Life-Cycle Economic Analysis and Optimization for Urban Air Mobility (UAM)

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Abstract

The increased population concentration in urban centers worldwide has caused challenges for urban and suburban mobility. Congestion along major US highways has caused economic productivity losses and increased environmental impacts. The Urban Air Mobility (UAM) concept has the potential to mitigate some of these concerns. One example of a potential early adopter is an airport shuttle service that connects high value passengers from urban edges to major airports over a fixed route. This paper presents a parametric study of supply and demand matching for a selected market. On the demand side, the total addressable market size is estimated based on comparing ticket price to estimated Value of Travel Time Savings (VTTS) throughout the day for various population income levels located within vertiports catchment areas. The supply side analysis involves establishing ride cost per trip by parametrically estimating vehicle fleet size and vertiport sizing based on available demand to calculate vehicle and infrastructure operating costs. The analysis can be used to examine breakeven price, benefits, costs, and risks in various contexts to inform vehicle developers, city planners and policy makers alike.

Introduction

The increased population concentration in urban centers worldwide has caused challenges for urban and suburban mobility. Congestion along major US highways has increased average commute time along with pollution, especially in large metroplexes like Atlanta, Miami, and Los Angeles. The Urban Air Mobility (UAM) concept has the potential to mitigate some of these concerns.

Many electric Vertical Takeoff and Landing (eVTOL) concepts are being considered to play a major role in UAM advancement. These aircraft will operate between vertiports located in strategic areas within an urban center. However, UAM operational concepts will have quantifiable economic and environmental benefits only if they are affordable enough to serve a large segment of the population.

Two major factors play tightly coupled and competing roles in determining the affordability of UAM and are the focus of this paper. The first is the operator's total ownership cost (TOC) including vehicle acquisition, operations and support, along with the infrastructure which is directly influenced by vehicle design and technology enablers. On the opposite end is the demand prediction for the UAM market which is a function of population density, the current level of congestion, and ticket price among other factors.

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The estimation of total ownership costs includes the development, production, and operation of eVTOL aircraft and its supporting infrastructure such as vertiports and charging stations. A multi-level activity-based cost analytic framework will be used to decompose a vehicle concept and infrastructure design and perform detailed estimation based on analytic techniques on historical and current data. Risks associated with technology maturity, performance, and production demand are analyzed to assess sensitivity and help define requirements for future concepts of operations.

On the demand side, the door-to-door travel times for several origin and destination (O&D) pairs, within an urban and suburban environment, using personal cars will be evaluated. Then, travel times for a multimodal trip that includes eVTOL segments will be compared against the baseline personal cars to quantify economic benefits from time saved by eVTOL trips. These gains are then used as the value proposition basis to determine demand and revenue potential. Risks associated with the demands will be assessed.

The objective of this research is to create a parametric environment to analyze demand potential and total ownership cost of an eVTOL operation in the context of a UAM airport shuttle market. The resulting capability is to enable ones to analyze market feasibility and optimize ticket prices for a given population, eVTOL configurations, and vertiport locations. The results include the benefits, costs, and risks in terms of revenue per available seat mile (RASM) for a given eVTOL concept operating between a given O&D. Figure 1 below provides a generic view of the analysis framework and the interactions between the analysis modules.

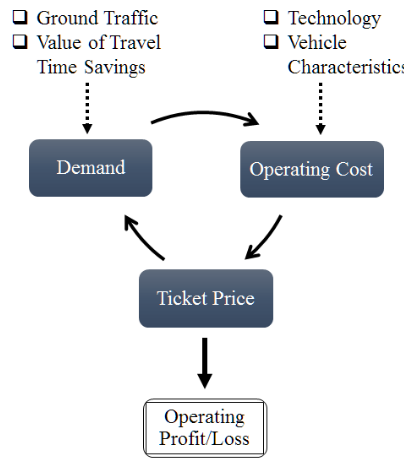

Figure 1. Generic supply and demand modeling and relationships for UAM market

Life-Cycle Economic Methodology

The analysis framework is divided into two parts. The first is the demand allocation analysis consisting of the intersection of four filtering layers;

1. population income data in catchment areas,
2. total airport outbound passenger segmentations,
3. trip time and cost comparison between automotive and eVTOL shuttle trip, and
4. rush hour vs non-rush hour traffic time analysis.

The resulting intersection of these layers results in a realizable UAM demand through a binary choice model comparing cost and time savings with the ticket price.

The second part of the framework is the supply side analysis which seeks to determine the vehicle performance characteristics using the NASA Design and Analysis of Rotorcraft (NDARC) software [1] and the total life cycle costs for the vehicle and ground infrastructure using PRICE Systems' TruePlanning® software [2]. The resulting costs are used to drive the ticket cost calculation. Finally, through the binary choice model, the Value of Travel Time Savings (VTTS) from using eVTOL service is compared against the ticket price to arrive at the realizable UAM demand, thus providing a path to determine the operator total profit/loss. The complication of determining ticket cost is the fact that at the beginning of the supply-side analysis the realizable UAM demand is the key input that comes from demand analysis, thus creating closed-loop feedback requiring some form of numerical converge algorithm. In this particular case, both sides of the analysis have to be solved simultaneously. The following paragraphs expand on the methodology and assumptions used to construct each of the numbered blocks in Figure 2 in more detail.

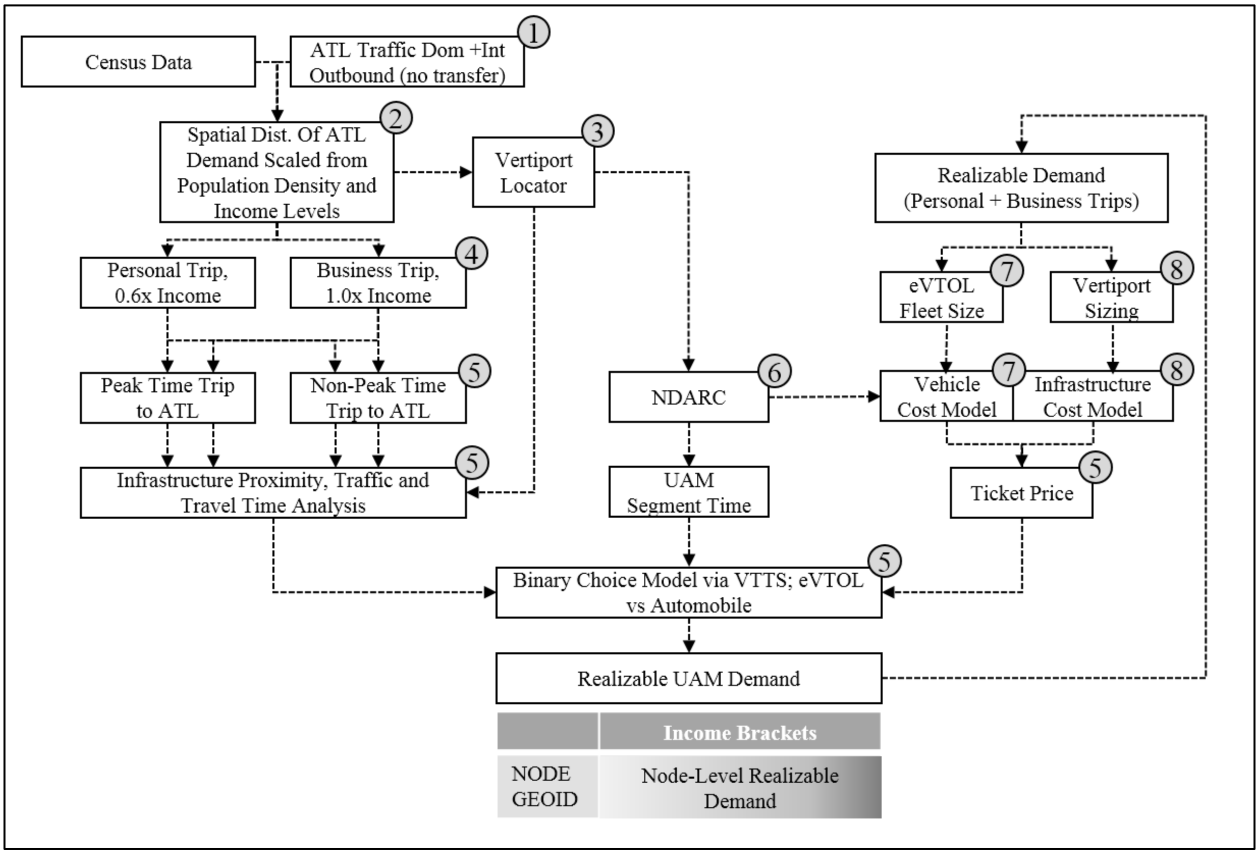

Figure 2. Life-Cycle Economic Methodology for Urban Air Mobility Operational Concepts

1. Demand Constraint

The purpose of the demand analysis is to allocate potential airport shuttle demand spatially across the airport catchment area. In this study, the airport shuttle demand is constrained to the total airport passenger outbound traffic excluding transferring passengers in Hartsfield-Jackson Atlanta International Airport (ATL). These are airline passengers originating in and around the Atlanta area and are potential customers for the airport shuttle services. The first-leg airline passenger data is based on a subset of data collected from the ATL Airport Statistics [3]. The estimated total airline passengers, domestic and international, who originate their first leg from the ATL airport is estimated at around 26.886 million in 2018. The data also shows a linear growth of 0.839 million passengers per year for the foreseeable future. The original dataset includes transferring flights that need to be excluded from the airport shuttle demand model. Based on interviews with subject matter experts, approximately 70% of Delta passengers and 20% of Delta’s partner’s passengers are connecting flights. All other airline passengers are assumed to start their first leg in ATL. Figure 3 shows the estimated domestic and international passengers demand excluding connecting passengers.

Figure 3. ATL airport statistics for outbound passengers [3]

2. Spatial Allocation of Demand (Airport Catchment Area)

Total airline passengers are spatially distributed based on two assumptions. First, all of the demand is contained within a 90-minute drive to the ATL airport under no traffic conditions. The logic is such that the edge of the catchment area is half-way between ATL and other major airports such as Birmingham-Shuttlesworth International Airport, Chattanooga Airport, Columbus Airport, and Middle Georgia Regional Airport, for example. The customers on the edge of the catchment may choose to start their first-leg from the near-by airports as opposed to driving to the ATL. The second assumption is that demand is spatially weighted based on population density and income level. The population density and income data are taken from the American FactFinder (AFF) tool from the United States Census Bureau as a source for tract-level data. The 2017 American Community Survey (ACS) 5-year estimates for individual earnings aged 16 years old and above (Table S2001) were used in this study covering Alabama and Georgia states [4]. The income weighted distribution is achieved by excluding a portion of the population that never travels by air from different income brackets. According to a survey of 1000 respondents on air travel frequency by income in the United States in 2015 [5], 32% of respondents with income below $40,000 per year has never flown, compared to 17% and 7% for respondents with income above $40,000 and $80,000 respectively. This survey data is used to exclude the population from demand allocation. This is a simplified assumption to attempt to distribute total air traffic demand for outbound flights, domestic and international, originated locally. The spatial distribution of air passengers in this catchment area is scaled by the income-weighted population density. Figure 4 shows the boundary of the ATL catchment area with a population density shown by the color intensity.

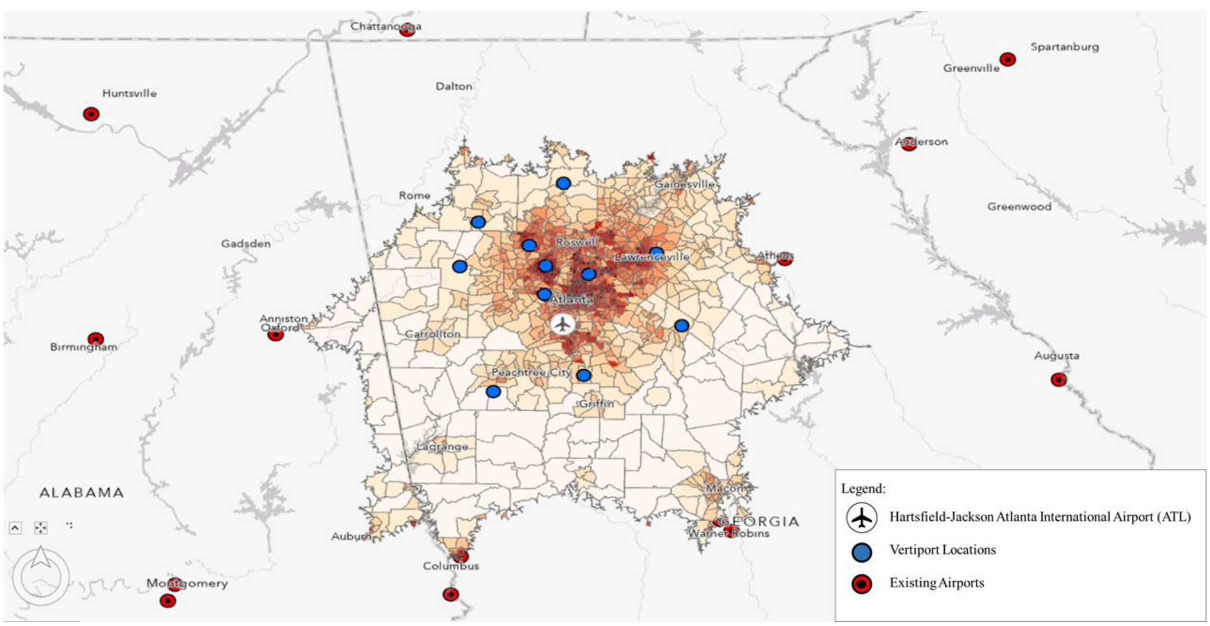

Figure 4. ATL catchment area distributed by population density and income level

3. UAM Ground Infrastructure Catchment

The near term implementation for the UAM market is focused on airport shuttle services using existing local airports within 50 nautical miles radius in a hub-and-spoke configuration. Based on this assumption, 10 local airports are selected. Table 1 lists each airport based on IATA airport code, geolocation, and distance to ATL airport. A ground infrastructure catchment area is defined by the 30-minute drive time from anywhere toward each facility. A polygon resulting from the union is then overlaid on to a grid of nodes to create discrete geolocation of approximately 2,200 nodes surrounding the selected infrastructure locations. The next step is to assign a service facility for each node based on the shortest drive time. Figure 5 graphically shows the service area segmentation for each UAM facility. A group of nodes near ATL airport is removed from the segmentation where drive time is less than 25 minutes since this area is unlikely to justify eVTOL operational feasibility.

Table 1. Selected local airports to support UAM ground operation

IATA Code	Long	Lat	Distance to ATL (nmi)
CCO	-84.78	33.31	26
HMP	-84.33	33.39	15
CVC	-83.84	33.63	30
FTY	-84.52	33.78	10
PDK	-84.30	33.88	16
PUJ	-84.94	33.91	31
LZU	-83.96	33.98	31
RYY	-84.60	34.01	25
VPC	-84.85	34.12	36
CNI	-84.43	34.31	41

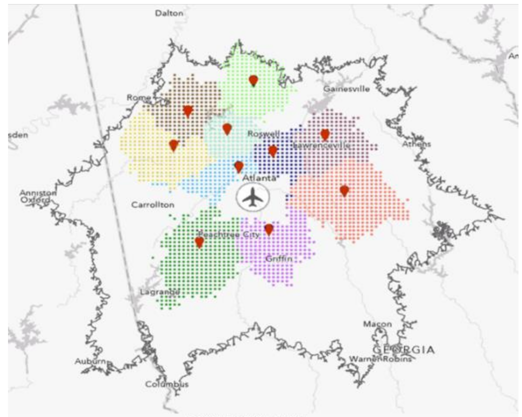

Figure 5. UAM ground infrastructure service area

4. Trip Purpose and Value of Travel Time Savings (VTTS)

According to Airlines for America® (A4A) research and survey on the airline traveler in 2015 [6], 31% of all air passenger traffic are business-related, while the remaining traffic is personal. The segmentation of trip purpose will be important in the calculation of the value of travel time saved later described in the paper as time saved during business trips is valued more than a person trip for any level of income. “The value of travel time is a critical factor in evaluating the benefits of transportation infrastructure investment and rulemaking initiatives. Reduction of delay in passenger or freight transportation is a major purpose of investments [7].” The U.S. Department of Transportation published guidance for evaluating the economics of travel time saved as a function of trip mode and purpose. Without considering factors such as reliability, amount of time saved, personal characteristics, comfort, income elasticity, and other preferences, the economic value of travel time saved is directly correlated with individual income. The plausible ranges for VTTS for personal and business trips are 35% - 60% and 80% - 120% of hourly rate earnings, respectively [7]. Assuming a typical 2,087 working hours per year a full-time worker would spend, a passenger on a business trip whose earning is $100,000 per year would be willing to pay approximately $0.64 - $0.96 per minute of time saved on a local trip to the airport. In this study, a fix 60% and 100% of a person’s earnings are used for VTTS calculations for personal and business trips, respectively.

5. Binary Choice Model

Two competing modes of transportation are considered – between using a personal automobile and an eVTOL shuttle service. Traffic throughout the day is simplified by considering only two distinct time slots -- maximum and minimum traffic conditions. Historical traffic information and Network Analyst module in ArcGIS Pro software [8] is used to analyze trip time from spatially defined nodes within the ground infrastructure catchment areas. Historical traffic data stores relative speeds or speed profiles throughout the day compared to free-flow conditions. When combined with speed limits for each road segment the trip time can be assembled and calculated. Although traffic varies throughout the day, in this simplified analysis, two traffic conditions are defined as a step function where a percentage from the total operational hours during the rush-hour period. A 15-hour daily operation between 6 am - 9 pm with a 30% rush-hour period is assumed. Drive time from each node location can then be established for both traffic conditions. The proportion of peak traffic hours to non-peak hours provide a way to inform traveler choice modeling throughout the day, and according to trip purpose. As a result, the total ATL demand is segregated into 4 mutually exclusive segments -- peak time vs non-peak time, and business vs personal. The model assumes a 100% probability of switching from automobile mode to eVTOL mode when the ticket price is lower than the sum of value travel time savings and the cost savings from a shorter driving distance at $0.58 per automotive mile driven [9]. Ticket price is defined as

$$Ticket\ Price = \frac{Booking\ Fee + (1 - CDR) \times CPFH}{Load\ Factor \times Number\ of\ Seats}$$

where Booking Fee is a fixed cost per ride, Cost Discount Rate (CDR) represents a fractional discount rate from the total Cost Per Flight Hour (CPFH) rate, Load Factor is a measure of utilized capacity, and Number of Seats is the maximum passenger capacity for the eVTOL design. The conditional argument for switching to eVTOL service is achieved when

$$\begin{aligned} Ticket\ Price < VTTS \times Earning & \\ \times \left(Drive\ Time_{ATL}\right. & \\ \left. - Drive\ Time_{vertiport}\right) & \\ + \$0.58 & \\ \times \left(Distance_{ATL}\right. & \\ \left. - Distance_{vertiport}\right), & \end{aligned}$$

where (VTTS x Earning) represents a currency value as a percentage of earning for a given time saved in minutes and varies according to trip purpose. Drive Time and Distance are measures of automobile drive time and distance between origin node to the destination. The Drive Time values also vary according to whether the journey takes place during rush or non-rush hour.

6. Vehicle Sizing Model - NDARC

The NASA Design and Analysis of Rotorcraft (NDARC) software is used to perform the sizing of a vehicle for the airport shuttle missions. NDARC is an aircraft system analysis tool intended to support both conceptual design efforts and technology impact assessments. In this regard, it is used to size an aircraft in order to meet specific requirements, including the ability to perform vertical takeoff and landing operations, and then to analyze the performance of the aircraft for a set of conditions or for a set of missions.

The multi-copter designed for the airport shuttle operations is inspired by the electric quadcopter described in Johnson et al. [10] although the mission requirements are different. The mission requirements are provided in Figure 6 and Table 2. The vehicle carries one pilot and has a capacity of four passengers. The design mission is made of four identical flights making up two round trips before a recharge is required. Each flight consists of a 20nm one-way trip flown at 7,500ft at best range speed from an airport at an altitude of 6,000ft mean sea level (MSL) to another airport at 6,000ft MSL and includes a 30-second hold before landing. The flight is repeated four times before the mission ends with a final 10 minute reserve flown at best endurance speed. In addition, two sizing conditions are considered: a requirement for a maximum gross weight hovering out of ground effect at full payload and at 8,000ft MSL, and a 500ft/min climb rate at the maximum gross weight at an altitude of 10,000ft MSL.

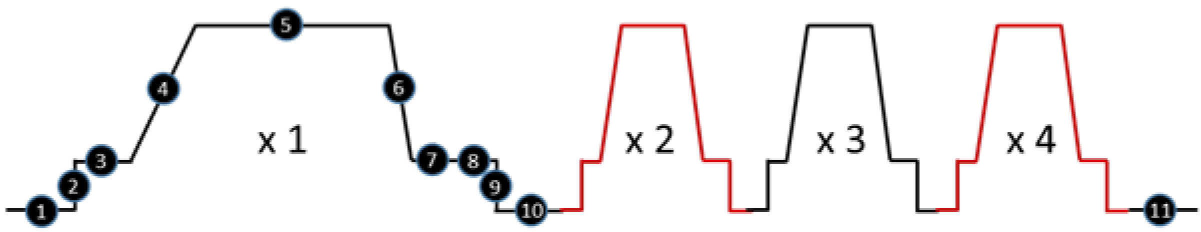

Figure 6. Design mission profile

Table 2. Design Mission Description and Design Conditions

Design Mission						
1	Taxi / Hover	15 sec	6,000 ft	6,000 ft	ISA Conditions – No Wind	4 pax + 1 pilot
2	Vertical Climb	100 ft/min	6,000 ft	6,050 ft	ISA Conditions – No Wind	4 pax + 1 pilot
3	Transition	10 sec	6,050 ft	6,050 ft	ISA Conditions – No Wind	4 pax + 1 pilot
4	Cruise Climb	500 ft/min at 80kt	6,050 ft	7,500 ft	ISA Conditions – No Wind	4 pax + 1 pilot
5	Cruise	20 nm at best range speed	7,500 ft	7,500 ft	ISA Conditions – No Wind	4 pax + 1 pilot
6	Descent	-500 ft/min	7,500 ft	6,050 ft	ISA Conditions – No Wind	4 pax + 1 pilot
7	Transition	10 sec	6,050 ft	6,050 ft	ISA Conditions – No Wind	4 pax + 1 pilot
8	Holding / Hover	30 sec	6,050 ft	6,050 ft	ISA Conditions – No Wind	4 pax + 1 pilot
9	Vertical Descent	-100 ft/min	6,050 ft	6,000 ft	ISA Conditions – No Wind	4 pax + 1 pilot
10	Taxi	15 sec	6,000 ft	6,000 ft	ISA Conditions – No Wind	4 pax + 1 pilot
11	Reserve	10 min at best endurance speed	6,000 ft	6,000 ft	ISA Conditions – No Wind	4 pax + 1 pilot
Design Conditions						
1	Hover	Out of ground effect	8,000 ft	8,000 ft	ISA Conditions – No Wind	4 pax + 1 pilot
2	Cruise Climb	500 ft/min	10,000 ft	10,000 ft	ISA Conditions – No Wind	4 pax + 1 pilot

The list of technology factors and technology assumptions used within the NDARC tool is given in Table 3. These are largely inspired by the technology assumptions used in the Johnson et al. [10] paper. The usable battery specific energy density is assumed to be 400Wh/kg at the pack level. This is accounting for longevity issues and assuming that at most 80% of the battery capacity is used during operations.

Table 3. Technology assumptions

Fuselage	
Basic	0.759
Crashworthiness	0.900
Landing Gear	
Basic	1.000
Crash Weight	1.000
Rotor	
Blade	0.916
Hub	0.759

Drive System	
Gear Box	0.738
Drive Shaft	0.690
Motor	
Cowling	0.503
Pylon	0.850
Support	1.104
Accessories	0.816
Energy Storage	
Usable energy density (Wh/kg)	400

These assumptions result in a quadrotor vehicle design with the following key characteristics: an empty weight of 4,308lb, a battery weight of 1,708lb, an installed power of 480hp, and a maximum take-off weight is 5,318lb. The vehicle design characteristics are shown in Table 4 and Figure 7.

Table 4. Vehicle characteristics

Overall Dimensions & Weight		**Propulsion System**	
Ground footprint	55 ft x 55 ft	Power Installed	4 x 120 hp
Max Gross Weight	5319 lb	Max Continuous	4 x 80 hp
Operating Empty Weight	4518 lb	Motor Weight	4 x 33 lb
Fuselage		**Energy Storage**	
Fuselage Length	25 ft	Installed Capacity	388 kWh
Fuselage Width	6.0 ft	Usable Capacity	310 kWh
Fuselage Height	5.1 ft	Battery Weight	1,709 lb
Rotor		**Other Metrics**	
Number	4	Disk Loading	3 lb/ft2
Blades	3	Power Loading	11.1 hp/ft2
Radius	11.9 ft	Autorotation Index	1.875
Chord	0.74 ft	**Performance**	
Aspect Ratio	16.0	Max Payload	800 lb
Solidity	0.059	Best Range Speed	95 kt
Tip Speed	550 ft/sec	Best Endurance Speed	53 kt
Total Disk Area	1773 ft2	Max Range	92 nm + 10min reserve

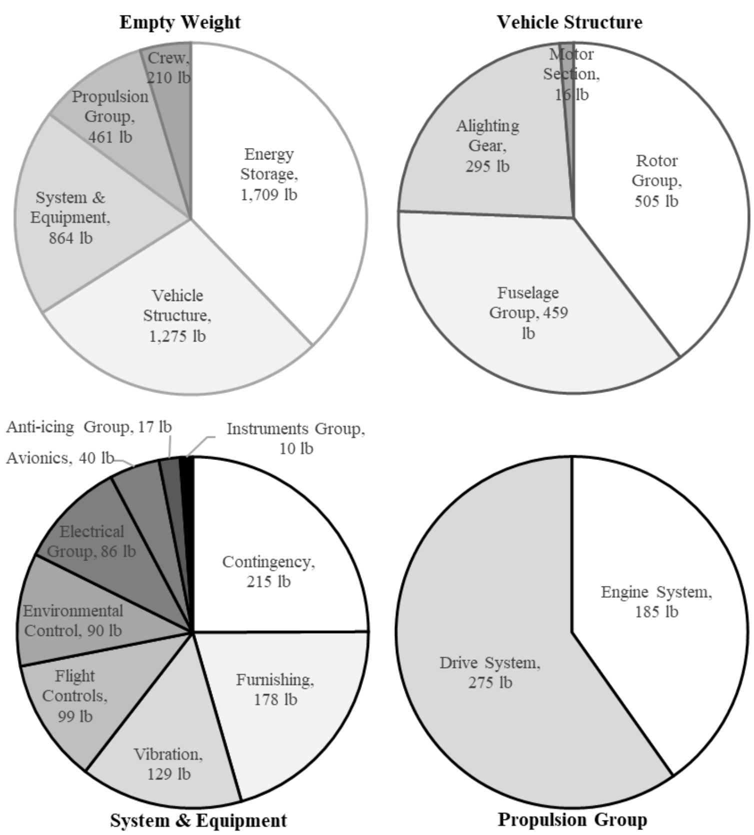

Figure 7. Component weight distribution

In order to estimate the performance of the vehicle on a variety of airport shuttle missions, surrogate models are generated to quickly assess off-design performance. The surrogate models are created by sweeping the range of a single flight mission between 10nm and 90nm. This single flight mission profile is similar to that described in Figure 6 except that the take-off and landing altitudes are set at 1,027ft which is the altitude of ATL, and the cruising altitude is set at 2,500ft. Some of the results are highlighted in Figure 8.

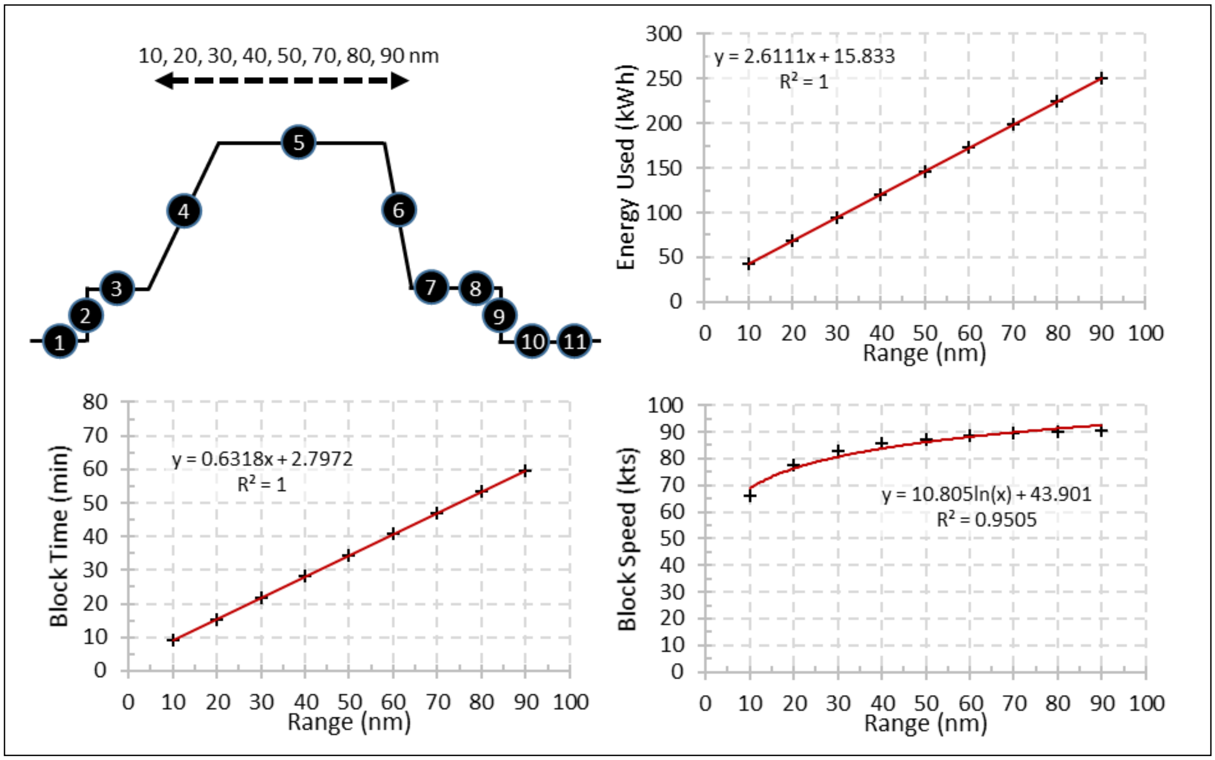

Figure 8. Off-design mission analysis

7. Vehicle Lifecycle Cost Model

The lifecycle cost estimation of the vehicle is performed using the PRICE Systems© Rotorcraft model [11]. The algorithm was based originally from the spreadsheet tool called PC Based Cost Model [12] developed by Bell Helicopter Textron, Inc. The Rotorcraft model is an improved cost engineering tool with adjustments to the base functionalities to support electric VTOL aircraft estimates where traditional drive trains can be replaced with an electric drive system. Cost algorithms for electric drive components were included to reflect current cost data. The model utilizes a multi-level parametric approach to estimate development, recurring and nonrecurring production and operating and support (O&S) costs for the entire fleet of vehicles. The model is set up to accommodate inputs to labor rates structure. This allows various manufacturing scenarios to be studied for recurring production costs. Inputs for this modeling approach utilizes information available at a project's pre-design stage such as those inputs available from NDARC analysis. The model consists of one aircraft-level object representing overall aircraft activity costs, and 11 sub-system objects representing inputs and activity costs for major rotorcraft components.

Total development cost calculations start with an estimation of engineering design man-hours for given system weights, and aircraft configuration parameters. The algorithm parametrically estimates manufacturing engineering, tooling cost, test and evaluation, prototype manufacturing cost, logistics, and all other developmental costs. Other inputs such as the percentage of new design for each aircraft system, and technology factors are also used for relative sizing and complexity adjustment. For simplification, development costs are considered negligible when the cost is spread over all the thousands of production aircraft, hundreds of flight hours per month, and decades of vertiport operation. Although development costs are not included in the cost per flight hour calculation, they form the basis for estimation of production and O&S phase costs.

Recurring and non-recurring production cost calculations utilize configuration inputs already defined in the development phase. System weights are the primary cost drivers. The aircraft configuration inputs adjust the complexities to yield a first unit (T1) production cost and labor requirements. The programmatic inputs of production schedule and rate determine the average recurring production cost considering learning improvement over time.

Outputs from the recurring production cost model are used to determine the vehicle total cost per flight hour (CPFH) including the depreciation costs for the airframe and battery, energy requirement, insurance, and maintenance costs.

Figure 9 illustrates the interface for vehicle life cycle cost modeling, and Table 5 contains the cost categories, assumptions, and Cost Estimate Relationships (CERs) in more detail.

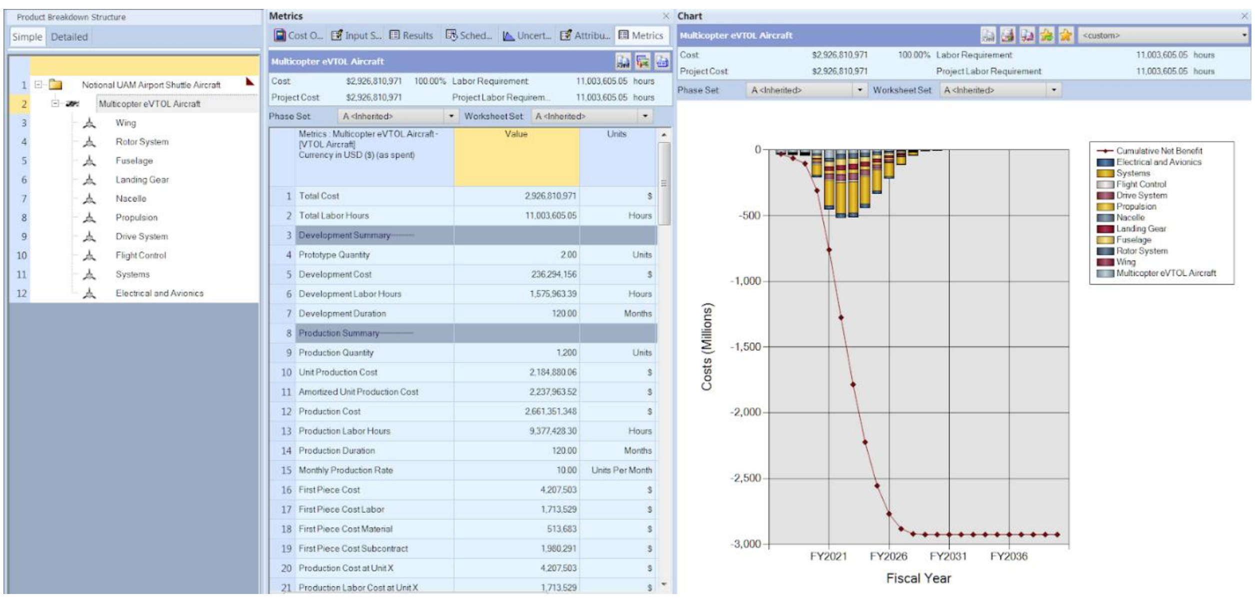

Figure 9. PRICE Systems® Rotorcraft model graphical interface for vehicle life cycle cost analysis

Table 5. Cost Estimate Relationships (CERs) for vehicle cost per flight hour estimates

Vehicle CPFH Cost Catagories	Cost Estimate Relationships (CERs)	Assumptions
Energy	= $/kWh x Avg. kWh/FH	1. Energy rate is $0.32/kWh. 2. Average power requirement per FH is calculated from NDARC mission analysis at best range cruise speed.
Crew	= $150/hr	Assumed fixed.
Insurance	= 0.3714 x (AmorUnitCost x Markup)^0.8516 x #ofMotor^-0.2554	1. "AmorUnitCost" is the aircraft flyaway cost including non-recurring production costs calculated from Rotorcraft Model. 2. "Markup" is a sparepart markup factor, assumed to be fixed at a factor of 2. 3. "#ofMotor" is the total number of electric motors.
Airframe Depreciation	= (AmorUnitCost x (1-ResaleValue)) / (YearofDepreciation * FH/yr)	A linear depreciation model is used assuming a 13 years operational life and a 30% resale value remaining.
Battery Depreciation	= (BatteryWeight x BatteryCostDensity x (1-ResaleValue)) / (YearofDepreciation * FH/yr)	1. A linear depreciation model is used assuming a 13 years operational life and a 30% resale value remaining. 2. "BatteryWeight" is calculated from NDARC mission analysis. 3. "BatteryCostDensity" is assumed fixed at $400/kWh at pack level for the current technology level.
Maintenance (Part and Labor) Scheduled		Based on PRICE Systems© Rotorcraft cost algorithm.
Inspection	= f(Empty Weight (EW), #ofMotor)	
Rotor	= f(rotor weight, hub type)	
Part Retirement (Motor, Drive System, Main Rotor, Tail Rotor, Flight Controls)	= f(EW, #ofRotor)	
Unscheduled		
Airframe	= f(component weight, material type, component reliability)	
Landing Gear	= f(component weight, material type, component reliability)	
Flight control	= f(component weight, component reliability)	
Electrical and Avionic		
Rotor		
Systems		
Motor and Drive	= f(component weight, #ofMotor, component reliability)	
Hanger, Training, Refurb, and Other Fixed Costs	= FixedCostFactor x ∑(CPFHi)	FixedCostFactor is assumed fixed at 20% of all other CPFH elements.

8. Ground Infrastructure Sizing and Cost Model

The infrastructure cost model was developed to address the construction and sustainment of UAM facilities of various sizes driven by location-based demand. The sizing of ground infrastructure requires consideration of the following aspects:

1.) Operational requirements surrounding the different types of vertiplace (vertistation, vertiport, vertihub) which are driven mainly by the peak-time demand for passenger gates, landing pads, passenger lounge area, vehicle chargers, and vehicle dimension,

2.) Federal Aviation Administration (FAA) guidance for heliport and facility design particularly issues surrounding sizing of the landing zone, taxiways, gate areas, and lighting requirements, and

3.) Energy requirements for battery recharge.

the 2018/19 update of the DOD Facility Pricing Guide created by the Whole Building Design Guide (WBDG) [13] was used as a data source for square footage rates for various infrastructure construction elements. WBDG uses different data sources to estimate both the Replacement Unit Cost (RUC) and Sustainment Unit Cost (SUC) for approximately 500 different DOD facility types. The data also includes 10,000 location factors that allow cost adjustment based on locations.

Type of Vertiplace

The vertiplace main objectives are divided into two main functions. The first objective is the passenger-side operations that handle incoming passengers up to the gate areas, and the second part is the air-side operations that handle eVTOL take-off, landing and charging operations. As the number of landing pads increases, additional supporting infrastructure may be required, such as dedicated communication tower, emergency ramp, fire station, parking structure, and etc. The classification of vertiplace has been proposed [14] to include the following three different types, Figure 10:

1. Vertihub -- The largest of all facility types that serve as a centralized location similar to an airport. The minimum number of landing pads to be classified as Vertihub is ten.
2. Vertiport -- Infrastructure created on converted rooftops or parking garages in commercial districts. The capability to handle between 3 and 10 landing pads is assumed.
3. Vertistation -- Landing structures implemented in high-value neighborhoods with minimal infrastructure features serving between 1 and 3 landing pads.

Figure 10. Types of vertiplace [14]

Air Operation Sizing

FAA regulations [15] categorizes facilities for air taxi operations to fall under "general aviation" for certification purposes if the gross weight of the final prototypes is below 12,500 pounds. As such, the requirements for landing areas, taxiways, and gates that serve as recharging spaces for the eVTOL can be established.

The landing area consists of the Touchdown and Liftoff (TLOF) area, the Final Approach and Takeoff (FATO) area, as well as a residual area of open space that serves as a safety precaution. These areas are derived from the eVTOL maximum overall length and diameter of the rotors group [15]. These dimensions are further adjusted based upon the location of the landing area (ground vs rooftop) and the elevation level of a rooftop landing area. Figure 11 is representative of the additional FATO length required for above ground landing pads according to FAA helipad regulations. The potentially drastic increase to the FATO area found in buildings exceeding 1,600 feet in height is due to security concerns surrounding the angle of approach for aircraft which increase the overall size of the air operation areas.

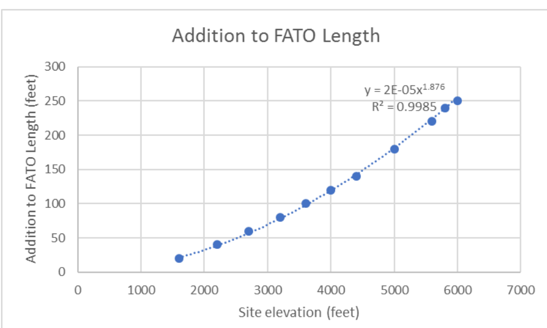

Figure 11. Elevation effect on FATO length based on FAA regulations

The number of passenger gates for each landing pad is an important parameter that defines the air operation efficiency. The optimal gate-to-pad ratio that maximizes pad utilization rate under most configurations is between 4- and 5-to-1 [16]. Taking into account factors such as construction cost, sustainment cost, demand uncertainty, operational tempo, load factor, etc., a fixed 4:1 ratio is assumed for any facility type in this study for simplicity. Each gate is assumed to occupy the same area as TLOF.

Finally, the taxiways and safety areas are assumed to occupy the same area as the combined landing zone and gate areas. This air operation sizing configuration parallels the current Dallas heliport's layout, Figure 12.

Figure 12. Dallas heliport layout

Passenger Terminal Sizing

To address potential passenger intake operations that cannot be handled by existing facilities or when a completely new ground infrastructure is installed, it may be necessary to create an additional terminal to address potential additional or new traffic. FAA A/C 150/5300-13, Airport Design guidance [17] sets forth the recommended square footage requirements for a terminal building which includes areas for waiting lounge, management/operations, public conveniences, concession area, and circulation, storage, HVAC. An estimated 49 square footage of the general terminal build area is needed for each pilot/passenger during peak hour. This determines overall size of passenger terminal building required.

Electrical Power Requirements

Addressing electrical power requirements involve many uncertain aspects and can vary significantly from site to site. Available square footage, equipment loading, electrical grid distribution voltages, charging power, electrical grid infrastructure capacity, and UAM vehicle design characteristics are some of the factors that are addressed through a range of assumptions.

Budget estimate based on the power requirements also adds one more layer of uncertainties. Utility upgrade for the new UAM site can range from a new 1 MW service supply extension costing $100,000 to a new 20 MW substation costing up to $80,000,000 [18]. For the sake of brevity, the costs related to utility upgrade to bring the power on-site are assumed to be a one-time expense absorbed by the utility company and recovered over time through electricity usage rate at $0.32/kWh.

The main concerns for vertiport sizing and cost estimate then involve estimation of on-site infrastructure and electrical equipment based on the required number of chargers. The general design principles proposed by Black & Veatch [19] are followed, Figure 13. The charging infrastructure is organized into pods consisting of three 600 kW power units and dispensers (chargers), powered by a 2,500 A switchboard and a 2MVA transformer. Additional pods are scaled based on the number of chargers required for the site. Table 6 lists the equipment replacement unit costs (RUCs) and sustainment unit costs (SUCs) based on the cost data found in the Whole Building Design Guide (WBDG)

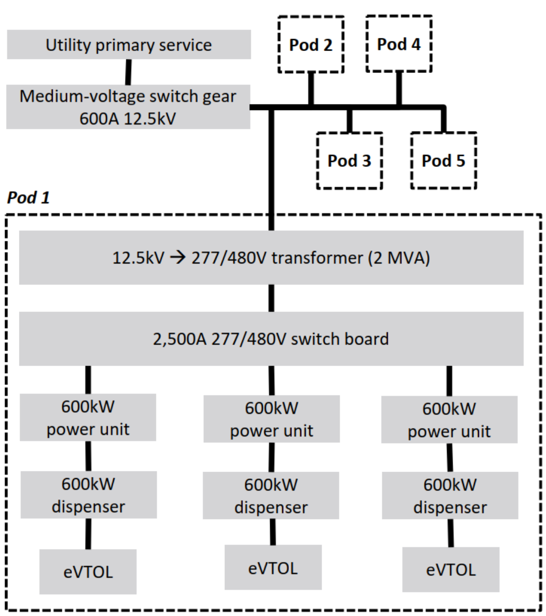

Figure 13. Pod system diagram for eVTOL charging infrastructure [19]

Table 6. Pod equipment unit cost [13]

Pod Equipment	RUC (FY2019)	SUC (FY2019)
600 kW Power Unit	$238,000	$58,200
2500 A Switching Board	$91,660	$8,067
2 MVA Transformer	$64,760	$14,100

The infrastructure cost is based on the conversion of 10 existing regional airports to support near-team UAM operation. The retrofitting activities may include, reassign landing zone, install lighting and ground signage, install new charging infrastructure, etc. Although a fraction of the Replacement Unit Cost (RUC) may be required when converting from existing airport to eVTOL vertiport, the model assumes a full RUC for the current analysis to add to the margins of conservatism. The decision to convert 10 existing airports resulted in a fixed infrastructure cost that can be converted into a cost per trip based on the flight per day calculation.

Integrated Engineering Environment

All the major analysis modules are discussed in the previous sections. In the following paragraphs, the modules are integrated to enable the rapid discovery of market feasibility space as well as to perform sensitivity analyses of the assumptions. The five modules are connected using Phoenix Integration® ModelCenter environment. Figure 14 illustrates the inputs and outputs for each module and the flow of information. The process starts with the Ticket Pricing Model that defines ticket price per trip per passenger for each vertiport location. The fixed and variable pricing scheme is based on the analysis of vehicle and infrastructure cost per flight hour (CPFH) as discussed earlier. The demand for each vertiport location depends on whether the ticket price is lower than the value of travel time saved which is a function of population density in each income bracket and trip time comparison during two different times of the day (rush vs. non-rush hours). The vehicle CPFH and infrastructure CPFH analyses are in turn the direct results from the NDARC performance model and Demand Model, respectively.

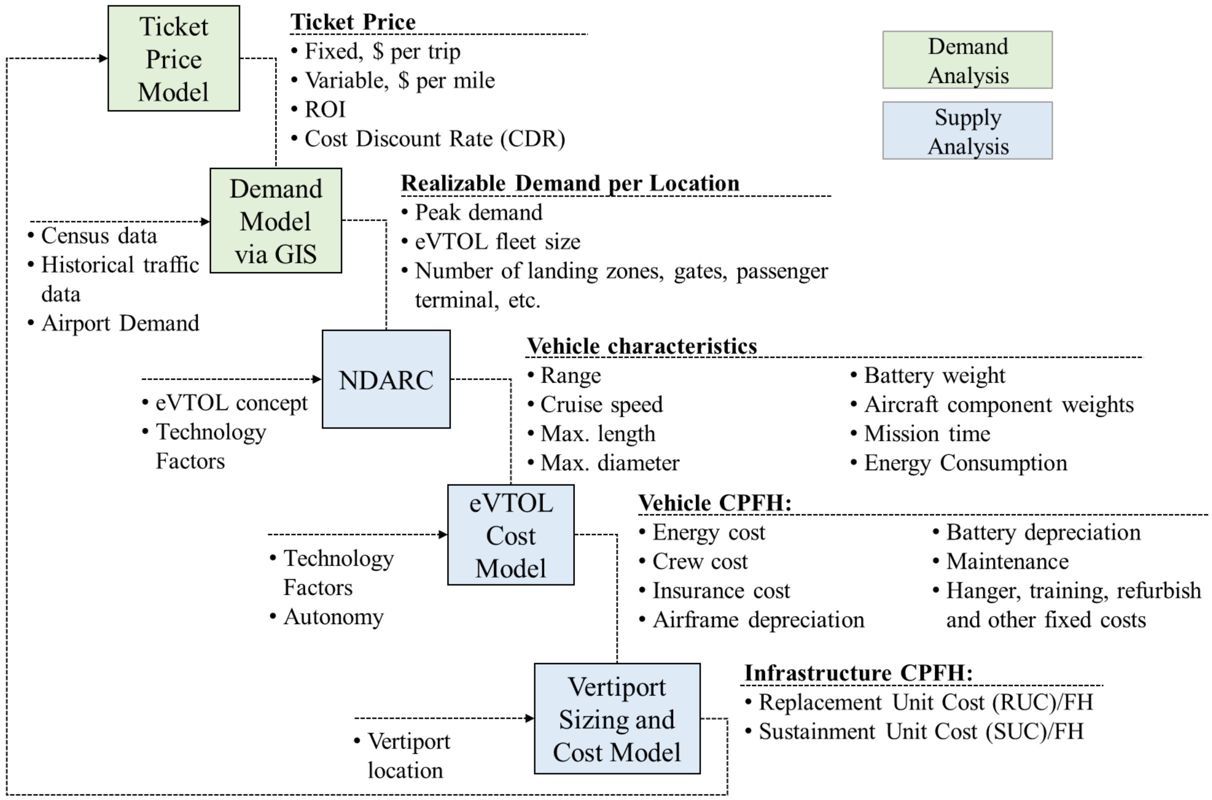

Figure 14. Analysis integration using ModelCenter® environment

Convergence of Demand

Ticket price is the starting point of the analysis. The variable element in the ticket price, Cost Discount Rate (CDR), ranges from 100% discount (free ticket) to 0% where ticket price equal ticket cost, to any negative CDR values representing profit per flight hour for the vehicle operator. The fix cost element, Booking Fee, is set as a fixed ticket price per passenger per trip. The analysis requires a convergence of the number of production units and vehicle utilization rates (FH/MO) for a given ticket price. The model converges when the ticket price is low enough to generate demand, which in turn allows enough number of vehicles to be produced and operated. The cheaper the ticker price, the more demand is generated up to the maximum demand potential. On the other hand, a combination of high CPFH, low CDR, and high Booking Fee can cause shortages in demand, thus driving CPFH even higher causing some or all of the vertiport locations to not have any demand, which leads to non-convergence conditions. Demand drop-off is a symptom of the high operating costs that manifests itself in the high ticket prices and not enough discounts to encourage demand. The downward spiral of demand causes the production units to continue to drop, thus further increasing vehicle and battery depreciation costs, infrastructure costs, etc. If the model does not converge, the ticket price can be artificially reduced. However, this may likely result in negative income. Other factors can also be used to improve the likelihood of model convergence, such as autonomous capability, cruise speed, battery cost density, battery power density, rush hour traffic multiplier, and income growth factor. These factors represent future technology improvements or the future state of the city and its population. As a result, market feasibility if not achieved today, can improve at some future time horizon.

Analysis Results

In this section, initial results and analysis of the UAM airport shuttle market in the Atlanta area are discussed. The maximum potential airport shuttle demand is presented. This happens when the entire population can ride on the eVTOL route for free. Then the key economics and engineering metrics sensitivities are discussed. Finally, the results from ticket price analysis and overall market feasibility analysis over the short-, medium- and long-term are presented.

Potential Demand (Final Catchment Area)

This analysis only looks at the demand-side analysis to determine the upper limit of demand from the current population, without regard to the costs associated with eVTOL operations. The potential airport shuttle model will focus on people who typically drive to the airport for business and personal trips. Passengers would switch to eVTOL service when the sum of the value of time savings and automobile cost savings is positive. The ticket fixed price is set to zero while the Cost Discount Rate (CDR) is set to 100%, representing zero ride cost. The heat map plot,

Figure 15 below shows the concentration of the population who benefit from eVTOL UAM shuttle service considering peak traffic hours, income level, eVTOL designed range and speed, and proximity to vertiport location. As can be seen, the final catchment areas naturally include high-value passengers living around vertiplaces that receive time-saving benefits. It is likely that most vertiplaces do not generate enough demand to justify their construction in the first place when the costs of vehicle and ground infrastructure operations are considered.

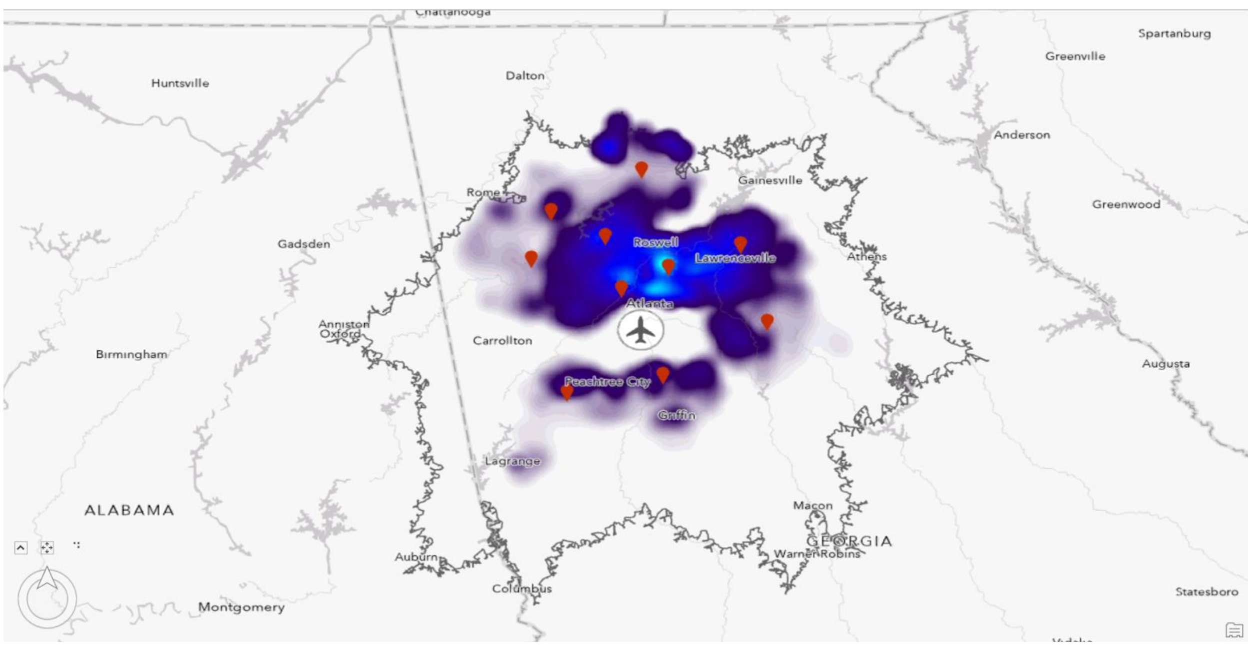

Figure 15. Final UAM catchment area show maximum economic potential from selected infrastructure

Optimal Market Feasibility

The objective of market feasibility analysis is to search for the optimal ticket pricing scheme that maximizes overall operating profit. The algorithm applies the same ticket pricing scheme across all facilities regardless of whether an individual facility is operating at a profit or loss The problem formulation can be expressed as follows.

Maximize:	average daily profit per aircraft
With respect to:	ticket price = booking fee + variable rate per flight time
Subject to:	daily demand ∈ (0, total first-leg air passengers demand per day)
	production volume ∈ (0, ∞)
	average aircraft utilization (FH/MO) ∈ (0, 465)

As can be seen in Table 7, the 2020 optimal ticket prices result in half of the facilities without any demand. The remaining facilities, except one, are operating at a daily loss. However, the only profitable facility generates enough demand and profit to offset the remaining money-losing facilities.

Table 7. Optimal ticket price and daily profit/loss per facility

2020 Optimal Market Condition				
IATA Code	**Distance to ATL (mi)**	**Ticket Price**	**Daily Demand**	**Daily Profit/ Loss**
CCO	30	$ 114	0	$ -
HMP	18	$ 88	0	$ -
CVC	34	$ 124	0	$ -
FTY	11	$ 74	0	$ -
PDK	19	$ 91	141	$ 1,883
PUJ	35	$ 127	0	$ -
LZU	36	$ 128	40	$ (245)
RYY	29	$ 113	13	$ (76)
VPC	42	$ 141	6	$ (195)
CNI	47	$ 153	18	$ (368)

The next analysis speculates on future technology improvements in the areas of battery cost density ($/kWh) and autonomous capability to see how these important technology improvements may play a role in accelerating profitability and rate of adoption of UAM services in the future. The results in Table 8 below show the optimal market conditions in terms of the ticket price, operating burden, and estimated demand and demand captured for three different time frames -- 2020, 2025, and 2030 respectively. The key findings from this analysis show a path toward higher profitability with improved technology by way of reduction of CPFH and better aircraft utilization. Between 2020 and 2025, the improvement in battery cost density from $400/kWh to $200/kWh results in an approximately 8% reduction in CPFH. During the same time period, the moderate increase in average ticket prices while capturing a higher percentage of demand resulted in a marked improvement in profitability. The introduction of autonomous capability introduced in 2030 resulted in better profitability by lowering the operating cost per flight hour while requiring less number of vehicles. Finally, the result in this study shows that the optimal UAM market is still limited to only business-related trips during rush hour period of the day serving the highest income-bracket customers as can be seen from the demand distribution.

Table 8. Summary of market analysis result

		2020 Estimate		2025 Estimate		2030 Estimate	
		- Current Demand - $400/kWh Battery Pack		- +5yr Demand - $200/kWh Battery Pack		- +10yr Demand - $200/kWh Battery Pack - Autonomous Capability	
Ticket	Booking Fee	$38		$46		$53	
	Cost Discount Rate (CDR)	30%		34%		10%	
	Average Ticket Price	$105		$109		$113	
Operating Burden	Avg. Cost Per Flight Hour (CPFH)	$1032		$945		$829	
	Number of eVTOLs (units)	27		36		30	
	Utilization (FH/MO)	34		41		38	
Demand	Total Yearly Demand (First-leg Air Passengers)	28.6 M		32.8 M		37.0 M	
	Demand Captured During Rush Hours, (%) (B: Business, P: Personal)	79,641 (0.278%)		110,940 (0.338%)		112,606 (0.304%)	
		B: 79,641	P: 0	B: 110,940	P: 0	B: 112,606	P: 0
	Demand Captured During Non Rush Hours, (%) (B: Business, P: Personal)	0 (0%)		0 (0%)		0 (0%)	
		B: 0	P: 0	B: 0	P: 0	B: 0	P: 0
Avg Daily Operating Profit per Aircraft		**$37**		**$77**		**$453**	

Figure 16 shows the Return on Investment (ROI) for each facility for each of the three timeframes. The plot shows a marked improvement in profitability in 2030 when all 5 of the operating facilities turned a profit, as compared to the year 2020 where only one facility, and the year 2025 where two out of five facilities are profitable.

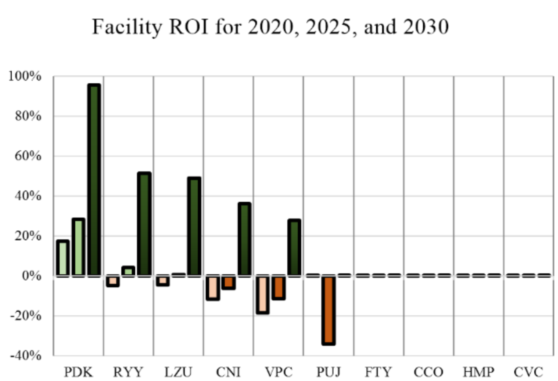

Figure 16. Return on Investment (ROI) over three timeframes from each facility

Conclusion

A methodology to determine optimal economic conditions for UAM airport shuttle services is proposed. The co-optimization of demand and supply is the key contribution which requires that both sides of the analyses are solved simultaneously. Analysis modules include demand analysis and allocation, trip time analysis for automobile trip and eVTOL service from selected vertiports, vehicle sizing and performance analysis, vehicle lifecycle cost modeling, vertiport sizing, and cost modeling, and finally, binary choice model comparing ticket price variable against value of travel time savings (VTTS) given various trip purpose, time of day, and income level. The key findings are that market feasibility can be achieved even with today's technology. However, the service only makes economic sense to the most affluent class of customers during rush hour traffic and for business-related trips where the value of time savings is at its highest level.

Recommendations and Future Work

The utility of the analysis and methodology presented in this study is considered a proof-of-concept. The research team aims to improve accuracy and expand the work in several areas. The demand analysis which forms the constraining conditions for the optimization is based on a series of assumptions that can be improved with a more accurate and granular dataset on travel behavior, population income, and location of origination. The binary choice model may not be an accurate representation to model the behavior of switching especially when the saving margin is small. Travel time is separated into two discrete portions during the day represented by a percentage of rush hours from normal operating hours. Better traffic modeling with a continuous traffic profile may help improve the accuracy of travel time analysis. Lastly, the vehicle and infrastructure cost models will be further improved with additional eVTOL component cost data and validation studies on vehicle components and infrastructure costs.

In addition to the proposed improvements to existing modeling capability, the research team also envisions expansion on the methodology in several areas. First, the current study presents a quadcopter vehicle concept sized for a short mission. In the future, a mix of vehicle concepts can be introduced to demonstrate a wider operational concept to include intracity travel using eVTOL. A new vertiport locator algorithm will be developed to take advantage of a population distribution to capture more latent demand beyond existing infrastructure locations. Several candidate cities are also planned to be included. Lastly, since vertiport catchment areas are by and large mutually exclusive in terms of population served, it is possible to maximize overall market feasibility and profitability by optimizing the ticket pricing scheme for each vertiport location.

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