Strategies for Posing a Well-Defined Problem for Urban Air Mobility Vehicles

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Over the past decade, the use of electric vertical take-off and landing (eVTOL) aircraft for urban air mobility (UAM) has seen a dramatic rise in interest from both the private and public sectors. Motivated by a surge in commuter air travel, the industry is rapidly proposing and adopting new vehicle concepts to meet consumer demands. However, variability in mission profiles and strong interdependencies of vehicle components present several challenges when implementing traditional aircraft design methodologies. Due to the absence of a "tried-and-true" approach, eVTOL concepts have come in all imaginable sizes and configurations. This has led to the creation of high-dimensional and computationally expensive optimization problems. In this paper, potential design strategies are presented and compared, identifying design variables and constraints which take precedence during a particular optimization. A novel weight build-up approach to estimating operating empty weight is also introduced. The results of this study were then used to restructure the methodology employed in the preliminary stages of conceptual eVTOL design. This work precedes a larger study to quantify post-optimality sensitivities of constraints, which will allow for the removal of implicitly resolved parameters and a reduction in computational cost.

Nomenclature

AR	Aspect Ratio
b	Wing Span
r_{prop}	Propeller Radius
v_{cruise}	Cruise Speed
v_{asc}	Ascent Rate
v_{dsc}	Descent Rate
v_{ts}	Propeller Tip Speed
x_{fp}	Vehicle Footprint
DL	Disc Loading
PL	Power Loading
E_b	Battery Energy
$V_{b_{OC}}$	Open-Circuit Voltage
$V_{b_{UL}}$	Under-Load Voltage
C_b	C-rating
$C_{b_{burst}}$	C-rating burst

I. Introduction

A. Background

American cities dominate the top 10 list of the most congested cities around the world, with Los Angeles (first), New York (third), San Francisco (fourth), Atlanta (eighth) and Miami (tenth).[1] Researchers predict that this problem will only be exacerbated by growing populations and rising urbanization over the coming decades. In many states, there simply is no more physical space to build new transportation infrastructure. One offered solution is a data driven approach to balance transportation network supply and demand. Another, which this paper focuses on, is the utilization of the three-dimensional airspace to alleviate vehicle congestion on the ground.[2]

Capable of taking off, hovering, and landing vertically, eVTOL aircraft have the potential to address some of the major shortcomings of present and future urban mobility. From transporting people within urban

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and suburban areas during peak travel times, to relaxing air traffic at major hubs, these vehicles offer a viable alternative to commuters. Moreover, with routes insusceptible to delays such as traffic and accidents, eVTOLs provide a greater sense of predictability in estimated times of arrival (ETAs).

Closely linked to the use of electric propulsion for VTOL aircraft is the onerous development of electric batteries as the energy source, with energy density standing out as one of the major hurdles. This is one of the primary factors in eVTOL sizing as it limits how much payload or passengers can be carried. Even the best Lithium-based batteries available today that store about 250 Wh/kg are insufficient for long-range commutes.[3]Studies suggest that electric aircraft must operate on batteries with energy densities above 300 Wh/kg to meet mission range requirements.[4]

B. Research Objectives

To date, evtol.news has tracked the development of over 70 unique eVTOL designs, most of which have gone public within the last decade.[5] Despite being at varying stages of realization - some being conceptual teasers and while others being full-sized operating prototypes - it has become apparent that several lingering questions surrounding vehicle configuration remain unanswered. What has been missing is the formality in the process by which these aircraft are designed and analyzed. This paper expounds upon problem formulation strategies to create a well-posed set of requirements to meet a specific objective.

1. Defining a clear area of concern

In the realm of UAM, we believe that the primary areas of concern will be (1) the time required to complete a mission, (2) vehicle weight, (3) battery efficiency and (4) range. Though vastly different, these concerns share one principle - they all directly impact the profitability of a vehicle fleet.

2. Defining relevance to the consumer and specifying objective(s)

This ultimately boils down to the market strategy and the target audience upon which design decisions are made. Below are some insights into what could potentially influence the decision:

- Mission Time - Companies which offer a wider range of services and routes may opt to design a vehicle that weighs the performance of all segments equally. Here, we define a mission as the total flight path from one vertiport to another
- Maximum Take-off Weight (MTOW) - This will always remain a goal in aircraft design. A lighter aircraft requires less energy to propel through the air and hover during arrival and departure procedures. Additionally, a lighter vehicle drives down production costs, battery charging costs and thus the idle time between flights
- Battery Efficiency - Reducing the amount of energy expended during flight decreases the time required to recharge at vertiports. This in turn reduces idle time spent on the ground during recharging
- Range - A business strategy which serves longer distances over 150 km may opt to prioritize cruise efficiency over that of arrival/descent procedures to vertiports

3. Identifying Design Variables

One may ask, how vast is the design variable space for eVTOLs. Let's look at some of the common vehicle attributes which characterize an aircraft to gain further appreciation. First, consider the wing(s) of an eVTOL, provided it has. The parameters associated with wing definition include span, chord distribution, twist distribution, dihedral, wing area, aspect ratio, taper, and camber. Secondly for the propulsion system, design parameters include the number of rotors/propellers, disc area, blade solidity, and twist, chord, and incidence distributions of the rotor blade. Without considering the battery and motor properties, we can draw several relationships between component attributes, leading to a large multi-nodal problem. As a result, identifying and quantifying the behavior of design variables and constraints becomes vital to accelerating the early stages of a conceptual design.

II. Methodology

A. SUAVE

SUAVE is an open-source conceptual design tool. Its high degree of modularity allows for the swift design of drastically different aircraft configurations with varying aerodynamic fidelity analyses.[6,7] Wings, fuselages (or battery pods), and propulsion systems can be easily appended and positioned to create an entire vehicle. SUAVE provides the capability to define entire missions as well as an energy network and its components. These include the batteries, motors, and propellers. This paper capitalizes of SUAVE's new versatility to study the performance of eVTOLs at different stages of the mission; allowing for a comparison between design choices.

In this paper, we have selected one class of winged eVTOLs to highlight how the choice of design objective affects the final design. Shown below in Figure 1 is Kitty Hawk′s Cora, a fixed-wing, stopped rotor aircraft used as the source of inspiration for the eVTOL configuration modeled in this study. The SUAVE-OpenVSP API allows us to visualize this model shown in Figure 2. The forward and lift propellers are not shown.

Figure 1: Kitty Hawk Cora

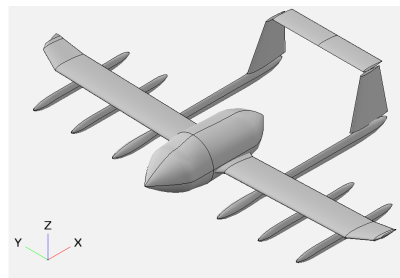


Figure 2: Stopped-Rotor eVTOL generated using SUAVE-OpenVSP

As seen in Figure 2, the vehicle model assumed an ellipsoid fuselage as an approximation of the vehicle main cabin. This proved to be sufficient for SUAVE's low-fidelity aerodynamic analysis tool. To reduce the number of design variables associated with the wing, the planform was linearly scaled through the wing area and aspect ratio. To maintain the benefit of a level field for the comparison after optimization, the energy stored and drive-train available to the vehicles were standardized, using a 400 kg lithium-ion battery with a pack-level energy density of 450 Wh/kg and a motor of comparable power density to the Siemens SP260D, with 5 kW/kg of continuous power.[8] After optimization, each vehicle was subject to the same mission to test feasibility. This mission was based on market predictions with an initial take-off/hover, followed by a 1000 ft ascent at 600 ft/min, a cruise of 100 miles at 150 mph, 1000 ft descent at 300 ft/min, and a reserve hover/loiter as suitable to the configuration of the aircraft.[9,10]

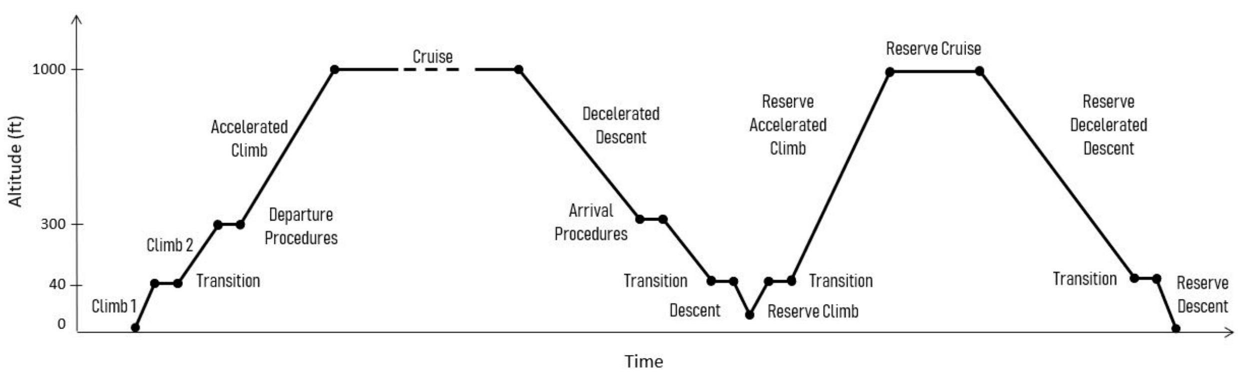


Figure 3: eVTOL Flight Profile with Emergency Reserve Mission

B. Weight Build-Ups

As with all aircraft, vehicle weight is a critical design parameter to consider in the evaluation of mission feasibility. Particularly for eVTOL capable vehicles, total weight directly determines the thrust requirements for takeoff, as well as the ongoing energy usage during transit. Beyond this, for electric aircraft using on-board batteries as an energy store, there is no option to reduce fuel load in exchange for payload or to simply improve the efficiency of the flight. By comparison to combustion fueled aircraft, electric vehicles operate as if they have a full fuel load for the entire flight. Thus, to achieve the desired performance, understanding the impact of design choices on structural weight requirements is a critical element in the evaluation of any proposal evaluation.

Typically, in the early stages, designers can rely on historical data to inform weight estimation. While each aircraft is unique, for conventional designs such as tube-and-wing commercial aircraft, or smaller general aviation vehicles, assumptions about available materials and flight conditions can allow for component weights to be inferred directly from geometric parameters. For the emerging class of eVTOLs, correlations with historical data fail for several reasons. Fundamentally, reduction in the cost of carbon fiber reinforced polymer (CFRP) and other structural composites offering high strength-to-weight ratios have made them the preferred construction material in recent proposals, whereas most aircraft to this point have relied on aluminum, steel, and nickel-based alloys. In addition, the flight and loading conditions of an eVTOL are significantly different from those of any other class of vehicle, and as such are likely to be driven by a different set of considerations than previous vehicles. It was therefore necessary to develop a method of estimating the weight of a proposed eVTOL which relies only on the properties of the presented vehicle without reference to historical data. To this end, we propose the use of component-by-component, loading-driven buildup of the weight estimate. This approach has several appealing properties, particularly for comparative studies, however it also has several hazards which must be carefully considered. An example using this method to estimate the weight of the stopped-rotor eVTOL with a battery sized to complete the baseline mission outlined in this study is provided in Figure 4. Included in this battery sizing is the 10% reserve.

Category	Element	Weight (lbs.)
Structural	Lift Rotors	22.81
	Thrust Rotor	6.12
	Hubs	63.80
	Fuselage	176.92
	Landing Gear	72.36
	Main Wing	418.94
Seats		66.00
Avionics		33.00
Battery		1717.42
Motors		319.00
Servos		17.16
Wiring		43.11
BRS		35.20
Passengers (Not Pictured)		440.00
MTOW		**3618**

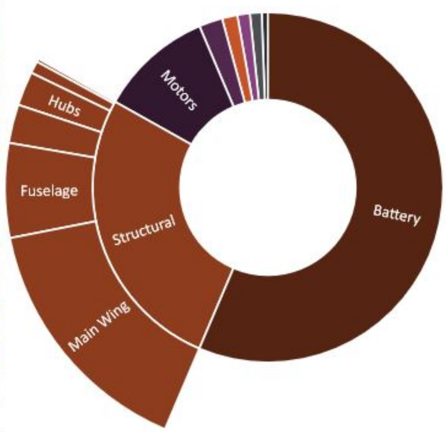


Figure 4: Stopped-rotor eVTOL Weight Build-Up (2 pass., 250Wh/kg)

In comparison to correlative methods, which can minimize the biasing effect of model assumptions via comparison with real-world outcomes, build-up methods rely on designer assumptions regarding material choice, properties, and which conditions will drive the sizing of components. By making our model flexible and easily able to consider alternate assumptions, we can guarantee our ability to incorporate new information as it emerges. Furthermore, by making the model as broadly applicable as possible, we can establish a level playing field between competing proposals, and if necessary, consider different combinations of material selection and sizing conditions within the same study. For this study, specific assumptions have been made in four separate areas:

Assumptions

1. Non-Parameterized Details of Vehicle Geometry

Our model assumes an ellipsoid fuselage, a straight, elliptical wing with a cross sectional thickness which can be approximated by the NACA 4-series profile.

2. Structural Material Selection

We have assembled a library of properties for AISI 4340 steel, 6061-T6 aluminum, nickel-cobalt chromoly alloy, carbon fiber reinforced polymer, and polymethyl methacrylate (acrylic) based on median values of available manufacturer reported data. Vehicle skin is modeled as a multi-layer assembly of a CFRP honeycomb substrate, bi-directional woven CFRP, and a top layer of polyepoxide and vinyl coating. Uni-directional CFRP, aluminum, and steel are used in modeling load-bearing members as necessary, with acrylic used as canopy material. Chromoly alloy is used exclusively as leading edge protection in rotor weight estimation.

3. Wiring

Communication and power cabling are estimated based on geometric parameters such as the location of motors or the size of the fuselage.

4. Sizing Criteria

Our primary sizing criteria were assumed to be critical load tolerances, as opposed to structural frequency, or fluid-structure interaction concerns which are valid alternative choices, but which require a level of fidelity exceeding that considered herein. We proceed by sizing wing skin thickness based on applicable torsion loads, spar and flap thickness based on bending, and similarly with rotors, though with the appropriate changes to assumptions regarding geometry and materials. Fuselage keel weight is estimated based on lifting moment due to motor thrust and wing root bending moment as well as landing impact load. Communication and power cabling is based on the estimated thickness needed to carry power demanded by the motors, and the length necessary to reach them based on specified location in the configuration.

C. Optimization Framework and Mission Specification

PyOpt, a Python-based package for formulating and solving the nonlinear constrained optimization problems was used in this study.[11] The algorithm of choice was SNOPT (Sparse Nonlinear OPTimizer), which employs a sequential quadratic programming (SQP) method for finding global minima.[12] Four different design strategies were studied. The first three consist of a single objective functions while the fourth is composed of a weighted exponential sum method for multi-objective optimization[13] outlined below:

$$f(x) = \sum_{i=1}^{m} w_i(f_i(x) - y_i^{goal})^p \tag{1}$$

where $\boldsymbol{w}$ is a vector of equivalent weights that sum to 1, $\boldsymbol{y}$ is a vector of component-wise optima, and p is an exponent similar to that used in the L_p norm. The list of objectives functions used in this study is summarized below:

- Minimizing Mission Time
- Minimizing MTOW
- Minimizing Energy Consumption
- Multi-objective (Mission Time, MTOW & Energy Consumption)

Wing area, aspect ratio, lift rotor radius, forward propeller radius, cruise speed and ascent/descent rates were the design variables chosen in this preliminary study. Constraints and bounds of design variables were chosen based on literature surveyed about flight regulations as well as the current state of technology. For example, cruise speeds under 1000 ft must not exceed 230 mph and ascent and descent rates of the vehicle must not exceed gravitational forces that would induce passenger discomfort.[14,15]

The mission solver of SUAVE iterates through the specified flight conditions until a converged solution is found with the output being propeller RPM, battery draw, propulsion efficiencies, throttles, and aerodynamic coefficients. To allow for bursts in propeller RPM and power drawn during vehicle hover-cruise transition phases as the vehicle balances forces, some constraints were relaxed during these segments of the mission.[16,10] These relaxed constraints have upper bounds which are also provided below in the optimization problem formulation.

$$
\begin{aligned}
\min_{x} \quad & f(\mathbf{X}) \text{ where, } X = [S, AR, r_{lift}, r_{forward}, v_{asc}, v_{dsc}, v_{cruise}] \\
\text{s.t.} \quad & v_{asc} \leq 600\ ft/min \\
& v_{dsc} \leq 300\ ft/min \\
& v_{cruise} \leq 200\ mph \\
& v_{ts} \leq 500\ ft/s \text{ in cruise} \qquad ; v_{ts} \leq 700\ ft/s \text{ in transition} \\
& x_{fp} \leq 50\ ft \\
& DL \leq 20\ lb/ft^2 \\
& PL \leq 20\ lb/hp \\
& E_b \geq 10\% \text{ of max battery charge} \\
& V_{OC} \geq 300\ V \\
& V_{UL} \geq 300\ V \\
& C \leq 4\ C \qquad ; C_{burst} \leq 30\ C
\end{aligned}
$$

III. Results and Discussion

A. Baseline Configuration Performance

Depicted in Figure 5 is the propeller throttles and battery energy consumption of the baseline stopped-rotor configuration over the mission outlined above. Surges in the propeller throttle correspond to transition stages between hover/climb and forward-flight modes. These brief periods represent off-design conditions where there are sharp rises in rpm, thrust and motor torque. See AppendixIV

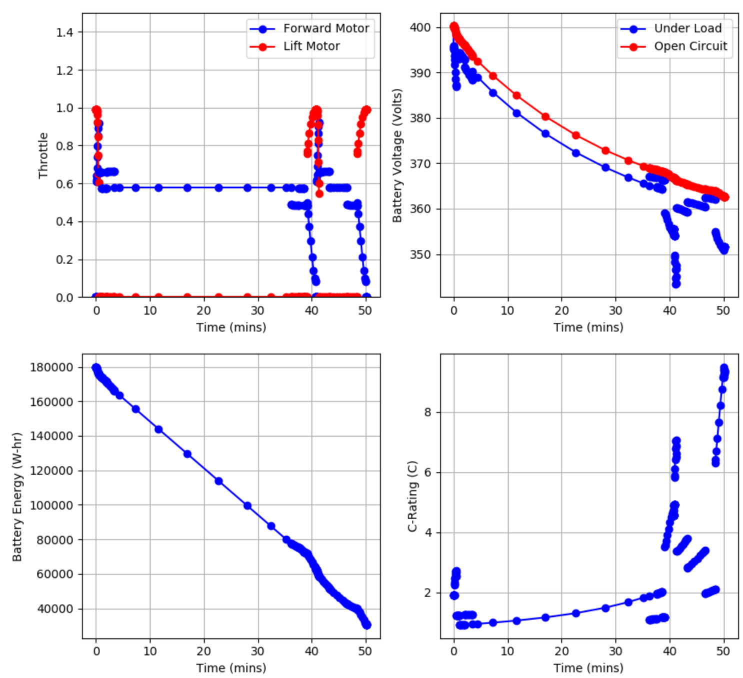
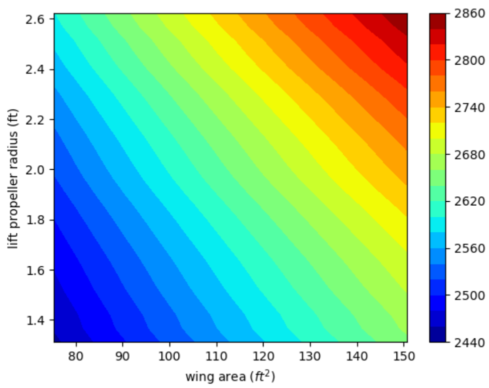


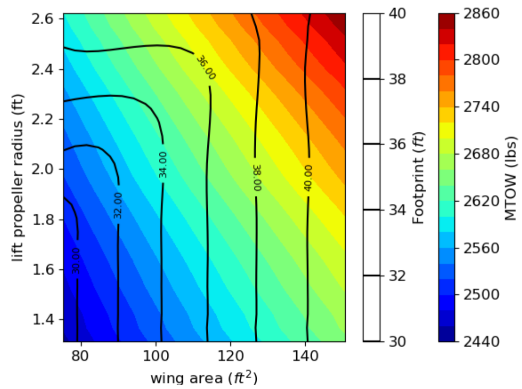
Figure 5: Baseline Performance of Stopped-Rotor eVTOL

B. Design Spaces

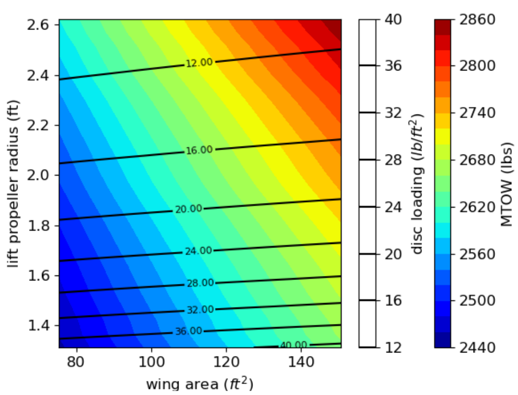
Design spaces were first constructed to form intuition of the full design envelope. This served as a sanity check prior to performing gradient evaluations and updates in the optimization. Shown below is a sample of the contour plots generated for the stopped-rotor eVTOL configuration. Figures 6a to 6d depict how the MTOW varies as a function of lift propeller radius and wing area. Vehicle footprint, disc loading and power loading are also overlain on subplots b to d. It must be noted that the footprint was measured from the outer most feature of the eVTOL and not necessarily the wingspan. As the propeller radius increases, there can be an instance where the blade radius of the outer most boom protrudes beyond the wingtip. This was particularly seen in the cases of small wing areas where propeller tips defined the bounds for vehicle footprint. As seen below, disc loading behaves as expected, with a very strong dependence on propeller radius.



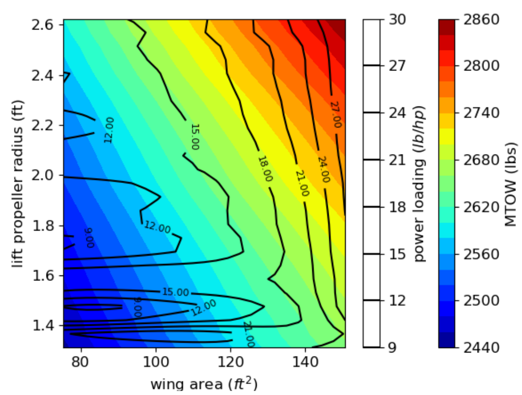
(a) MTOW



(b) Footprint



(c) Disc Loading



(d) Power Loading

Figure 6: Stopped-Rotor eVTOL Concepts

C. Optimization Results

Table 1 summarizes the results of vehicle design variables after employing the aforementioned optimization strategies, while Table 2 shows a comparison of the objective goals. Table 3 below lists the constraints active and inactive for each optimization strategy.

Design Variable	**Baseline**	**MTOW Obj.**	**Battery Energy Obj.**	**Mission Time Obj.**	**Multi-Obj.**
S (ft^2)	113.8	75.34	75.75	108.38	106.70
AR	11.3	12.6	15.0	14.04	13.7
r_{lift} (ft)	2.0	2.11	2.18	1.98	2.01
$r_{forward}$ (ft)	3.5	2.93	3.14	3.39	2.98
v_{asc}(ft/min)	500	525	600	501	565
v_{dsc}(ft/min)	400	385	434	401	390
v_{cruise}(mph)	110	105	115	161	121

Table 1: Summary of Optimized Design Parameters for the Stopped-Rotor eVTOL Concept

	MTOW (lb)	**Battery Energy(% remaining)**	**Time (min)**
Baseline	2798	16	50.16
MTOW Obj.	2541	26.8	48.51
Battery Obj.	2627	30.8	49.45
Mission Time Obj.	2647	10.07	38.85
Multi-Obj.	2605	29.1	43.9

Table 2: Summary of Objective Goals

Constraint \ Objective	MTOW Obj.	Battery Energy Obj.	Mission Time Obj.	Multi-Obj.
r_{asc} (u.b.)	inactive	active	active	active
r_{asc} (l.b.)	inactive	inactive	inactive	inactive
r_{dsc} (u.b.)	inactive	inactive	active	inactive
r_{dsc} (l.b.)	inactive	inactive	inactive	inactive
v_{cruise}	inactive	inactive	active	inactive
$v_{t.s.}$ (cruise)	active	active	active	active
$v_{t.s.}$ (transition)	active	active	active	active
$x_{f.p.}$	inactive	inactive	inactive	inactive
DL	active	active	active	active
PL	active	active	active	active
C	inactive	inactive	inactive	inactive
C_{burst}	inactive	inactive	inactive	inactive
V_{OC}	active	active	active	active
V_{UL}	active	active	active	active
$E_{B_{final}}$	inactive	inactive	active	inactive

Table 3: Summary of Active & Inactive Constraints

D. Constraint Analysis

Examination of the constraint conditions following optimization reveals that the time-minimizing design is the most constrained. That is, faster vehicles are likely possible if the constraints could be relaxed. However, relaxing of those constraints would require further study into whether the benefits of increased speed warrant the evolution required to move the constraints. As eVTOLs enter the market space competing primarily with ground transportation, enhanced speed is a key differentiator, but it remains something of an open question as to where the points of diminishing return will emerge, and how severe the tapering of user response to increased speed will be.

By contrast, the MTOW-minimizing design is the least constrained, with no active constraints which are unique to its configuration. This suggests a minimum viable set of constraints for the design problem, consisting of those which are active for the MTOW-minimizing design - tip speed, disk loading, power loading, and battery voltages. This set is somewhat implicit in the construction of the problem, as these constraints stem from physical limitations which are not captured by the low-fidelity models used in this study. An example of which is the speed of sound bound for blade tip speed.

These two optimizations mentioned above represent the extrema for constraints. The other two design objectives, energy-minimizing and the Multi-Objective approach lie between those two extremes - with no design having a constraint active which is inactive on the time-minimizing design, and none having a constraint inactive which is active on the MTOW-minimizing design. This suggests that these constraints - particularly rates of ascent and descent which varyingly are active at either the lower or upper bound, are the most sensitive aspects of the vehicle-mission design, and must be especially considered.

E. Comparison of Performance

As evidenced by the summary of objective goals detailed in Table 2, many of the potential choices of primary optimization criteria are in close harmony. Naturally, compared to the baseline performance, the Multi-Objective optimized design is able to improve upon all three dimensions of the evaluation. Each of the other resultant optimized designs may be characterized by what trade-offs it makes relative to the Multi-Objective Design.

The MTOW-minimizing design is able to reduce vehicle weight by nearly 10 percent compared to the baseline, 3 percent improvement of the Multi-Objective Design. While MTOW can be used as a proxy for manufacturing and supply costs for the vehicle, we see that this design also trades off significant increases in both vehicle travel time and energy usage, suggesting that there are significant increases in propulsive and aerodynamic efficiency to be had for modest increases in weight. Designers and system evaluators must be careful to weigh these costs against potential savings in manufacturing.

Indeed the energy-minimizing design provides an immediate contrast, as it too is able to significantly improve on the baseline MTOW, and achieve a much lower energy-drain, but at the cost of mission time, which is only modestly improved from the baseline - the worst among the optimized vehicles. The insight that can be gained here is that relatively similar vehicles, from a parameterization standpoint, can produce very different mission results depending on their exact flight profile.

A direct comparison can be made then, between the energy-minimizing design and the time-minimizing design via inspection of their energy consumption in Figure 7 and mission profiles presented in Figure 8. The time-minimizing design is clearly actively constrained by the 10 percent threshold in further optimizing for its objective. This suggests that it is, again, as with the comparison between the MTOW-minimizing and energy-minimizing designs, not so heavily a question of how the aircraft is configured that determines mission performance, but how it is flown, with optimization for that flight profile resulting in only second-order effects on vehicle parameters.

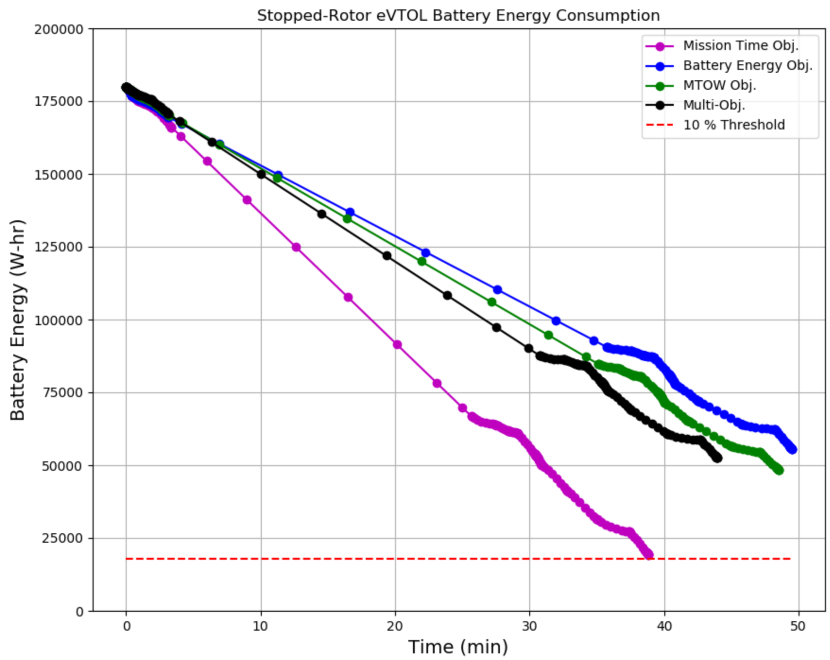


Figure 7: Energy Consumption of Optimized eVTOLs

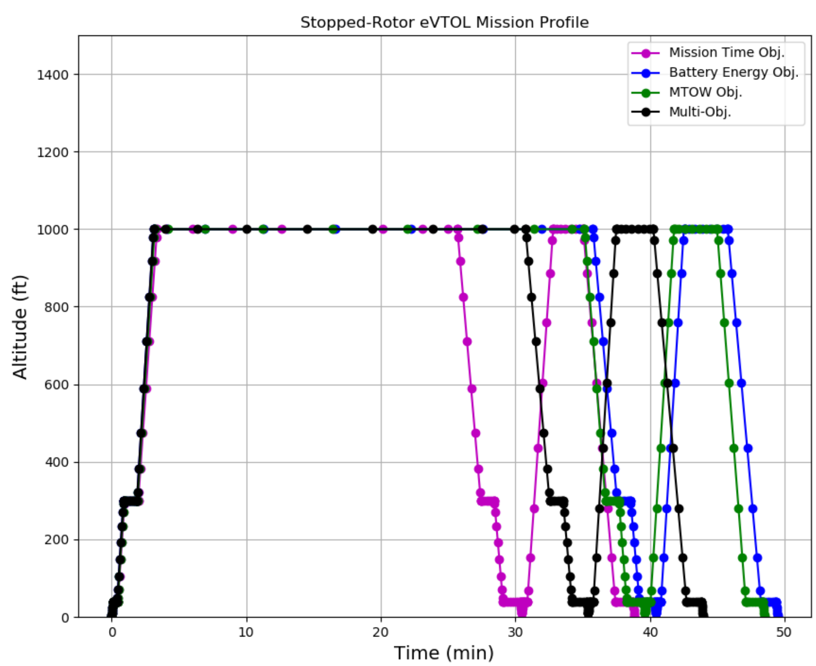


Figure 8: Flight Profiles of Optimized eVTOLs

F. Restructuring Aircraft Design for UAM

The results obtained in this study suggest that eVTOL design is particularly sensitive to mission profile and flight speeds. This has led to the proposal of a new methodology for UAM aircraft design which deviates from the traditional approach. The major takeaway shown in Figure 9 is the consideration of intended flight profile at an earlier stage of the conceptual process. Realistically, this can be envisioned through the determination of speed and flight path bounds which the aircraft cannot exceed. These bounds can be solicited from governing transportation regulatory agencies such as the FAA in partnership with local governments, cities and states.

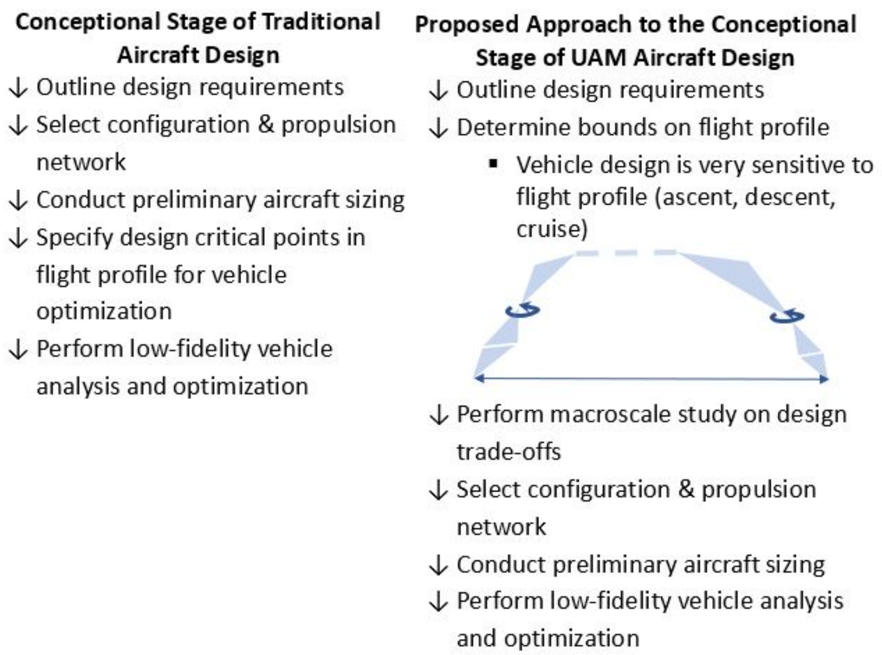


Figure 9: Comparison of the Conceptional Stages of Traditional Aircraft Design and the New Proposed Approach to UAM Aircraft Design

IV. Conclusion

In this study, several potential formalizations of the design problem for eVTOL vehicles for UAM were considered. Particular attention was paid to the selection of objectives and constraints. The comparison of performance indicated a strong dependence on the mission profile chosen. This was evident through closely parameterized configurations having varying levels of performance for a given mission objective. Future work in this area includes the creation of novel eVTOL models informed by the insights gained here to better explore the design space. Given the insight into how strongly design is driven by mission selection, a framework for developing UAM vehicles in tandem with optimizing their mission profiles will be proposed.

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Appendix

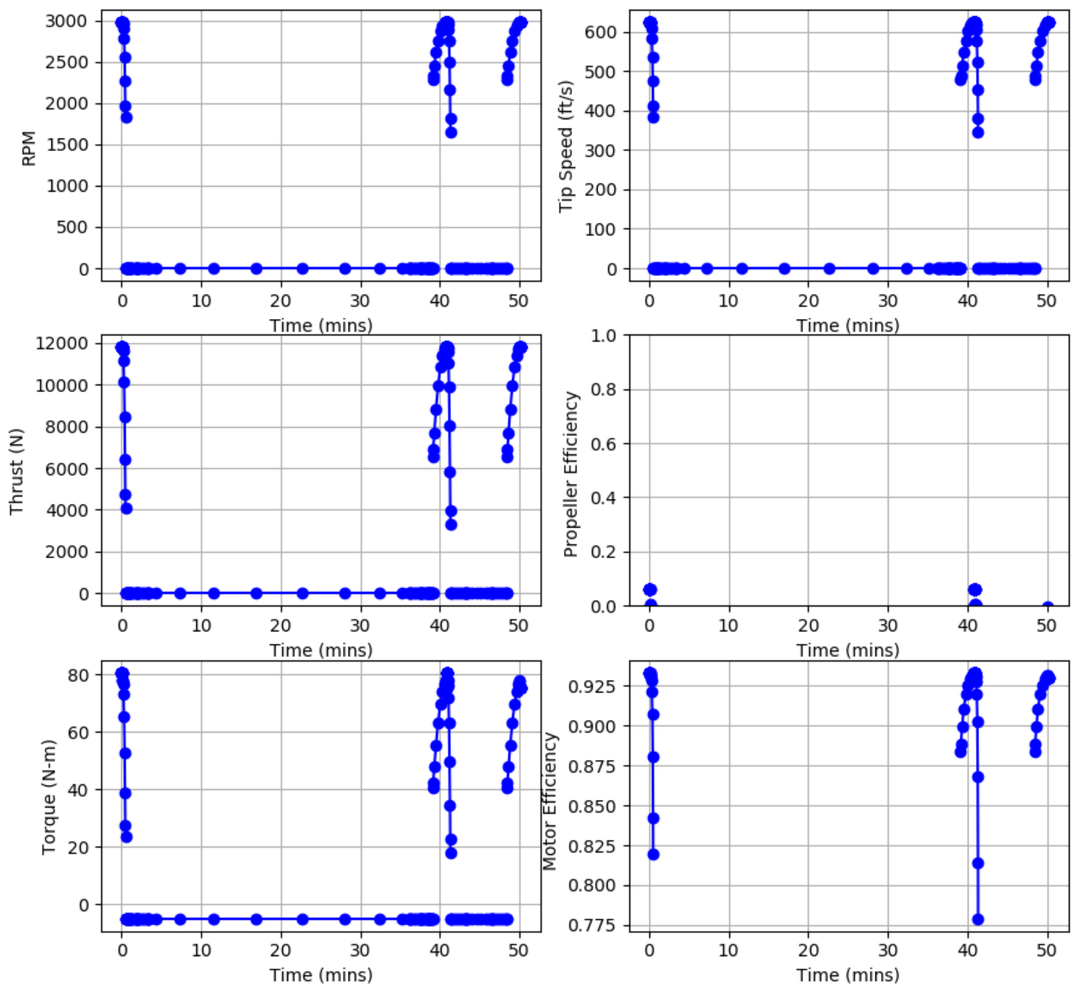

Figure 10: Performance of the Stopped-Rotor Lift Propulsor Network

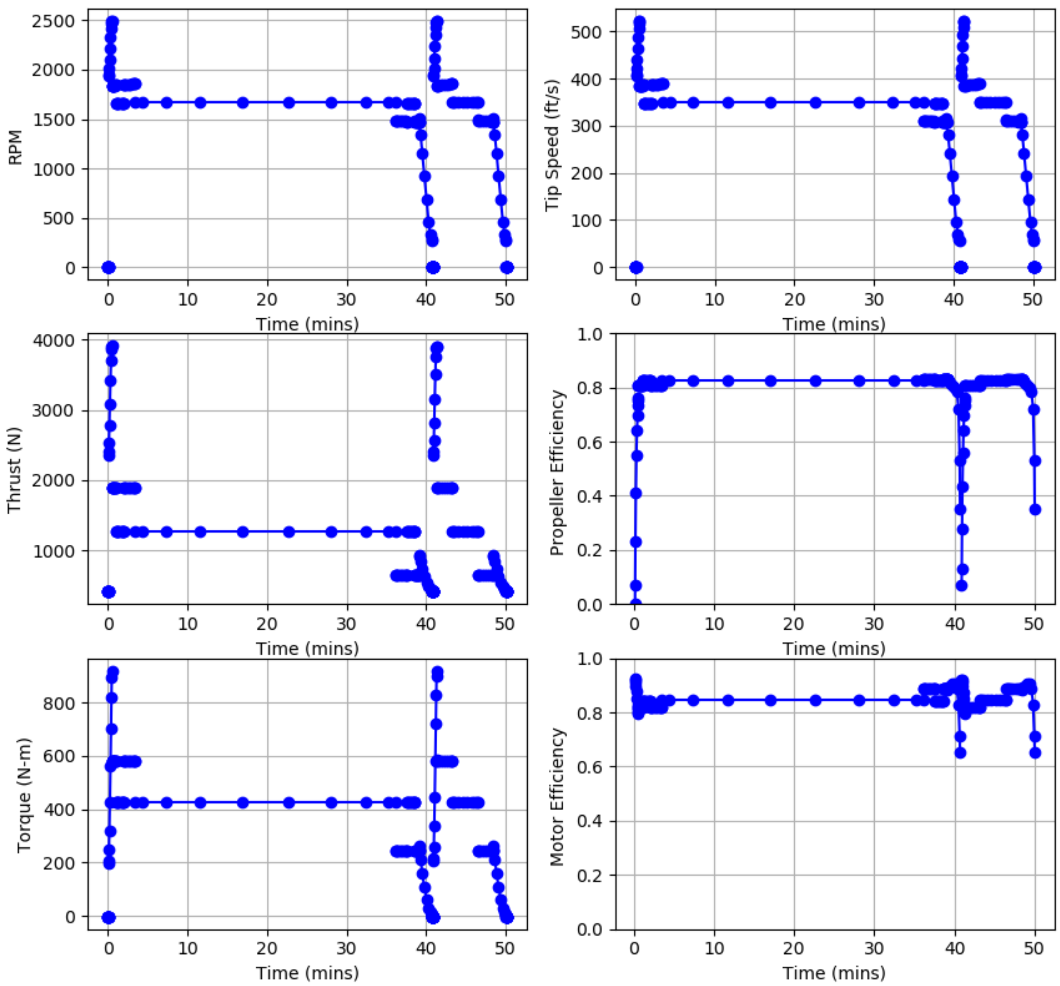

Figure 11: Performance of the Stopped-Rotor Forward Propulsor Network