method is re-optimization, where the problem is re-optimized every time new information becomes available. Depending on the problem's size, degree of dynamism, and the time available for solving the problem, exact, approximate, or heuristic methods could be employed to update the solution with the new information.

The occurrence of an event (e.g., the arrival of a new request) could trigger the beginning of a decision epoch, or decision epochs could be scheduled at prespecified times (e.g., every 15 minutes). We assume that the decision epochs are determined exogenously, and they are scheduled every Δt^{UPDATE}. Furthermore, we use the dispatching policy presented in (10) by re-optimizing the problem at each decision epoch. This policy, called *Capacitated Location-Allocation-Routing Problem with Time Windows and Short Repositioning Elimination* (CLARPTW-SRE), covers acceptance and rejection decisions, the allocation of requests to flight legs, demand consolidation, and the routing and scheduling of the fleet of UAT aircraft. Additionally, the aerial network is defined so that the short empty repositioning legs are eliminated. The following sections briefly explain the dispatching strategy.

A detailed mathematical formulation is included in the full paper, and will be presented at the conference. Here, we focus on the numerical experiments.

NUMERICAL EXPERIMENTS

Simulation provides a tool for evaluating various strategies for the system's operation. *Discrete-event simulations* (DES) are well suited for modeling systems with complex queuing theory and resource allocation problems. This study uses DES to examine the impacts of various design and exogenous parameters on UAT fleet performance.

Experiment Design

When operating UAT, consolidating the requests is only possible if requests are sufficiently close. Therefore, we generate the requests in clusters to study the impacts of request consolidation. Each cluster represents a town or suburb of a metropolitan area. The centroids are located on the vertices of a square with the edges of length δ. Consequently, the network has 12 OD pairs with an average Euclidean distance of 1.138δ.

Let Δt^{UPDATE} denote the interval between two decision epochs. If new requests arrive within Δt^{UPDATE}, the problem will be re-optimized to update the current solution. The origin $\boldsymbol{O}_r$ and destination $\boldsymbol{D}_r$ of request r are randomly generated around the centroids using isotropic Gaussian distributions with the standard deviation of σ. Therefore, σ represents the spread of the demand around the centroids. The corresponding centroids of the request's origin and destination are randomly chosen from the four centroids. Let Δ^{OD} denote the minimum distance between the origin and destination of a request to qualify for a UAT trip. Consequently, the origin and destination of request r are generated so that the distance between origin and destination exceeds Δ^{OD} (i.e., $D_r^{OD} \geq \Delta^{OD}$). Furthermore, let Δ^{EMPTY} denote the minimum Euclidean distance to justify an empty repositioning flight leg. The request arrival process is a Poisson process with the intensity of λ. The Values of parameters used in the experiments are shown in the Table.

	$\mathcal{T}^{INT}$ (second)	σ (mile)	v^{DRIVE} (mph)	v^{AIR} (mph)	ω (minutes)	$\mathcal{T}^{ADV}$ (minutes)	α/β
Base Values	**20**	**2**	**20**	**150**	**15**	**30**	**2**
Exogenous Parameters							
Experiment 1	10, 15, **20**, 25, 30, 40	2	20	150	10	15	2
Experiment 2	20	1, **2**, 3, 4	20	150	10	15	2
Experiment 3	20	2	10, **20**, 30	150	10	15	2
Design Parameters							
Experiment 4	20	2	20	100, 125, **150**, 175	10	15	2
Experiment 5	20	2	20	150	5, 10, **15**, 20	15	2
Experiment 6	20	2	20	150	10	1, 5, 10, 20, **30**, 40, 60	2
Experiment 7	20	2	20	150	10	15	1.2, 1.5, **2**, 2.5

In addition to the synthetic network, We also demonstrate the framework using the actual network of the Chicago metropolitan area.

KEY FINDINGS

The results show that providing service with short delays while relocating passengers on the ground hinges on fast and reliable ground-based transportation. For the synthetic network used in this study, increasing the driving speed from 10 mph to 20 mph results in a 14% increase in the average load factor. However, achieving the ground speed of 20 mph over short distances might be challenging, particularly in downtown areas of a densely populated city.

Another significant factor in demand consolidation is the spread of the demand. For the given experiment with the driving speed of 20 mph and the maximum delay of 15 minutes, reducing the standard deviation of the Gaussian distribution of the requests around the centroids from 2 miles to 1 results in a 25% increase in average load factor. Closely spread demand would result in the average load factor of 90%, which is well beyond the range of 50%-80% estimated in (4). Nonetheless, ground speed and demand spread, as the highly influential factors in demand consolidation, are exogenous information and are primarily beyond the control of the UAT operator. However, special attention should be given to these factors when selecting the passenger UAM market, particularly in the initial stages of the operation. Moreover, placing the UAM ports in locations that provide a short and reliable ground access time to a dense and closely spread demand is another challenge facing UAM operations in the early stages.

Among the design parameters, aerial speed is an influential factor in reducing the rate of request rejection. The results suggest that a similar rejection rate could be achieved whether using high-speed aircraft with no demand consolidation or low-speed aircraft with demand consolidation, highlighting the value of demand consolidation in selecting the aircraft technology.

Increasing the reservation time window and maximum acceptable delay decreases the rejection rate and increases the average load factor. However, when the maximum acceptable delay is long enough to allow the UAT operator to relocate the passengers on the ground for demand consolidation and move the UAT aircraft in the network to serve them, the UAT operator could immediately serve the requests with no advance notice required. For the synthetic network in this study, the rejection rate is almost zero for a maximum acceptable delay of 20 minutes, while with a maximum reservation time of 60 minutes, some requests could not be served. Consequently, the maximum acceptable delay has a noticeable impact on the average load factor. However, the maximum acceptable delay cannot be increased to the point that it diminishes the travel time savings.

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