MODELING THE LIFE-CYCLE COST EFFECTS OF DISTRIBUTED ELECTRIC MOBILITY IN ARMY AVIATION

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Abstract

A procedure for economic analysis of electric and hybrid-electric aircraft is detailed. Specific examples of cost prediction using the method are given for aircraft concepts suitable for applications in the distributed mobility paradigm of transportation as it could be applied to both military and civilian roles. The insights gained through the adaptation of existing aircraft cost models and the development of new cost models for the unique features of electric aircraft are discussed with a view to future modeling applications that will evaluate the specific benefits of distributed electric mobility aviation.

1. Introduction

New types of aviation always require extrapolation of historical evidence to predict how they may serve future users. The insights provided by this process of hypothesis and investigation often serve to shape the future of applications and investment in the field. In the case of distributed electric mobility, both the adaptation of conceptual tools for its assessment and the identification of potential use-cases for vehicles of the type are beneficial to the long term outlook of the aviation field. Besides evaluating the potential benefits of the new systems, the supporting research prompts a reevaluation of the existing status quo of transportation and how it can be improved.

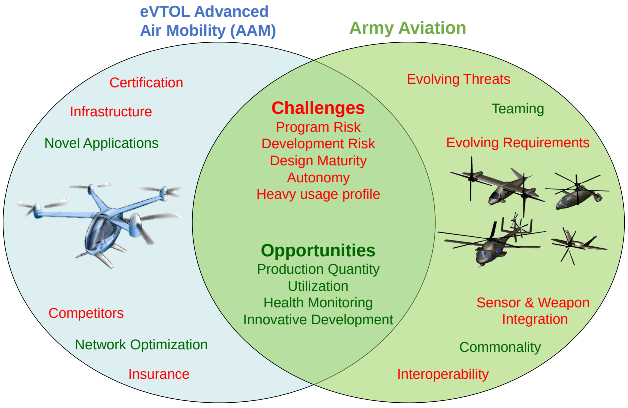

Figure 1: Common opportunities & challenges between advanced conventional and electric rotorcraft

Electric vertical takeoff machines compel the designer and the cost analyst alike to reevaluate their expectations of an aircraft. As Fig. 1 shows, electric electrical vertical takeoff and landing (eVTOL) concepts offer unique potential because their architecture removes many of the most complex and expensive components of conventional rotorcraft. As Fig. 1 also shows, replacing these expensive propulsion and dynamic system components with new electric technology also implies significant risks and tradeoffs in performance. Confronting these challenges presents an opportunity to address new and old problems alike from a fresh perspective. A direct analysis such as the one presented here will result in new tools to evaluate a potential solution. Its quantification of the impacts and trades of the solution also stand to motivate reconsideration of the technological and institutional obstacles of the status quo from a fresh perspective.

2. Motivation

Every new configuration of aircraft requires some modification to cost assessment methods depend-

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ing on its degree of departure from established legacy designs. Compared to conventional helicopters, the most traits of eVTOL aircraft which shape the modeling features used to assess them are:

- Electric motors and batteries instead of fuel burning propulsion systems
- Distributed propulsion based on multiple rotors, propulsors, and motor systems
- Emphasis on intelligent vehicle flight and systems management which include some degree of autonomous flight

Several studies have generated design concepts with these features based on estimates made of their potential capabilities from the best direct analysis and the most informed engineering judgment currently available.[1], [2]. These studies offer a starting point for cost assessment, but the models used need to satisfy a high standard of flexibility in order to generate meaningful insights in a nascent field. They must encompass a sufficiently broad range of an aircraft's life-cycle to weigh relative tradeoffs between different phases. They also must mirror the known engineering effects of scale and complexity in aircraft design. Finally, any cost model used to evaluate new electric aircraft must consider all of these effects while working within the scope of conceptual design activities. In other words, the models must be effective at considering all of the pertinent effects without requiring overly detailed design and performance information.

Table 1 identifies a set of key recent affordability studies with these attributes of adaptability which the present work seeks to build upon. The methods of cost analysis used and the specific aspects of design technology to which they are applied illustrates the progress of the field in addressing the remaining electric vertical flight. Over the past decade, advanced parametric methods have replaced analogy methods, first in conventional aircraft, then increasingly in electric fixed wing and rotorcraft, with the methods extended to include more phases of the vehicle life-cycle.

The persistent source of uncertainty in studies of eVTOL affordability stems from the limited characterization of design and cost trends inherent to its key technology. In most of the given references, motors, batteries, and their support and management systems were addressed by reverting to the simpler analogy methods based on cost per power or cost per energy capacity[5, 7].

Reference	Technology (Method)	Life-Cycle Phase
Harris[4] (2012)	Conventional rotorcraft (Parametric)	O&S
Stoll, Mikić[5] (2016)	Hybrid-electric fixed wing (Hybrid Param-Analogy)	P, O&S
Scott[6] (2018)	Conventional rotorcraft (Parametric)	P
Sirirojvisuth[7] (2020)	eVTOL AAM (Parametric)	O
Scott, Vegh[8] (2020)	Battery-electric propulsion (Hybrid Param-Analogy)	D, P, O&S

Table 1: Recent conceptual cost models developed for rotorcraft (D=Development, P=Procurement, O&S=Operation and Support)

In addition to direct analysis of electric propulsion architectures, the present work is informed by the emerging need to consider advanced air mobility technology from the non-commercial perspective of Military Electric Distributed Mobility (MEDM). In this discussion, MEDM will refer to the leveraging of eVTOL concepts within the urban and advanced aerial mobility paradigms to yield positive impacts to military aviation productivity and affordability. MEDM operations envision a long term goal of achieving economic parity with existing commercial aircraft with conventional propulsion as well as a new and unique capability set enabled by electric propulsion.

This work serves as a status update in the progress, application, and outstanding needs of conceptual cost modeling with respect to MEDM aviation. Its three primary objectives are:

1. Develop new parametric cost estimating relationship equations to assess relevant electric propulsion components
2. Apply the new equations within the existing cost analysis toolset developed by the previous work on relevant design concepts such as electric and hybrid-electric rotorcraft
3. Quantify the results from a military perspective using government cost analysis metrics

Future trade studies will benefit from the capability set established in this work. In government and private environments where acquisition funding is progressively more competitive, conceptual design and assessment tools must anticipate future technology trends in order to identify the most promising technology and design concepts.

3. Model Development - Production Cost

Efficient design practice seeks to match the degree of modeling sophistication with the complexity of the question. In conceptual design and assessment matters like study, this implies a strong preference for parametric models based on actual historical reference data due to their empirical value and their flexible scaling behavior. Many cost models of this format have already demonstrated successful outcomes. Single equation models have demonstrated verifiable levels of accuracy within 10-20% when tested against basic cost metrics of legacy aircraft powered by conventional engines and fuel types[3]. At a higher analytical workload, component-based models increase the analysis workload from one predictive equation to as many as 20-30 relationships, but have been shown to reduce the margin of error to less than 10% with repeatable accuracy for conventional helicopter and fixed wing configurations[6]. The major strength of such component-level weight and cost models beyond a marginal improvement in accuracy emerges when the aircraft in question is a non-conventional concept requiring subjective adjustment of conventional trends.

Assessing the specific technology enablers behind electric propulsion can be abstracted as a substitution of components. The immediate effects replace conventional propulsion systems with electric components. Secondary cost effects like assembly costs and installation effects in the airframe follow from the measurable weight changes in the design and the best available assessment of the unique effects of the technology.

To accomplish this objective, the analysis presented here adds two new component models to the set of procurement cost equations for airframe and system components - one for piston internal combustion engines for aviation applications and another for electric motors.

3.1. Piston Engines

Internal combustion (IC) piston engines, while always popular in general aviation, have enjoyed renewed popularity in small platforms like UAV's. They are also frequently identified for applications in hybrid-electric propulsion systems. Figure 2 gives the average procurement cost trend developed by adapting a previous equation from Roskam's 1989 work[9]. The new relationships include an inflation correction bringing the older database up to 2021 dollars. They also consider several new engines added to the reference population from more recent surveys of commercially available piston engines, including one example of an aviation diesel engine.

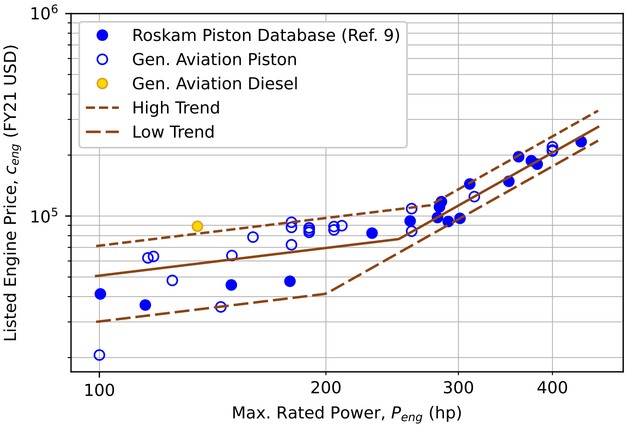

Figure 2: Procurement prices and trends for aviation piston engines

Besides the trend itself the new data also leads to the addition of high and low trend lines representing the limits of the existing data scatter given the current limitation of the model to the one independent variable of maximum rated horsepower. Roskam's work noted a break point in the trend correlated to maximum rated engine power where the procurement cost trend is steeper above 200 horsepower. The three trends retain this form with both the slopes and breakpoints adjusted to fit the updated engine population.

Middle of trend:

$$(1)\quad \begin{aligned} \hat{c}_{eng} &= 6287.5\, P_{eng}^{0.4536} && \text{for } P_{eng} \leq 250 \text{ hp} \\ \hat{c}_{eng} &= 0.7240\, P_{eng}^{2.0917} && \text{for } P_{eng} > 250 \text{ hp} \end{aligned}$$

Low trend:

$$(2)\quad \begin{aligned} \hat{c}_{eng} &= 3733.2 P_{eng}^{0.4536} && \text{for } P_{eng} \leq 200 \text{ hp} \\ \hat{c}_{eng} &= 0.6350 P_{eng}^{2.0917} && \text{for } P_{eng} > 200 \text{ hp} \end{aligned}$$

High trend:

$$(3)\quad \begin{aligned} \hat{c}_{eng} &= 8841.8 P_{eng}^{0.4536} && \text{for } P_{eng} \leq 275 \text{ hp} \\ \hat{c}_{eng} &= 0.8926 P_{eng}^{2.0917} && \text{for } P_{eng} > 275 \text{ hp} \end{aligned}$$

3.2. Electric Motors

The perceived simplicity of electric motors motivates much of the current thinking in conceptual design studies. Several examples of recent studies have used models to predict motor weight based on either the power or torque of the system. In the preliminary investigations to find a useful cost relationship, the design-specified nominal RPM of the motor (Ω_Q) emerged as a significant predictor. While electric motors do not always share a common definition of operating profiles, Ω_Q in this case denotes the RPM where maximum power is achieved and maximum non-instantaneous torque can be maintained. The presence of this term in conjunction with power suggests that maximum power and torque ratings are related cost-driving characteristics in the design of motors. Given the physical relationship among power, torque, and angular velocity in rotating systems ($P = Q\,\Omega$), power and RPM were selected as the primary terms of the cost equation because they are readily translatable to aircraft propulsion scaling. Eqn. 4 gives the final form of the equation for estimate motor procurement cost:

$$\hat{c}_{motor} = 359.06\, P_{motor}^{0.7288} \left(\frac{\Omega_Q}{1,000}\right)^{-0.3960} \times k_{PM} \tag{4}$$

Where Ω_Q is the nominal RPM of the motor, P_{motor} is the maximum rated non-instantaneous power of the motor, translated to horsepower for compatibility with the majority of US-based helicopter performance codes, and k_{PM} is a complexity term for the type of motor where

$$k_{PM} = \begin{cases} 1.0 & \text{Induction motors} \\ 0.7873 & \text{Permanent magnet motors} \end{cases}$$

Since both permanent magnet and induction-type electric motors have been selected in similar cases across a range of applications, the choice between these alternatives appears to be a contextual decision involving complexity and weight considerations. The significance of power and RPM present in Eqn. 4 conjunction with one another raises the potential for future affordability studies investigating the tradeoffs related to drive systems in electric configurations. While direct-drive rotor systems offer a major simplification, the addition of a drive system with gearboxes may promote operation of the propulsion group closer to the optimal speeds of each of the constituent systems as seen in conventional helicopters.

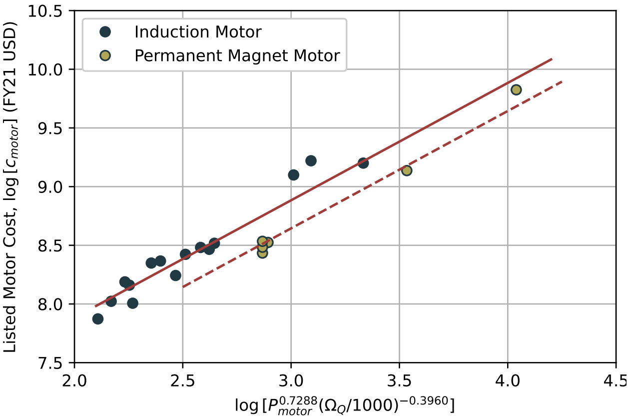

Figure 3: Procurement prices and trends for high power-to-weight electric motors

3.3. Batteries

The pace of battery progression in weight, efficiency, and price improvement seems to overwhelm most of the independent variables driven by design considerations. Although energy storage in secondary (rechargeable) chemical batteries carries challenges for aviation applications above those faced by ground vehicles, the most important cost driver from a high-level conceptual perspective appears to be the evolving influence of technological maturity and supply chain availability. The automotive industry's progression of material preferences represents a significant example of this - progressing from cobalt and manganese to iron and aluminum as the preferred active cathode materials based on cycle life as well as supplier concerns. Even within these chemical options, substantial room has been noted for future cell performance improvement derived from tailoring of the proportions of each metal depending on the targeted application[10].

The technology assumptions (battery chemistry, packaging, cooling, and management) associated with the projected time-frame of the study in question drive both the gravimetric energy density (Whr/kg) and cost per energy ($/Whr). Previous conceptual design work in a semi-empirical battery analysis code led to the relationship given in Eqn. 5

$$\hat{c}_{batt} = (1060.8 - 4.207 e_{batt}) \left(\frac{r_{prod}}{1,000}\right)^{-0.113} \tag{5}$$

Where e_{batt} is the energy density in Whr/kg and r_{prod} is the annual battery production rate. The equation is considered valid to best extant assessment practices for pack level energy density up to 200 Whr/kg and production rate up to 10,000 packs per year, synonymous with most contemporary lithium-metal battery chemistry types. Constant reevaluation of this equation will track effects of promising new technologies among lithium-metal chemistry options as well as longer term candidates including lithium-air designs.

3.4. Model Development - Maintenance Cost

Operating costs typically occupy the largest percentage of the total life-cycle cost of an aircraft. Maintenance is an important contributor to operations and support expenses, and thus a key aspect of the MEDM value proposition. It is also one of the most difficult metrics to predict accurately due to the influence of the user and operating environment on the day to day performance and reliability of an aircraft.

MEDM applications of hybrid-electric aircraft share aspects of both military and commercial operational concepts. The model divides components of O&S into variable costs estimated on a per flight hour basis ($/FH) and fixed costs estimated on a calendar year basis. While an analyst can consider O&S in terms of any basis, programs falling under the US DoD CAPE structure usually prefer to express cost in terms of annual cost per aircraft per year ($/AC/yr). Commercial and civil applications operating within the FAA Form 41 structure tend to emphasize an aircraft's cost per flight hour. The total annual operating cost of a single aircraft is thus:

$$C_{AC/yr} = \sum_i \underbrace{c_{i/FH}\,(FH/yr)}_{\substack{\text{Variable}\\ \text{Costs}}} + \sum_j \underbrace{C_{j/AC/yr}}_{\substack{\text{Fixed}\\ \text{Costs}}} \tag{6}$$

Where dividing the left and right sides of eqn. 6 by FH/yr yields the same total cost in terms of dollars per flight hour averaged over the calendar year. In reality, not all components of operating cost are purely fixed or variable, and in some cases the definition changes depending on the convention.
Table 2 describes the typical cost structure used in the United States by commercial operators, where the direct operating costs (DOC) are aptly named for the maintenance, crew, fuel, and refurbishment costs incurred in the immediate sense when the aircraft is flown. Indirect operating costs in a commercial and military sense receive less attention in the conceptual assessment field due to their association with the type of facilities overhead and ground personnel expenses that are generally considered invariant with respect to aircraft design characteristics.

Variable Cost ($/FH)	Operations (Fuel)	Direct Operating Cost
	Maintenance (Parts + Labor)	
Fixed Cost ($/AC/yr)	Personnel (Crew)	
	Reinvestment	
	Indirect (System)	

Table 2: Commercial O&S Cost Categorization

Following the general form of several O&S cost models, the new set of prediction tools developed in this work expresses maintenance as a variable component in terms of dollars per flight hour. The new practices adopted in this work relate to the subdivision of maintenance components. Using data surveyed from both commercial and government operating cost databases, this work presents a higher fidelity set of parametric equations dividing maintenance into the 8 major components shown in Table 3 as addressed in Eqns. 9 through 14 and 15 through 16:

Component	Method	Basis	Source
Rotor	Parametric	$/FH	Eqn. 9
Drive	Parametric	$/FH	Eqn. 10
Turboshaft	Parametric	$/FH	Eqn. 11
IC/Piston Engine	Parametric	$/FH	Eqn. 12
Airframe & Systems	Parametric	$/FH	Eqn. 13
Inspections	Parametric	$/FH	Eqn. 14
Electric Motor	Retire/Replace	$	Eqn. 4, 15
Battery	Retire/Replace	$	Eqn. 5, 16
Unsched. Maint.	Fractional	$/FH	Eqn. 7
Annual Labor	Parametric	$/AC/yr	Eqn. 8

Table 3: Maintenance Model Components and Prediction Methods

Generating an estimate of an aircraft's operating cost may involve all of the equations in Table 3 or only a subset depending on the type of configuration. Components assessed on a $/FH basis are major aircraft assemblies where the cost per flight hour is a composite set of parts and assemblies averaged over a representative quantity of flying hours. The final line of Table 3 holds a reserve component for unscheduled maintenance. The model estimates unscheduled maintenance as a fractional element of the total maintenance costs. Depending on the primary mission role and operating environment of the vehicle, unscheduled maintenance may add 25-50% ($\zeta_{unsched} = 0.25 - 0.50$) additional cost to the known scheduled maintenance items.

(7) $\hat{c}_{unsched/FH} = \zeta_{unsched}\, \hat{c}_{sched/FH}$

Previous research[8] has shown that many of the remaining ownership bills related to an aircraft flow in a progression from major direct cost drivers like maintenance. An organization that possesses in-house personnel systems regards the majority of salary charges as fixed since a large percentage of positions are budgeted on an annual basis. Even still, crew and maintainers form part of direct operating cost and obviously bear some relation to the operator's desired frequency of flying operations. Labor costs along with aspects of training and support equipment replenishment are considered to share aspects of both fixed and variable costs as shown in Table 4. In the OSD CAPE O&S format used in the United States Dept. of Defense, Personnel or Manpower (1.0) and the Sustaining Support (4.0) categories capture the majority of these personnel expenses.

The dual nature of personnel costs as fixed costs which are still loosely influenced by aircraft quantity and operational rate in particular is visible in the regression model, with (FH/yr) having a significant, but not linearly proportional relationship to annual crew and maintainer budget. Conversely, The new equations developed for rotor, drive, airframe, system, and engine maintenance represent strictly variable costs on a per flight hour basis, making them directly proportional to operational rate.

	Category	Variable	Fixed
1.0	Personnel	✓	✓
2.0	Operations	✓	
3.0	Maintenance	✓	
4.0	Sustaining Support	✓	✓
5.0	Cont. Sys. Improvement		✓
6.0	Indirect		✓

Table 4: OSD CAPE Level 1 O&S Categories and types

Since the new prediction capabilities for both procurement and maintenance costs presented in this work add insights to to the prediction of the quantities used to predict annual personnel outlays C_p in Eqn. 8, they are expected to provide higher confidence in the analysis of both fixed and variable quantities.

(8)
$$C_p = 329.61 c_{FA}^{0.1871} \left(\frac{c_{FA}}{WE}\right)^{0.2871} \times \left(\frac{C_{maint}}{WE}\right)^{0.2857} \left(\frac{FH}{yr}\right)^{0.5628} \times \kappa_{UAV}$$

Where

$$\kappa_{UAV} = \begin{cases} 1.0 & \text{Non-UAV Aircraft} \\ 0.2946 & \text{UAV Aircraft} \end{cases}$$

3.5. Rotor Maintenance

Given the variability of reported maintenance costs in both commercial and military rotorcraft, Harris' approach of first establishing upper and lower bounds of data spread in the population has proven to be one of the most useful approaches in predicting the maintenance prices of both existing platforms and hypothetical aircraft concepts.

Eqn. 9 and Figure 4 show the rotor maintenance trend with upper and lower bounds of spread in dollars per flight hour surveyed from both the commercial and military operators databases available to the study.

(9) $\hat{c}_{rotor/FH} = \chi_{(rotor/FH)}\, w_{rotor}^{1.1875}$

Where w_{rotor} is the weight of all rotors in pounds, including tail rotors ($w_{rotor} = w_{MR} + w_{TR}$) and

$$\chi_{(rotor/FH)} = \begin{cases} 0.0219 & \text{low maint. rotors} \\ 0.0514 & \text{middle of trend} \\ 0.1024 & \text{high maint. rotors} \end{cases}$$

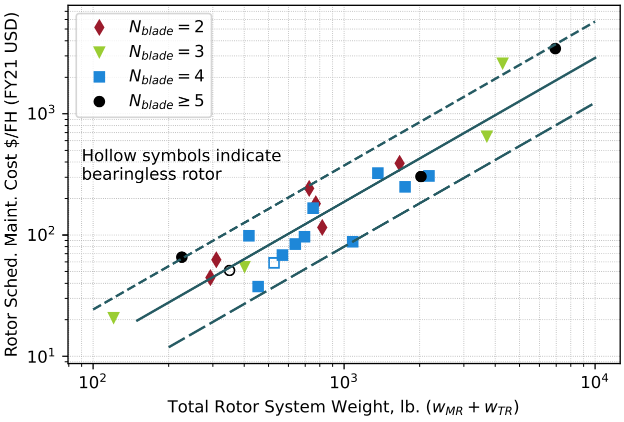

Figure 4: Scheduled maintenance cost per flight hour trends in conventional helicopter rotor systems

Significantly, the study must pause to note that Fig. 4 depends on conventional rotor systems to establish its trends. A variety of rotor systems ranging in size from 100 to 10,000 pounds total weight are available for reference, making an appraisal of distributed multi-rotor systems popular in electric VTOL configurations plausible, but still an area for further research as these concepts mature in production and adoption. Although the details of rotor systems such as hub type and blade number may be cited as identifying features of a low maintenance design, the study does not find major correlation with these attributes at this time, which also warrants deeper investigation in future work.

3.6. Drive System Maintenance

Along with rotors, the transmission or drive system of a helicopter makes up the majority of the scheduled maintenance costs of the vehicle's dynamic components. Internal statistical studies[6] have found that drive system weight and power rating are nearly interchangeable for the prediction of production costs, so rated power was chosen in this case to coordinate the choice of explanatory variables with the power ratings of the installed engines. Eqn. 10 and Fig. 5 give the dollar per flight hour estimating relationship for drives, with bounds for best and worst practice.

$$(10)\quad \hat{c}_{xmsn/FH} = \chi_{(xmsn/FH)}\, P_{xmsn}^{1.0690}$$

Where P_{xmsn} is the is the maximum rated horsepower of the drive system and

$$\chi_{(xmsn/FH)} = \begin{cases} 0.0178 & \text{low maint. drive systems} \\ 0.0417 & \text{middle of trend} \\ 0.0938 & \text{high maint. drive systems} \end{cases}$$

Given the greater variety of drive configurations and their dependence on aircraft layout, the year of 1st production aircraft completion was used as a second independent variable to illustrate trends, again with limited success as evidenced by the spread observed in Fig. 5.

3.7. Engine Maintenance

Engine maintenance cost is driven by the scheduled overhauled cost and flight time interval between overhaul servicing, but also includes periodic routine maintenance activities. Fig. 6 and eqns. 11 and 12 illustrate the separate trends and installed power ranges of turboshaft and internal combustion engines respectively.

$$(11)\quad \hat{c}_{eng/FH} = \chi_{(inspect/FH)}\, P_{eng}^{0.9470}$$

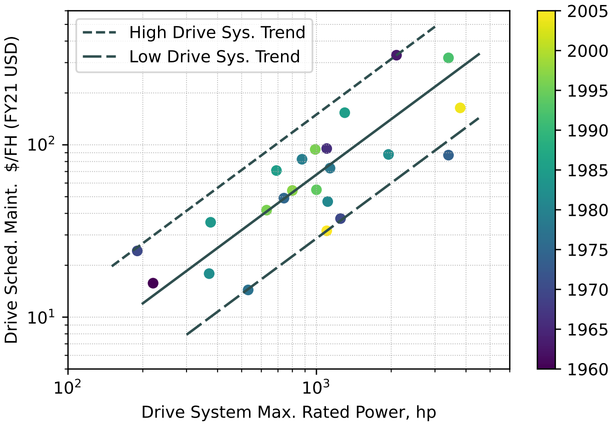

Figure 5: Scheduled maintenance cost per flight hour trends in conventional helicopter drive systems

Where P_{eng} is the maximum rated engine power of one turboshaft in horsepower and the calibration factor coefficients are:

$$\chi_{(eng/FH)} = \begin{cases} 0.1412 & \text{low maint. engine} \\ 0.2256 & \text{middle of trend} \\ 0.3949 & \text{high maint. engine} \end{cases}$$

$$(12)\quad \hat{c}_{eng/FH} = \chi_{(eng/FH)}\, P_{eng}^{0.9255}$$

Where P_{eng} is the maximum rated engine power of one IC engine in horsepower and the calibration factor coefficients are:

$$\chi_{(eng/FH)} = \begin{cases} 0.0941 & \text{low maint. engine} \\ 0.1506 & \text{middle of trend} \\ 0.2199 & \text{high maint. engine} \end{cases}$$

The power limits and trend offsets observed in

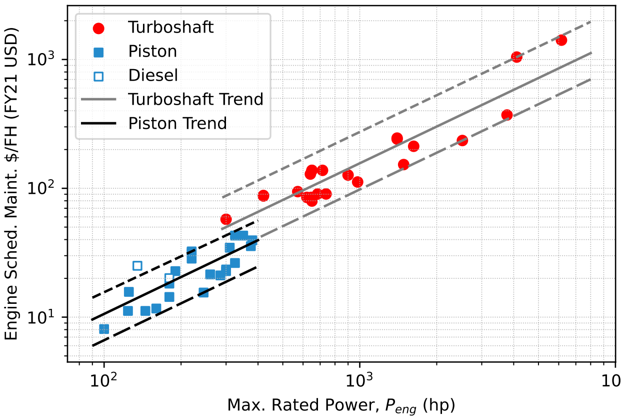

Figure 6: Scheduled maintenance & overhaul cost per flight hour trends in turbine and piston propulsion systems

6 display some of the affordability potential of IC engines compared to turboshafts. Non-APU turboshafts are available with listed prices down to 300 horsepower, below which IC engines are a widely available propulsion solution. Future work will investigate smaller turbine engine alternatives as they are designed with potential UAS and hybrid propulsion applications.

3.8. Airframe, Avionics, Controls, and Systems Maintenance

Airframe and systems costs in Eqn. 13 cover the remaining scheduled maintenance components in helicopter not covered by the rotor, drive system, and engines.

$$(13)\quad \hat{c}_{airfsys/FH} = \chi_{(airfsys/FH)}\, WE^{0.5715}$$

Where WE is the is the empty weight of the vehicle in pounds and the upper and lower limits of established base configuration systems are defined by the coefficients:

$$\chi_{(airfsys/FH)} = \begin{cases} 0.0978 & \text{low maint. airframe} \\ 0.1983 & \text{middle of trend} \\ 0.4139 & \text{high maint. airframe} \end{cases}$$

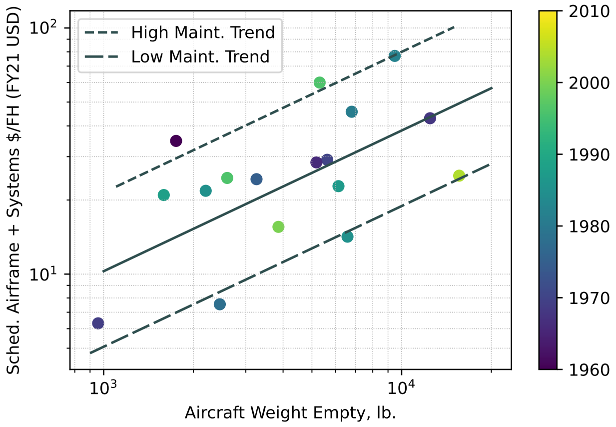

Figure 7: Scheduled maintenance total cost per flight hour trends in conventional helicopter airframe, avionics, and systems components

For this cost estimating relationship, Figure 7 and likewise Eqn. 13 are derived strictly from commercial rotorcraft and represent the base cabin, systems, and avionics packages. Military aircraft may experience much higher contributions to total maintenance from systems given the sensor packages demanded in their roles, particularly in scout, observation, and attack missions.

3.9. Periodic Inspections

Routine inspections occur in varying intervals of flight time. The average cost of inspections is estimated on a per flight hour basis.

$$(14)\quad \hat{c}_{inspect/FH} = \chi_{(inspect/FH)}\, WE^{0.5260}$$

Where WE is the is the empty weight of the vehicle in pounds and

$$\chi_{(inspect/FH)} = \begin{cases} 0.1234 & \text{low inspections} \\ 0.3086 & \text{middle of trend} \\ 0.8694 & \text{high inspections} \end{cases}$$

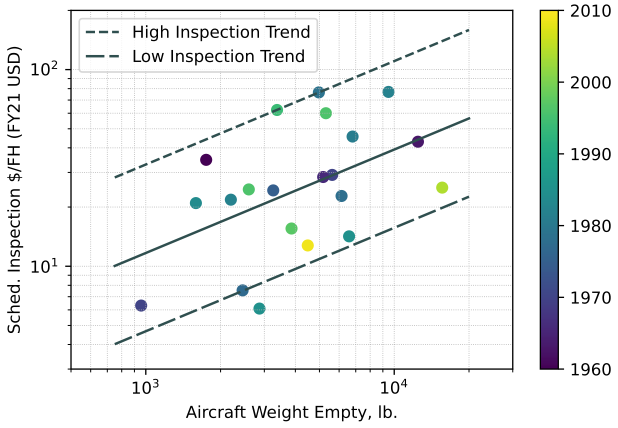

Figure 8: Periodic inspection costs per flight hour of conventional helicopters

Given the generality of airframe & systems maintenance as well as periodic inspections, Figures 7 and 8 both provide the year of initial production for each helicopter plotted in an effort to isolate any technological progression or improvement in design practices. As with drive systems, no obvious effect was observed that could be related to time. The range of dollar per flight hour costs (between $5 and $100 per flight hour) for these categories is approximately one order of magnitude less than those of rotor and engine systems (up to $1,000 per flight hour for each). Based on this observation, it is possible that these categories serve as generalized bins for components with less influence on the overall operating cost of the vehicle.

3.10. Electric Propulsion Maintenance

Since electric propulsion components have limited maintenance history in an aviation context and are generally handled more as self-contained components which are replaced rather than repaired, the scheduled maintenance cost in $/FH is equivalent to the production cost divided by the service life of the component (time between replacement - TBR) as shown in Eqn. 15:

$$(15)\quad \hat{c}_{i/FH} = \frac{\hat{c}_i}{TBR_i}$$

Electric motors in this study were assumed to have service lives of 5,000 to 6,000 flight hours based on surveys of the few traction and primary propulsive electric motors with published maintenance data. The models makes a direct estimate of battery time between replacement using Vegh's equations for rechargeable battery life[8] measured in number of battery discharge cycles. The time between battery replacement becomes the product of lifetime cycles N_{cycle} and average time per discharge $\bar{t}_{cycle}$ as given in Eqn. 16:

$$(16)\quad \hat{c}_{batt/FH} = \frac{\hat{c}_{batt}}{N_{cycle}\,\bar{t}_{cycle}}$$

Aircraft performance assessment of the electric aircraft concept in question can provide the average battery discharge time from the average discharge current (C-rate, $\bar{x}_{batt}$) on the battery over the block time of a representative mission such as the vehicle's design mission. The average cycle time in hours is then the inverse of C-rate (1/hr):

$$(17)\quad \bar{t}_{cycle} = \frac{1}{\bar{x}_{batt}}$$

4. Evaluation

Development of better assessment capabilities for aircraft life-cycle cost depends on finding and exploring use cases which exercise new capabilities and highlight areas for future development. For this study, three non-conventional concepts were utilized for renewed analysis in the newly-developed models.

Since the analysis approaches each of the designs shown in Fig. 9 with the intention of evaluating them in the MEDM acquisition and operational context, the exact trend and value of the results contain inherent assumptions different from the affordability positions offered in other works that emphasize strictly commercial applications. The key differences in these assumptions can be generally summarized as:

- OPTEMPO (flying hour rate) between 250-500 annual flying hours for manned aircraft
- Avionics systems on par in functionality and cost with the expectations of operation in a potentially contested airspace
- Higher annual & fixed costs (especially personnel) representative of a large organic aviation infrastructure maintenance concept as would be found in Army Aviation
- Smaller production runs of military-specific aircraft variants in line with historical precedent (fewer than 1,000 vehicles purchased per year)

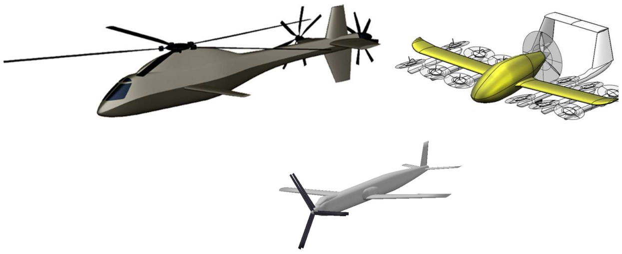

Figure 9: Configurations for study, Winged Compound (top left), Electric Lift+Cruise (top right), Hybrid Tailsitter (bottom)

The notable exceptions to these assumptions centered on the electric lift plus cruise concept. Since this aircraft is closest of the three to the configurations envisioned by commercial advanced mobility with a view to adapted military applications, comprise assumptions of 2,000 FH/yr and 1,000 aircraft purchased were used to reflect the competing affordability influences on future MEDM aviation.

Table 5 summarizes the design attributes of the three concepts shown in Fig. 9. The designs selected for this demonstration exhibit a wide range of scale and configuration, but the propulsion systems present the contrast of greatest interest. The winged compound represents a high performance advanced rotorcraft configuration which is otherwise largely conventional is its constituent components, and is powered by a turboshaft engine. The lift+cruise configuration is powered completely by electric motors drawing current from batteries. The tailsitter design features a hybrid propulsion system with a diesel engine supplemented by an electric drivetrain.

While the major contrasts among each of the designs relate to their size and propulsion architecture, several factors influence the respective cost estimates which must be factored in the starting assumptions. Avionics systems in particular represent a persistently increasing percentage of total aircraft cost in rotorcraft, even for the base platform prior to the installation of specialized mission equipment. The procurement and operating cost assessments

	Winged Compound[11]	Lift+ Cruise[12]	Hybrid Tailsitter[1]
WMTO (lb)	14,838	2,876	6,743
WE (lb)	10,579	2,478	5,749
P_{inst} (hp)	3,000	663	732
N_{engine}	1	13	1
N_{rotor}	1	12	2
$N_{propeller}$	1	1	0
Fuel Type	JP-8	Electric	Hybrid
Fuel Capacity	241 gal	69.1 kWh	111 gal 4.6 kWh
Wingspan (ft)	27.9	36	30.7
Length (ft)	38.4	21.0	31.1
Main Rotor Diam. (ft)	38.0	4.0	22.4

Table 5: Design summary of concepts used in cost evaluation.

made in this study treat the lift+cruise design as a optionally unmanned platform and a the tailsitter as a strictly unmanned platform, resulting in higher avionics costs. The compound design, while conventionally crewed, includes additional risk factors representative of the modern avionics and control systems required in configurations intended for attack and scout mission roles. The overall effect of these assumptions is that the two unmanned concepts in the study assume the highest risk cost trend for their avionics systems. The winged compound assumed a lower, but still elevated avionics cost trend.

4.1. Procurement Cost

Procurement cost estimates were generated for each concept using the full set of conceptual procurement cost equations. Included in the updated model are the new features describes in Equations 1 through 5. Table 6 breaks down the propulsion section cost drivers in greater detail as assessed by the new equations.

The appeal of electric propulsion is clear from the trends shown across the different configuration in Table 6. Although the largest configuration of the three, the winged compound's turboshaft engine is still the most expensive on a power-adjusted basis. The hybrid system may present a compelling step in propulsion design progression in this case provided that the overhead of two separate drivetrains is not overly adverse. Additional design and cost analysis work is still required to confirm this trend. On the other hand, the weight efficiency of the turboshaft engine may continue to provide it with advantages that do not become apparent until performance and performance-adjusted O&S costs are considered.

FY21 USD (thousands)	Winged Compound	Lift+ Cruise	Hybrid Tailsitter
Turboshaft	919.4	–	–
Diesel Engine	–	–	643.0
Elect. Motor	–	67.3	0.7
Transmission	1072.5	–	15.6
Fuel System	423.0	–	110.8
Battery	–	17.7	0.5
Propeller	31.6	2.4	–
Total Prop. Group	**2446.4**	**87.4**	**770.7**

Table 6: Estimated propulsion group cost drivers by concept

FY21 USD (Mil.)	Winged Compound	Lift+ Cruise	Hybrid Tailsitter
Structure	6.89	2.19	4.51
Propulsion	2.45	0.13	0.77
Systems	6.31	2.35	4.58
Assembly & Profit	7.90	1.40	7.03
Flyaway Price	**23.55**	**6.06**	**16.88**
($/lb)	(2,226)	(2,447)	(2,937)

Table 7: Estimated average unit flyaway price comparison

Estimated unit flyaway price estimates are given in Table 7 and Fig. 10. In relation to the general purchase price trends of existing rotorcraft platforms, each of the concepts is generally predicted to fall near existing trends, which is a product of middle of practice economic assumptions and non-aggressive production rates across all of the assumed performances. Although the particular propulsion system design choices lead to noticeable different cost outcomes as seen in Table 6, the significance of avionics and controls systems as the increasingly dominant cost drivers of rotorcraft tends to pull the estimates back toward the trends

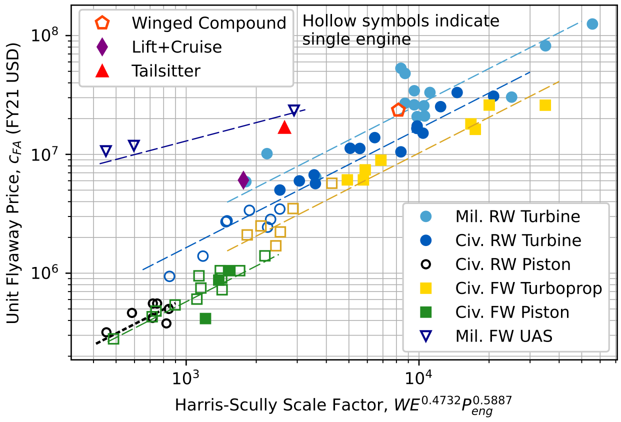

Figure 10: Comparison of vehicle flyaway prices between study concepts and prevailing military and commercial trends

of their respective size categories in Fig. 10. Electric components may yet prove to be a viable path to significant life-cycle cost savings as either a primary or augmenting propulsion system, but these expectations are still subject to the economic conditions of the procurement and operation. Indeed, much of the substantiating case for the procurement affordability positions anticipated in eVTOL concepts are more closely related to learning curve and production quantity than to specific design features. The individual contributions to flyaway price of each component and their overall effect are areas of ongoing cost research.

4.2. Operating Cost

Estimated direct operating costs are given in Table 8 and propagated forward to an annual ownership cost per aircraft given in Table 9. The contrast in operations cost related to energy presents a second compelling case for investigation of alternative propulsion systems, with the costs of energy in the electric and hybrid-electric designs much lower than the compound helicopter's consumption of strictly jet fuel.

The subtleties of propulsion design and their economic effects still present intriguing contrasts between the two design that utilize batteries. The electric drive system is treated as a replaceable unit with its per flight hour adjusted cost driven as much by component lifespan as by its price. Previous research in battery cycle life has shown that the effects of discharge rate play a large role in defining the service life of a battery. This effect is clearly seen between the lift+cruise and tailsitter designs when weighing the difference in battery charging (electricity) and battery replacement as the primary energy costs. The smaller battery of the tailsitter goes through both a greater quantity of cycles and a faster rate of discharge on average in each cycle, making its replacement costs higher on average than the larger battery pack of the lift+cruise design.

c/FH, FY21	Winged Compound	Lift + Cruise	Hybrid Tailsitter
Operations	**3,854**	**513**	**1,314**
Personnel	*3,618*	*471*	*1,145*
Fuel	*237*	–	*124*
Electricity	–	*19*	*0.31*
Battery	–	*23*	*45*
Maintenance	**1,990**	**168**	**1,444**
Scheduled	1,592	135	1,155
Rotors	*438*	*29*	*137*
Drives	*182*	–	*62*
Airframe & Sys.	*83*	*36*	*776*
Engines	*775*	–	*86*
Motors	–	*17*	*0.12*
Inspections	*114*	*53*	*95*
Unscheduled	380	33	289
Reinvestment	**172**	**21**	**113**
Total DOC ($/FH)	**6,016**	**702**	**2,871**
Useful Load / DOC lb / ($/FH)	0.71	0.57	0.35

Table 8: Estimated Direct Operating Cost per Flight Hour

The differences among the aircraft at a large scale support and sustainment level manifest in the annual ownership costs given in Table 9. The winged compound represents an advanced helicopter operated within the traditional support structure of Army Aviation. The two electric concepts have comparatively lower operating costs owing to their smaller size and low maintenance design features. However, when adjusted for scale, the useful load per $/FH of the winged compound is still the best due to the higher empty weight fractions of the electric lift+cruise hybrid tailsitter designs. The weight effects of batteries and motors at near-term technology levels may pose a size ceiling above which large-scale transportation is challenging from both an engineering and economic viewpoint. In this case, future studies may take the approach of repeating this analysis for similar design concepts as the efficiency assumptions of the electrical components receive updates.

	Winged Compound	Lift + Cruise	Hybrid Tailsitter
1.0 Personnel	1,808.9	454.9	259.8
2.0 Operations	118.3	84.3	84.5
3.0 Maintenance	995.0	78.0	121.8
4.0 Sust. Supp.	79.6	19.5	10.6
5.0 Cnt. Sys. Imp.	85.8	8.2	29.5
Total (\$/AC/Yr)	**3,087.6**	**645.0**	**506.1**

Table 9: Estimated annual ownership cost per aircraft

From a broader perspective of design alternatives and technology, the three concepts exhibit predicted maintenance costs which display the persistence of ongoing operational challenges with hints of promising affordability technology. Figure 10 shows that the winged compound is estimated to be slightly above conventional helicopter trends owing to its high performance rotor, control, and transmission features driving maintenance above legacy rotorcraft. The tailsitter concept as a UAS platform exhibits below average hourly maintenance costs, but this must be further investigated in light of the unique behavior of UAS maintenance costs and the potential influences of avionics and control equipment as well as ground support equipment, which is often treated as part of the aircraft system itself in military economic practices.

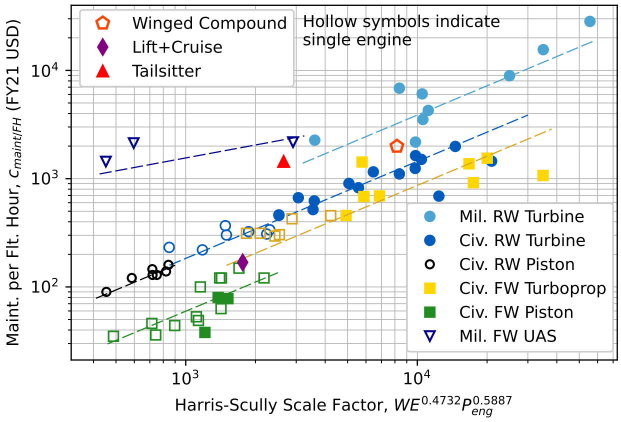

Figure 11: Comparison of hourly maintenance costs between study concepts and prevailing military and commercial trends

The tailsitter and lift+cruise designs exhibit very similar maintenance costs per hour and per year, but the overall personnel costs of the lift+cruise design is strongly influenced by the MEDM-influenced assumptions of a very high annual utilization rate of flight hours. Personnel costs for the electric lift+cruise are driven to the lowest of the three when considered hourly, but are greater than the unmanned tailsitter in Table 9 when the total number of flight hours per year returns to the calculation.

The lift+cruise configuration exhibits near-parity with existing civil rotorcraft, but this is largely an outcome of the preference in this study to consider the design from the perspective of MEDM and military ownership practices. The more aggressive cost-saving measures and economies of scale anticipated by the advanced air mobility paradigm would result in a lower operating cost per aircraft if the analysis adopted a commercial-leaning ownership paradigm, but the influence of new design features still has the potential to affect positive influences in military operational costs.

5. Conclusions

A set of new equations augmenting existing cost models has allowed for an-depth assessment of the key features of several advanced rotorcraft configurations. As discussed earlier, the results of the analysis show that the electric concepts in particular show sufficient potential for improved affordability to warrant deeper investigation of their unique design features and trends.

The number of interrelated design and economic variables noted in discussion of the results underscores both the strength of parametric analysis and the ongoing need to refine its assumptions. The contrasts between flyaway cost, flyaway cost per pound, operating cost, and load-adjusted operating cost are strongly influenced by economic assumptions not directly related to the design characteristics. These properties, like quantity of aircraft, number of crew, sustainment concept, and flight hours per year form foundational assumptions if they are found to enable improvement in capability and affordability.

Confident and objective assessment of operating costs in particular requires further research for all types of aircraft. Although general sensitivities for several new components of interest to eVTOL configurations were successfully established with respect to design variables, a high degree of variation was observed within the overarching trends across the range of vehicle sizes. This randomness of maintenance price within the established limits exhibited no firm direction or bias according to historical time frame or to configurational complexity choices of the particular vehicles surveyed. Given this outcome, future studies will necessarily examine the sensitivity of overall predicted operating cost to the assumption of maintenance practice inherent in the upper and lower bounds of spread seen in the historical reference data, especially in relation to the effects of aircraft usage spectrum and reliability-motivated design choices.

Ultimately, good design practices at the detailed level beyond the conceptual stage and in coordination with operators and maintainers may play the largest enduring role in maintenance costs. The design effects of such practices must be further researched and quantified. This requires iteration on designs internally in the design and analysis communities and externally in conjunction with the user community.

References

[1] Vegh, J.M., Alonso, J.J., Sinsay, J.D., “Modeling of Diesel and Diesel-Electric Hybrid Propulsion Systems for Conceptual Design of Rotorcraft," VFS Technical Meeting on Aeromechanics Design for Vertical Lift, San Francisco, January 2016.

[2] Johnson, W., Silva, C., Solis, E., “Concept Vehicles for VTOL Air Taxi Operations," VFS Technical Meeting on Aeromechanics Design for Transformative Vertical Flight, San Francisco, January 2018.

[3] Harris, F.D., Scully, M.P., "Helicopters Cost Too Much," 53rd Annual Forum of the American Helicopter Society (Vertical Flight Society), Virginia Beach, VA, April 1997.

[4] Harris, F.D., *Introduction to Autogyros, Helicopters, and Other V/STOL Aircraft, Volume II: Helicopters*, NASA/SP-2012-215959, 2012.

[5] Stoll, A.M., Mikić, “Design Studies of Thin-Haul Commuter Aircraft with Distributed Electric Propulsion," 2016 AIAA Aviation Conference, Washington, D.C., June 2016. AIAA 2016-3765

[6] Scott, R., ”A Design-Centric Evaluation of Multi-Fidelity Cost Modeling Approaches," 44th European Rotorcraft Forum, Delft, The Netherlands, September 2018.

[7] Sirirojvisuth, N., Briceno, S., Justin, C., “Life-Cycle Economic Analysis and Optimization for Urban Air Mobility (UAM), " VFS Aeromechanics for Advanced Vertical Flight Technical Meeting, San Jose, California, January 2020.

[8] Scott, R., Vegh, M. “Progress Toward a New Conceptual Assessment Tool for Aircraft Cost," VFS International 76th Annual Forum & Technology Display (Virtual), October 2020.

[9] Roskam, J., *Airplane Design, Part VIII: Airplane Cost Estimation: Design, Development, Manufacturing, and Operating*. Roskam Aviation and Engineering, Ottawa, Kansas, 1990.

[10] Duffner, F., Wentker, M., Greenwood, M., Leker, J., “Battery Cost Modeling: A Review and Directions for Future Research," Renewable and Sustainable Energy Reviews, Vol. 127, July 2020.

[11] Scott, R., Khurana, M., “Conceptual Design and Assessment of a Light Multirole Rotorcraft Using Uncertainty Quantification," AIAA Science and Technology Forum and Exposition, San Diego, January 2019.

[12] Vegh, J.M., Botero, E., Clarke, M., Smart, J., Alonso, J.J., “Current Capabilities and Challenges of NDARC and SUAVE for eVTOL Aircraft Design and Analysis," AIAA Propulsion and Energy Forum, Indianapolis, August 2019.