A COMPARISON OF THREE CONCEPTUAL DESIGN APPROACHES APPLIED TO AN ELECTRIC DISTRIBUTED LIFT AIRCRAFT

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Abstract

This paper serves as an introduction to a collaborative effort between the U.S. Army U.S. Army Combat Capabilities Development Command (DEVCOM) Aviation & Missile Center, ONERA, and DEVCOM Army Research Lab. Each organization employs their conceptual design toolchain (NDARC, CREATION, and HYDRA) on a common set of geometry. Initial weight, drag, and power estimates on this aircraft for a common sizing mission and set of assumptions are provided along with a component-based comparison of weight and drag estimates for each tool. Broad agreement for the baseline mission requirements was observed for all three tools. Design sensitivities showed substantial differences in performance estimates vs forward flight speed which has broader design implications. Wingspan and rotor radius were varied and optimized for each tool with different behavior for each. NDARC predicted a larger wingspan would reduce aircraft weight with little impact from changing the rotor radius. CREATION and HYDRA predicted that reducing the wingspan and increasing rotor radius would reduce aircraft weight. The different design conclusions from each tool reflect uncertainty in evaluating the structural and aerodynamic performance of similar systems with complicated interacting aerostructural behavior when using conceptual-level tools. Areas for further tool development were also identified.

1. INTRODUCTION

Conceptual design is among the earliest stages of aircraft development. With sufficient data and modeling intuition about a given aircraft or aircraft type, the conceptual design engineer may define not only the capabilities of a given vehicle, but also its physical attributes and scalability with respect to future customer requirements. In the case of electric vertical takeoff and landing (eVTOL) aircraft, design tools must rapidly evolve to provide assessment and prediction capabilities for future manufacturers and users beyond those currently envisioned. At this stage, defining and comparing the design practices and assumptions used for these new aircraft configurations across the design community to frame and quantify the results of future conceptual studies is of increasing importance. On the one hand, there is strong interest in eVTOL designs, with numerous proposed concepts. On the other hand, there is a lack of publicly available data to calibrate modern conceptual design tools. The technologies defining the eVTOL paradigm are rapidly evolving, but emerging traits many configurations share to date include:

- Distributed multirotor and multipropeller thrust and lift systems
- Dual flight mode designs such as tiltrotors, tiltwings, and lift+cruise configurations
- Propulsion systems featuring electric motors and batteries or hybrid fuel combinations

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- Novel power transmission solutions such as direct drive motors
- Overactuated systems with infinite trim solutions and nonstandard control schemes

To realize the derived insights from the conceptual design process for eVTOL configurations and their subsystems, certain challenges must be addressed. Historically, new analytical problems in rotorcraft have necessitated the development of modeling tools to address them. When this development is undertaken collaboratively, subsequent capabilities are often traceable to the insights gained from the comparison of tools and the results generated by applying them to a standardized problem (Ref. 1).

Progress in the study of eVTOL configurations and propulsion architectures has reached the point where a more ambitious tool comparison study may consider more of the specific design and performance drivers that distinguish eVTOL concepts from conventional rotorcraft. With this in mind, an international collaboration was initiated to inform areas of further study. This present paper is focused on initial comparison of three design approaches the conceptual tools as well as the design assumptions to benchmark the current state of the art and identify areas for future investigation. The collaborating teams (DEVCOM AvMC, ONERA, and DEVCOM ARL) have identified a lift+cruise configuration for further study. The associated OpenVSP model is pictured in Figure 1 (Ref. 2).

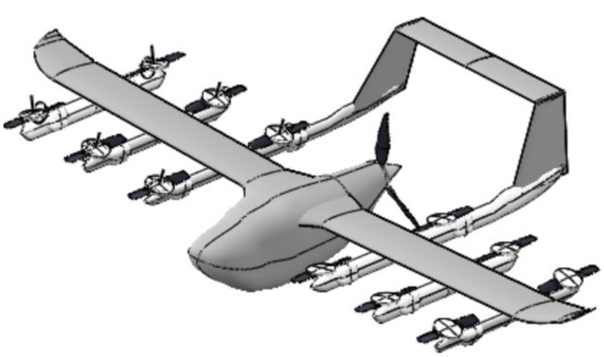


Figure 1: Generic Lift+Cruise Reference Model

This aircraft possesses several characteristics that make modeling the full vehicle challenging using conceptual-level rotorcraft design tools including: many distributed rotors with interacting flow fields (12 lifting rotors and one pusher propeller), unconventional load paths for the wing and lifting rotors, and overactuated control systems that may present challenges for trimming the aircraft for a given flight state. The design processes were applied in parallel to this lift+cruise configuration with the objective of performing four basic tasks:

1. Articulation and definition of different trim approaches
2. Comparison of component weight predictions
3. Comparison of predicted mission performance of the baseline design
4. Sizing sensitivity of the lift+cruise configuration

Expected benefits from this overarching study pertain to improving the predictive confidence of design codes and identification of areas for future modeling development. Due to computational limitations and possession of only a high-level vehicle description at the conceptual stage, most conceptual design tools rely at least in part on semi-empirical models for the prediction of weight, aerodynamic, and propulsive characteristics. This reliance on historical precedent introduces a fundamental challenge in the conceptual design of new configurations, as they may present aerodynamic or structural load arrangements for which good analogy cases for calibration are lacking. The objective outcomes of the study are thus:

1. Quantification of the existing level of agreement among assessment codes and processes in eVTOL configuration performance
2. Quantification of the range of predicted component weights among codes and processes
3. Design trend and performance-driver identification

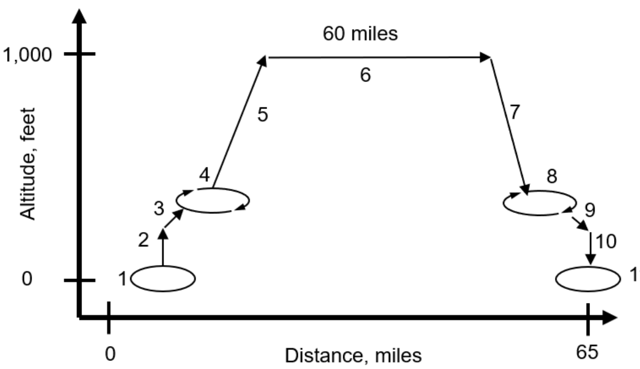
Objectives 1 and 2 address the issue of uncertainty in empirical methods applied to a new eVTOL configuration by defining a range of predicted performance and weights using standardized assumptions. In quantifying the performance sensitivity to mission assumptions, Objective 3 identifies the components of the generic lift+cruise configuration which have the greatest influence on performance and warrant future modeling investigation. Significant insights on future applications and technology needs are expected from the basic design trend analysis culminating from this study and subsequent research projects, even under a simplified "static pre-sizing" set of assumptions for performance.

2. APPROACH

This study builds on a previous tool comparison, using NDARC (NASA Design and Analysis of RotorCraft) - and SUAVE, an open-source design tool originally developed out of Stanford University (Ref. 3). In the prior study there was broad agreement in terms of overall gross takeoff weight of this configuration when selected for a prescribed mission. However, when observing design sensitivities and tradeoffs, the toolchains predicted opposing choices would result in lighter aircraft. These results acted as a guide and starting point for the more detailed comparison performed here.

Three tools are used in the present comparison: NDARC, CREATION, and HYDRA. NDARC is a rotorcraft design tool that leverages tunable parametric equations that can be fit to a combination of substantiating data and higher fidelity analysis (Ref. 4). NDARC has been used as the basis for a variety of generic reference models utilizing features common within the emerging eVTOL industry to inform technology development (Refs. 5, 6). A version of this NDARC model has also been utilized as a reference case for newly developed cost parametrics (Refs. 7, 8). CREATION (Concepts of Rotorcraft Enhanced Assessment Through Integrated Optimization Network) is a design toolchain developed by ONERA that utilizes a suite of low, medium and some higher fidelity tools, among them DynaPyVTOL (Ref. 9). DynaPyVTOL can model any aircraft combining rotary and/or fixed wings for the study of their flight dynamics (trims, failures, stability, controls etc.). HYDRA (Hybrid Design and Rotorcraft Analysis) employs a combination of parametric and physics-based subsystem weight models, with variable fidelity rotor and wing aerodynamics (Refs. 10, 11). All three codes have a recent history of investigation of aircraft configurations pertinent to electric distributed propulsion rotorcraft (see Refs. 3, 5 ,6, 11,12, 13).

A standardized set of basic vehicle and mission characteristics (Figure 2, Table 1) has been modeled in each team's respective design tool. Range credit for the climb, descent, and loiter segments was not assumed. Mission specifications were derived from a simplified version of a notional Uber Elevate profile (Ref. 14). Power requirements included an allocation of 14.9 kW of accessory power for environmental conditioning in hot climates and modern avionics equipment for integration into a crowded airspace.



Assumptions
- 400 lb (181.4 kg) payload
- Miss. takeoff cond: SL/ISA Aamos.
- Miss. range 60 mile (96.6 km)
- 300 W-hr/kg battery, gross weight fallout
- 20 hp (14.9 kW) vehicle accessory power

Figure 2: Generic eVTOL mobility & delivery-type mission.

Table 1: Mission Profile Definition

Segment	type	time (min)	speed (m/s)	ROC (m/s)
1	hover	0.5	0	0
2	climb	0.08	0	2.54
3	climb	0.52	28.3	2.54
4	loiter	1	36.0	0
5	climb	1.4	30.9	2.54
6	cruise	32.73	49.2	0
7	descent	1.4	30.9	-2.54
8	loiter	1	36.0	0
9	descent	0.52	28.3	-2.54
10	descent	0.13	0	-1.52
11	hover	0.5	0	0

Each tool requires a unique set of inputs; a rigorous adjudication process was consequently needed to ensure a consistent geometric representation of the aircraft. The common sets of geometric inputs used for this study can be seen in Tables 7-12 in Appendix A. Cant angle is considered positive when the inboard section of the rotor mid-plane is tilted above the fuselage and negative when tilted below the fuselage.

There were 18 available control inputs for this vehicle:13 propeller rpm settings, 2 wing flap deflection angles, 2 rudder deflection angles, and 1 elevator deflection angle) in addition to body pitch and roll. This yields 20 control variables for 6 Degree of Freedom (DoF) rigid body dynamics, resulting in an overactuated system. When trimming a single main rotor helicopter, there are traditionally four controls and two attitude angles (pitch and bank) corresponding to the six equations of rigid body dynamics. Under a single main helicopter control scheme, there is a single trim solution. When more than six control inputs are introduced, there are infinite solutions for this system of equations. In these situations, either new control laws must be developed, or trim must then be treated as an optimization problem. Many other proposed eVTOL concepts are similarly overactuated; this is a conscious decision to respond to emergency situations via redundancy instead of autorotation as in conventional rotorcraft. Control insights discovered on this configuration may be applicable to other concepts. The trim strategies utilized by each tool in this analysis are shown in Table 2.

NDARC utilized the VTOL trim strategy in segments 1, 2, 10, and 11, the Airplane strategy in segment 6 and the Compound strategy in segment 3-5, and 7-9. The wing lift fraction was set at 50% for segments 3 and 5 and 70% in segments 4 and 7-9. This differs from the approach in Ref. 3, which utilized an Airplane trim strategy for segments 3-9.

In NDARC, rotor rpm settings were collectively controlled with flaps deflected 15 degrees at airspeeds lower than cruise (49 m/s). CREATION and HYDRA each used optimization-based approaches to solve the overactuated trim problem with total power required acting as the objective function. Vehicle pitch angle was limited to +/- 8 degrees for each tool. In NDARC, this was achieved via trim strategy selection, flap deflection, and wing lift fraction. CREATION and HYDRA restricted pitch attitude via a formal optimization constraint. The pitch constraint was relaxed for segments 3 and 5 in the HYDRA model to allow for convergence in the absence of a flap model.

Table 2: Control Strategy Summary

Trim Strategy	VTOL	Airplane	Compound
NDARC Inputs	rotor rpm differential-rpm	pitch pusher rpm elevator	rotor rpm pusher rpm elevator pitch
NDARC Unknowns	force z moment z	force x force z moment y	force x force z moment y wing lift %
CREATION Inputs	pitch rotor rpms	pitch pusher rpm wing flap and stabilizer deflections	VTOL & Airplane controls (All)
CREATION Unknowns	force x force y force z moment x moment y moment z	force x force y force z moment x moment y moment z	force x force y force z moment x moment y moment z
HYDRA Inputs	pusher collective pitch	pusher collective pitch	pusher collective pitch
HYDRA Unknowns	force x force z	force x force z	force x force z

In CREATION each of the 20 potential inputs were individually controlled via an optimizer. For CREATION, a variety of optimization algorithms were attempted, including Sequential Least Squares Quadratic Programming (SLSQP), Constrained Optimization BY Linear Approximation (COBYLA), and trust region methods to solve this trim problem, but all were found to have difficulties in solving the problem robustly (Refs. 15-17). Optimal trim minimizing the required power for each flight case was finally computed within DynaPyVTOL by utilizing a custom algorithm using successive trim computations with the application of linear programing in order to find the global optimum.

HYDRA's trim strategy used an optimizer to find the values of pusher propeller thrust, rotor collective, and aircraft pitch that minimize power required. RPM control and flap modeling within HYDRA are areas of future code development.

A description of the component-level weight models for each toolchain can be seen in Table 13 in Appendix B. The structural weight estimation in NDARC relied on NASA Revolutionary Vertical Lift Technology (RVLT) assumptions which are described as "consciously optimistic" (Refs. 3, 5, 6). The model from Ref. 3 has been updated to utilize thermal management weight estimation methods implemented in NDARC 1.16. A new high torque-to-weight motor regression was utilized (Ref. 12).

In CREATION the structural weight of the wing and booms were calculated by accounting for the maximum thrust needed to cope with the concurrent failure of two of the 12 lifting rotors (see Ref. 13). This maximum thrust produces bending and torsion loads which size the wing structure. The demanding failure assumption was considered in the event that this aircraft experiences a failure in VTOL mode over populated areas. This condition was also used for the rotor and electric motor weight estimates. Composite structures were assumed for the wing, booms, and rotor blades. The NDARC and HYDRA models, in contrast used fixed thrust margin and motor power margins at the vertical climb condition (segment 2 of Table 1).

The HYDRA model leveraged the AFDD weight parametrics from NDARC. AFDD parametrics were uncalibrated for the HYDRA modeling in this paper, meaning the baseline equations were used without additional tuning for vehicle archetype or features (Ref.4). Other methods for estimating structural weight are available and are detailed in Ref. 11. Semi-empirical weight models were used for the motor, battery, and wiring (Refs. 18, 19). An empirical method was used for estimating the electric speed control (ESC) weight.

Weight estimation was performed by employing successive substitution to solve a fixed-point iteration problem for all three tools by iterating on Design Gross Weight (DGW). Table 14 in Appendix B summarizes the performance estimation methodology employed by each tool for this effort.

For NDARC performance modeling, the following tools and performance assumptions were used; finite wing theory models for lift and induced drag were calibrated to Athena Vortex Lattice (AVL) computations (Ref. 20). Rotor performance was calibrated to analysis performed using CAMRAD II (Ref. 21). NASA RVLT aerodynamic assumptions beyond current state of the art were used for parasite drag.

For CREATION, rotor performance models for the DynaPyVTOL tool were calibrated to Aero Multi Body (AMB) results. AMB is a lifting line code with a free wake model. Wing and empennage performance were estimated using separate wing polars computed with the aspect ratio and selected airfoils from Table 7, Table 11, and Table 12 in Appendix A.

In HYDRA, rotor performance was computed using momentum theory with profile corrections. Blade Element Momentum Theory (BEMT) is also an option for rotor performance. Wing loads were calculated using finite-wing theory with numerical lifting line theory as an alternative option. Parasite drag estimates from both CREATION (implemented in DynaPyVTOL) and HYDRA were informed by Computational Fluid Dynamics (CFD) computations using a visual OpenVSP model of the aircraft geometry, see Appendix A). The CFD data for CREATION and HYDRA were generated from separate models using Reynolds Averaged Navier Stokes each with a Spalart-Allmaras turbulence model (Ref. 22).

3. SIZING RESULTS

A summary weight breakdown for the aircraft can be seen in Table 3. Overall structural weight fraction was similar between NDARC and CREATION (~.3), with a lower structural weight estimate from HYDRA (~.26). Propulsion system weight was also similar across all three tools, with a ~43 kg difference between the highest estimate (CREATION) and the lowest estimate (HYDRA). A component-based comparison can be seen in Figure 3. Systems weight in Table 3 was the summation of Vibration weight and Other Systems/Equipment weight from Figure 3.

Table 3: Weights Summary (kg)

	NDARC	CREATION	HYDRA
GTOW	1,154	1,217	1,064
Empty	973	1,036	882
-Structural	344	371	273
-Propulsion	503	539	496
-Systems	128	126	114
Payload	181	181	181

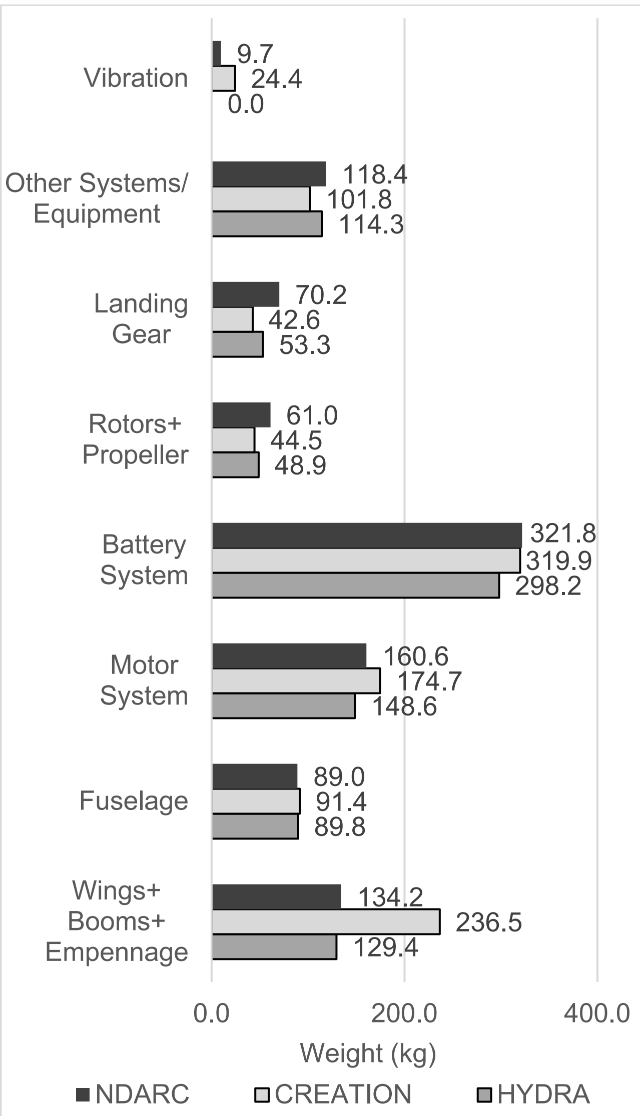


Figure 3: Component Weight Breakdown

In general, good agreement was observed for most components. The largest source of disagreement was in the combined wing-boom-empennage weight; CREATION predicted substantially higher weight for these components than NDARC or HYDRA; this was due to the use of a dual-rotor-failure condition to estimate wing, rotor, and electric motor weight. There is a lack of historical aircraft possessing a similar structural arrangement with lifting rotors/booms supported by both the wing and tail; this makes calibrating parametric models in the absence of higher fidelity analysis difficult.

A component-level flat plate drag comparison summary can be seen in Figure 4. The largest differences were in the fuselage and wing. HYDRA predicted nearly twice as much flat plate drag as NDARC and CREATION for the fuselage, while CREATION predicted nearly twice as much flat plate drag for the wing. Despite these large differences, some cancellation effects were observed when integrated across the system level. Combined rotor, hub, and pylon drag was similar across all three tools.

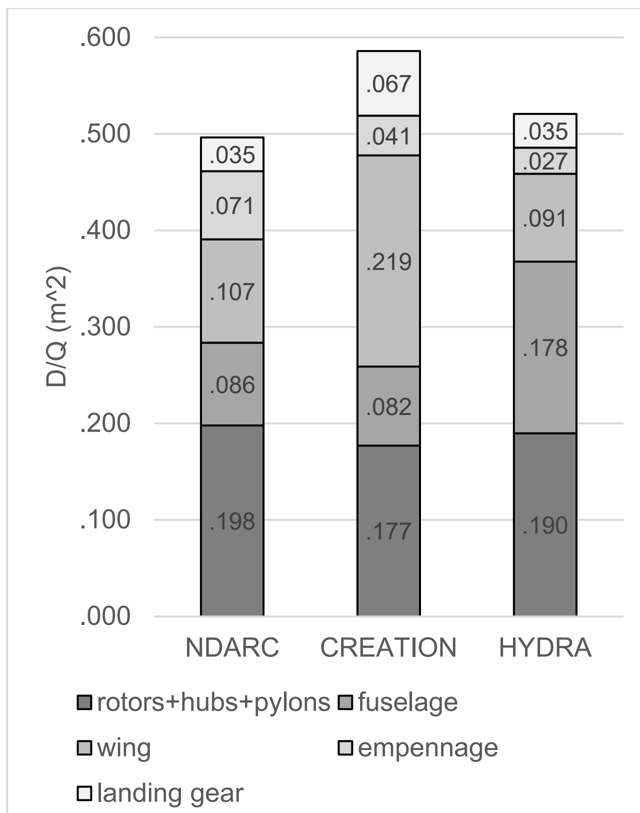


Figure 4: Component Flat Plate Drag Summary

Power required by segment for each tool is shown in Figure 5.

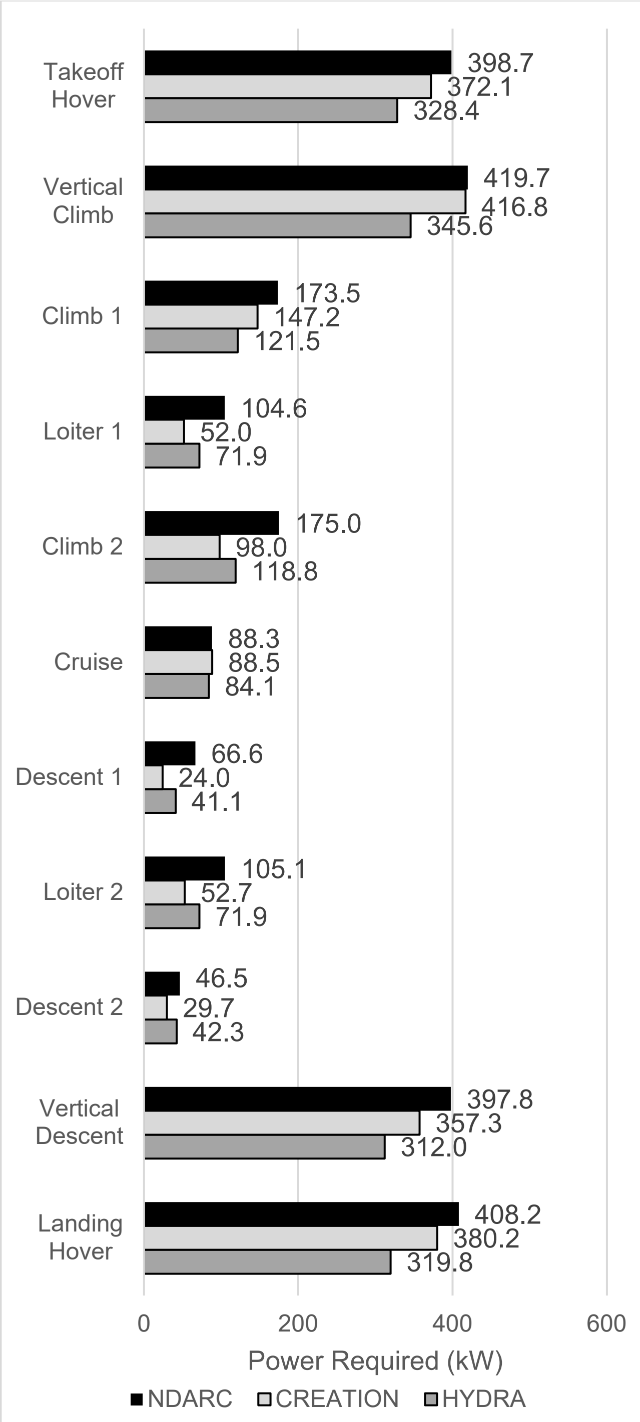


Figure 5: Power Required by Segment from the Battery

The lifting rotors for the NDARC and CREATION models operated in all flight states except cruise. Rotors were turned off in HYDRA for cruise and loiter but on for all other flight states; recall that for the HYDRA and CREATION models, rotor operation was determined by an optimizer to minimize power requirements. CREATION predicted favorable rotor-rotor interaction in hover, which reduced hover power requirements by ~11% compared to analysis run without this interaction. Figure 11 in Appendix C shows a simulation performed in hover (out of ground effect) with the Aero-Multi-Body free wake model, a tool of the CREATION numerical workshop (Ref. 9). The proximity of the rotors and their canted angles made this positive interactional effect significant. Neither NDARC (calibrated to CAMRAD II results), nor HYDRA showed this behavior. Investigation of this phenomenon using CFD is the basis for further collaboration efforts.

A comparison of wing lift fraction with labeled pitch angle and trim state can be seen in Figure 6. Aircraft pitch constraints of +/- 8 degrees were enforced as described in the APPROACH section of this paper; for the NDARC and CREATION models, this required rotor operation in all segments except for cruise. The trim state employed by NDARC is labeled in Figure 6. Wing lift fractions near 1 with modest pitch angles below three degrees were observed in cruise across all three toolchains.

In CREATION, the rotors provided some lift when stopped; further studies to verify the validity of this result are needed. Higher wing lift fraction (Figure 6) correlates strongly with lower power consumption (Figure 5), i.e. the wing is a more efficient lifting surface than the rotors above a certain flight speed. For example, NDARC predicted higher power requirements for the Loiter 1, Climb 2, Descent 1, and Loiter 2 segments and possesses lower wing lift fractions at these conditions than either CREATION or HYDRA. Note that the relative duration of all segments other than cruise was small; as a result, because cruise power requirements were similar for all three tools, the estimated battery weight was close. Differences in power and loads requirements for segments other than cruise were reflected in motor and structural weight estimates. Segment 2 (vertical climb) was the most stringent sizing condition for the rotors and motors (Table 1, Figure 2).

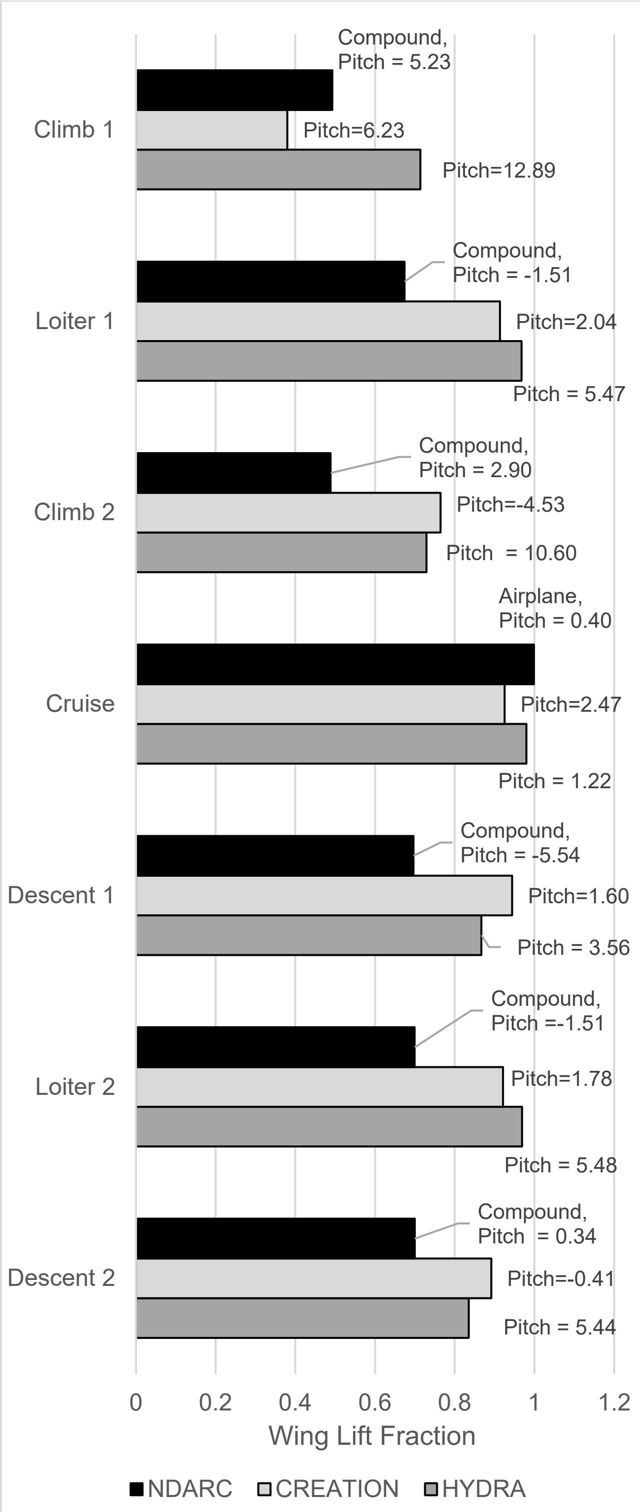


Figure 6: Wing Lift Fraction Comparison

A plot comparing rotor power, propeller power, and rotor+propeller power vs true airspeed for sea level standard conditions and 1,000 kg gross weight can be seen in Figure 7. Despite similar overall weight and performance estimates, power requirements across the flight envelope were markedly different for each of the three models. NDARC possessed the lowest hover power estimate and the broadest conversion corridor between ~20-45 m/s. To model this conversion corridor in NDARC, wing lift fraction was varied according to the schedule shown in Figure 12 in Appendix C. The rotors were stopped at flight speeds greater than ~45 m/s. Interactional aerodynamic models were turned off in CREATION for the analysis performed in Figure 7; this was due to computational limitations related to flow field predictions with an acceptable confidence level within the conversion region (see Figure 13 in Appendix C for a lift+cruise example case). Detailed investigation of this region using CFD is a further topic of investigation as part of this collaborative effort.

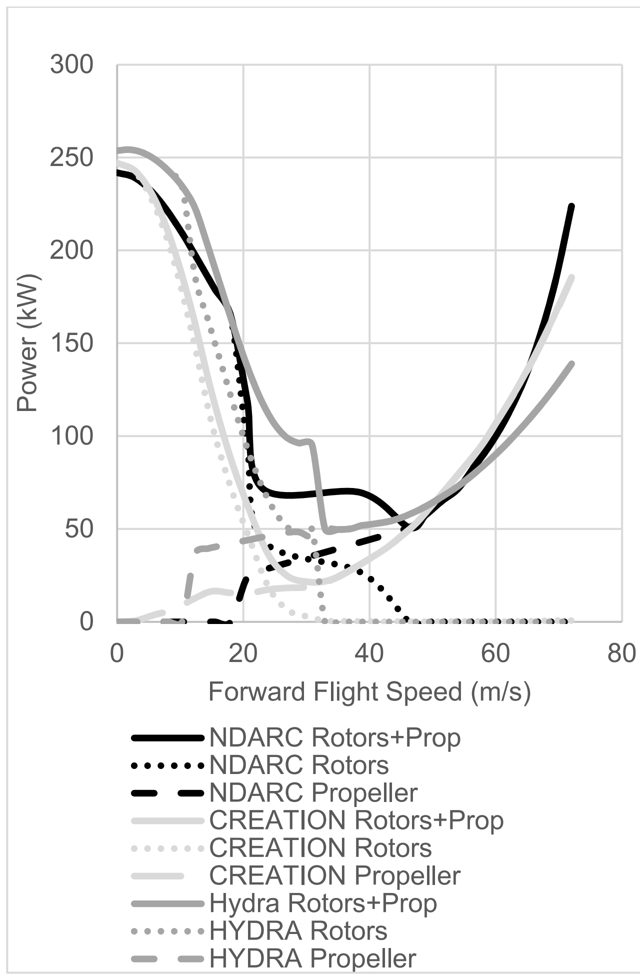


Figure 7: Rotor Power vs Speed Comparison

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With CREATION the conversion speed depended mainly on the wing flap efficiency and on the propeller efficiency. Flap deflection was limited to +/-15 degrees. CREATION's power requirement estimates at lower flight speeds (~20-40 m/s) were smaller than NDARC's and HYDRA's. All three tools estimated nearly identical power requirements around 50 m/s (roughly the aircraft cruise speed). HYDRA predicted lower power requirements at higher speeds.

The HYDRA model's power as a function of airspeed and transition schedule were strongly affected by the +/- 8 degrees pitch attitude constraint. While the stall speed of the aircraft with no body pitch constraint was approximately 29.5 m/s, constraining the body pitch to 8 degrees nose up required the lifting rotors to turn on earlier at 31 m/s. In airplane mode, all lifting rotors were "off" and contributed only to parasite drag. When the lifting rotors were turned on, there was a sudden rise in power required due to the profile power of the lifting rotors as modeled using HYDRA's variable pitch/fixed RPM model. This transition area ~31 m/s could be made more gradual by introducing a wing flap model into HYDRA's trim algorithm; this is an area of code development.

A summary of important aircraft-level performance parameters can be seen in Table 4. Electrical system efficiency included battery losses, motor losses, as well as other components associated with the electrical system of the aircraft. Segment 11 (landing hover, see Table 1) was used for hover performance estimates while segment 7 was used for cruise performance estimates. For this comparison, the following definitions for aircraft figure of merit in hover and L/De, in cruise were used:

$$FOM_{hover,aircraft} = \left(\frac{W}{P_{electric}}\right) * \sqrt{\frac{W}{2 * \rho * \sum A_{rotor}}}$$

$$L/De, cruise = \frac{WV}{P_{electric}}$$

where W is the DGW of the vehicle, V is flight speed, ρ is the atmospheric density, A_{rotor} is the area of an individual rotor, and $P_{electric}$ is the power drawn from the battery.

Table 4: Aircraft Performance Summary

	NDARC	CREATION	HYDRA
$FOM_{hover,aircraft}$	0.64	0.74	0.64
L/De, Cruise	6.32	6.64	6.09
$\eta_{propulsive,\ cruise}$	0.82	0.86	0.81
$\eta_{electric,\ cruise}$	0.89	0.88	0.94
$\eta_{electric,\ hover}$	0.84	0.87	0.90

Effective lift to drag ratio in cruise across all three tools was within 10%; this was reflected in similar power estimates in cruise (Figure 5) and similar battery weight estimates (Figure 3). NDARC and HYDRA possessed similar hover figures of merit. CREATION predicted higher L/De, and higher hover efficiency than the two other tools. Note that, while CREATION predicted a higher hover figure of merit than NDARC or HYDRA at their respective design gross weights; this was primarily due to the aforementioned rotor-rotor interaction at the hover condition reducing power consumption by 11% for the CREATION model compared to computations run without rotor interaction.

HYDRA predicted higher electric system efficiency in both cruise and hover than NDARC and CREATION but this was offset by higher induced drag estimates. NDARC predicted lower electrical system efficiency in hover than CREATION and HYDRA; this was due to NDARC's battery discharge model which was more sensitive to C-rate; CREATION's discharge model was less sensitive to discharge rate while HYDRA's lacked a sensitivity to state of charge. Battery discharge rates in hover were relatively high across all three models (~4C).

4. DESIGN SENSITIVITIES

The sensitivity of design gross weight with respect to wingspan can be seen in Figure 8. Constant wing area was maintained for varying wingspan.

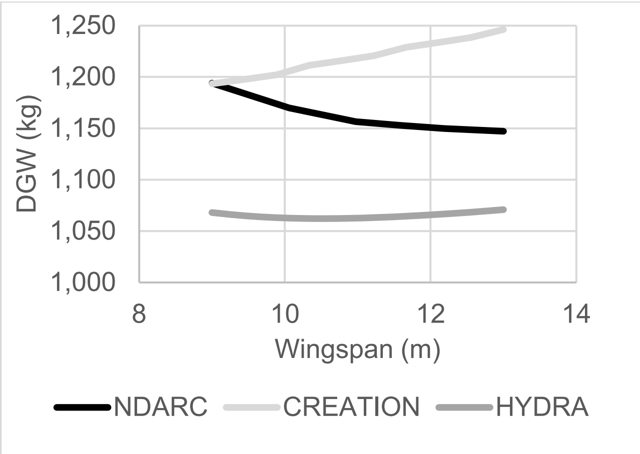

Figure 8: Wingspan-Weight Sensitivity

NDARC estimated decreasing DGW with wingspan, while CREATION shows the opposite trend. HYDRA, in contrast, showed a flat convex trend where the wingspan for minimum design gross weight was between 10-11 meters. Differences were a result of the relative impacts of improved cruise efficiency vs increased structural weight for increasing wingspan. Design sensitivities with respect to rotor radius can be seen in Figure 9. Geometric solidity of the rotor was maintained while rotor radius was varied.

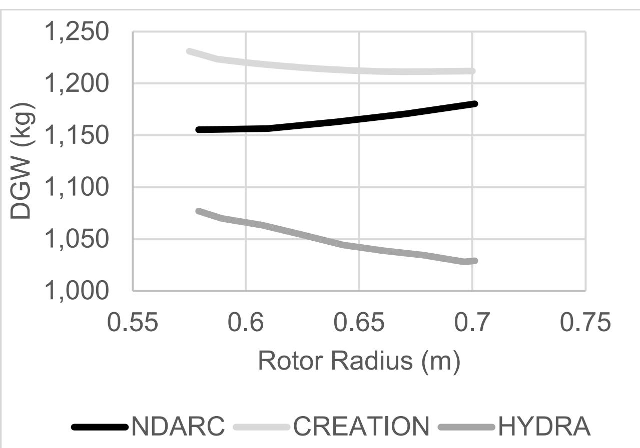

Figure 9: Rotor Radius-Weight Sensitivity

NDARC predicted increasing DGW with increasing rotor radius, while CREATION and HYDRA showed the opposite trend. Differences in the results are primarily a result of the weight and battery models; recall that CREATION's weight estimation procedure was more sensitive to hover performance due to the dual-rotor failure condition. On the other hand, the NDARC model was more sensitive to drag from the stopped rotors, i.e., reducing rotor drag proved more beneficial from a weight perspective than a reduction in hover power coming from increasing the rotor radius.

Some simple optimization cases were run for this geometry, varying wingspan and rotor radius in order to minimize the design gross weight of the aircraft. Results are shown in Table 5. NDARC results were computed using RCOTools (Ref. 23). Wingspan was bounded between 9 and 13 meters, while rotor radius was bounded between .5 and .7 meters.

Table 5: Optimization Results

	Wingspan (m)	Rotor Radius (m)	DGW (kg)
Baseline (NDARC)	10.97	0.61	1,154
Baseline (CREATION)	-	-	1,217
Baseline (HYDRA)	-	-	1,062
Opt (NDARC)	11.97	0.60	1,148
Opt (CREATION)	9.00	0.67	1,187
Opt (HYDRA)	9.95	0.70	1,025

A comparison of the baseline aircraft geometry with optimized results for each tool can be seen in Figure 10 A-D. High-level disagreement on the optimal design choices for weight reduction was observed. The NDARC model appears to be more sensitive to aerodynamic considerations; a higher aspect ratio wing coincides with improved aerodynamic performance. Rotor radius was largely unchanged from the baseline. This sensitivity to wingspan appears to be primarily due to the lower electrical system efficiency estimates compared to either CREATION or HYDRA. Note that for NDARC, this change was small, with a DGW reduction of only 6 kg. Differences between these results and those shown in Ref. 3 for the NDARC model were primarily a result of the new motor weight regression as well as different trim strategies used in climb, loiter, and descent.

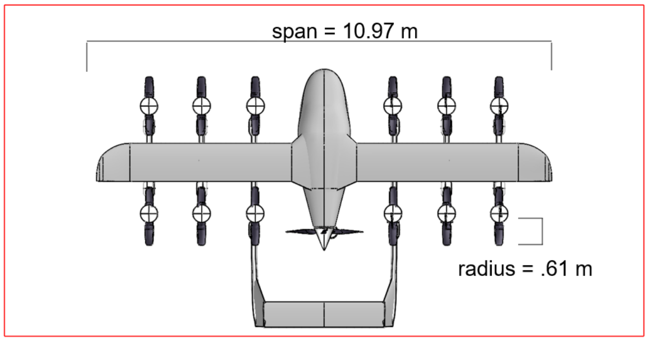

Figure 10A: Baseline Aircraft

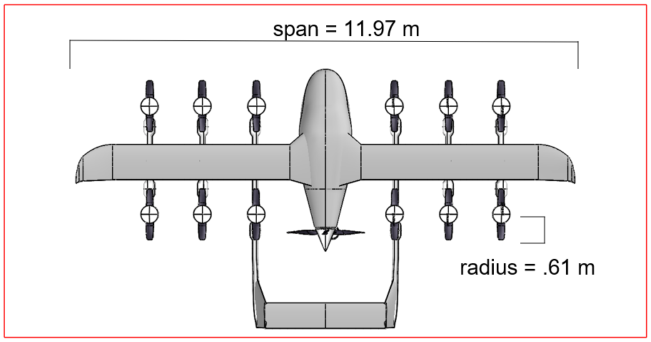

Figure 10B: NDARC Optimal Aircraft

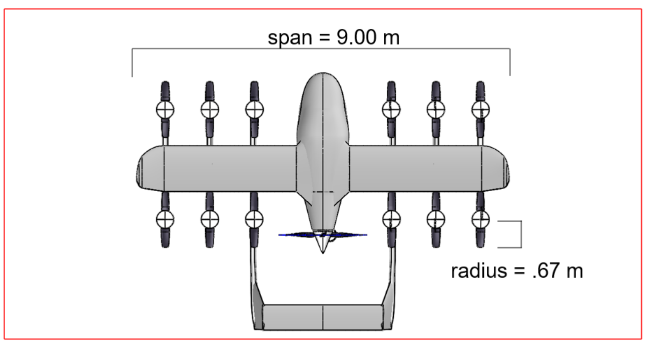

Figure 10C: CREATION Optimal Aircraft

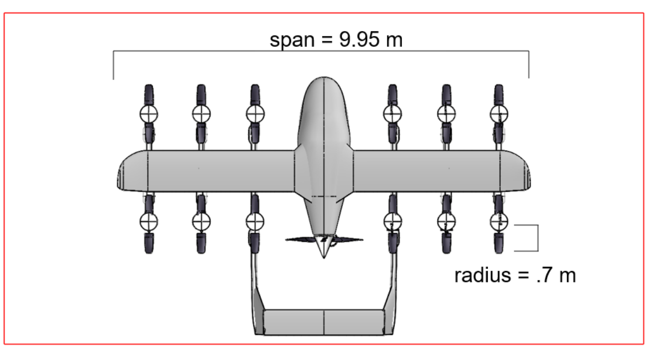

Figure 10D: HYDRA Optimal Aircraft

The CREATION model predicted that a smaller wing and larger rotor radius would be more weight-efficient than the baseline design. This result was mainly due to a more demanding structural sizing condition on the wing-boom-empennage arrangement (worst case twin rotor failure causing high wing load requirements). HYDRA also predicted that a smaller wing and larger rotor radius would reduce the DGW of this aircraft (although the sensitivity to wingspan was not as significant as with CREATION). Higher rotor radius correlates with smaller hover power and reduced motor size, but higher forward flight drag. A high-level qualitative summary of the relative vehicle metrics and performance can be seen in Table 6.

Table 6: Vehicle Estimate Comparison

	NDARC	CREATION	HYDRA
DGW	middle	highest	lowest
Empty Wt.	middle	highest	lowest
Struct. Wt.	middle	highest	lowest
Prop. Wt.	middle	highest	lowest
Hover Pwr.	lowest	middle	highest
Low Spd. Pwr.	highest	lowest	middle
High Spd. Pwr.	highest	middle	lowest
Flat Plate Drag	lowest	highest	middle
Prop. Efficiency	middle	highest	lowest
Elec. Efficiency	lowest	middle	highest
Opt. Rotor Rad.	lowest	middle	highest
Opt. Wingspan	highest	lowest	middle

Note that these comparisons are for the vehicle geometry, mission, and documented assumptions described in this work; applying these aircraft design tools to other configurations and/or under a different set of technology assumptions would necessarily yield different results. Hover, low speed power, and high speed power comparisons were with interactional aerodynamics turned off. For the metrics described in Table 6, one can note the following observations. NDARC possessed the highest forward flight power estimates, lowest hover power estimates, lowest flat plate drag, and the lowest electric system efficiency. CREATION possessed the highest weight estimates, highest flat plate drag, lowest low speed power estimates, and highest propulsive efficiency. HYDRA possessed the lowest weight estimates, highest hover power estimates, lowest high-speed power estimates, the lowest propeller efficiency, and the highest electrical system efficiency.

NDARC and CREATION structural weight fraction were similar (.298 vs .305) with a lower structural weight estimate from HYDRA (.257). Recall that CREATION utilized failure analysis to estimate wing, boom, and empennage structural weight while NDARC and HYDRA utilized fixed component-level margins. In-depth study into these failure cases and impact on overall vehicle weight is a topic of further research.

NDARC predicted the lowest electrical system efficiency for this vehicle; this was due to the battery discharge model which estimated resistive losses as an empirical function of both discharge rate and state of charge. CREATION's battery model utilized a model where voltage varies with state of charge while current was altered to meet power demands; this model was less sensitive to power demands in hover than either NDARC's or HYDRA's battery models. HYDRA's predicted electrical system efficiency was consistently higher than either of the other two tools.

5. CONCLUSIONS

A high-level design tool comparison based on a common set of geometry was performed. In general, good agreement was observed regarding overall aircraft-level weight estimation. At the component level, significant differences in the structural weight of the wing-boom-empennage were observed and highlighted as an area of uncertainty. While overall cruise power requirements were close across all three tools, significant differences in aircraft performance and trim estimation were observed when sweeping flight speed. Additionally, design gross weight trends vs rotor radius and wingspan were different for each tool. Three main areas for further investigations and improvements based on these initial comparisons are:

1. Weight impact of component-based structural sizing from distributed rotors/propellers accounting for failure cases
2. Optimal trim and controls of the over-actuated system
3. Detailed evaluation of interactional aerodynamic impacts and integration into early sizing

The present work acts as an introduction to this collaborative research effort. Further studies integrating these areas are ongoing.

APPENDIX

6.A Input Geometry

Table 7: Wing Geometry

Parameter	Value
Reference Area (m^2)	9.75
Mean Chord (m)	.889
Span (m)	10.97
MAC (m)	1.03
Dihedral ($\circ$)	3.64
Flap Area Fraction	.195
Airfoil	NACA 4418

Table 8: Rotor Geometry

Parameter	Value
Radius (m)	.61
Root Cutout (1/r)	.32
Taper Ratio	.75
Geometric Solidity	.205
Linear Twist ($\circ$)	-15
Outboard Cant Angles ($\circ$)	20
Midboard Cant Angles ($\circ$)	-10
Inboard Cant Angles	-12

Table 9: Propeller Geometry

Parameter	Value
Radius (m)	1.07
Root Cutout (1/r)	.1
Taper Ratio	.8
Geometric Solidity	.10
Linear Twist ($\circ$)	20

Table 10: Fuselage Geometry

Parameter	Value
Wetted Area (m^2)	19.05
Length (m)	3.79
Maximum Width (m)	1.32
Maximum Height (m)	1.32

Table 11: Horizontal Tail Geometry

Parameter	Value
Reference Area (m^2)	1.78
Mean Chord (m)	.61
Span (m)	2.91
Taper Ratio	1.0
Elevator Area Fraction	.25
Airfoil	NACA 23012

Table 12: Vertical Tail Geometry

Parameter	Value
Reference Area (m^2)	1.18
Mean Chord (m)	.95
Span (m)	2.44
Taper Ratio	.5
Rudder Area Fraction	.28
Airfoil	NACA 0012

6.B Methodology Comparison

Table 13: Weight Estimation Methodology

Component	NDARC	CREATION	HYDRA
Structural Weight (Wing)	Parametric (AFDD93, 25 basis aircraft, RVLT calibration)	Modified beam theory using loads and materials	Parametric (AFDD93) and physics-based
Structural Weight (Fuselage)	Parametric (AFDD84, mix of 35 fixed wing and helicopter basis aircraft, RVLT calibration)	Physics-based accounting for loads and materials	Parametric (AFDD84) and low-order FEA
Structural Weight (Tail)	Parametric (AFDD82, 13 aircraft calibrated to OV-10 with material improvement)	Parametric (from aircraft data base)	Parametric (AFDD82) and physics-based
Rotor Weight	Parametric (AFDD00, 51 basis aircraft, RVLT calibration)	Physics-based analytical model (strength of material methods)	Parametric (AFDD00) and physics-based
Hub Weight	Parametric (AFDD00, 51 basis aircraft, RVLT calibration)	Parametric (from aircraft data base)	Parametric (AFDD00)
Battery Weight	Pack buildup from mission energy & power	Series-parallel cell buildup from mission energy & power	Cell buildup from mission requirement
Wiring Weight	Included in battery installation weight	In battery weight (estimate with length)	Included in battery installation weight
Systems	Combination of parametric and fixed inputs	Combination of parametric and fixed inputs	Combination of parametric and fixed inputs
Sizing Method	Successive Substitution	Successive Substitution first, then MDO	Successive Substitution

Table 14: Performance Estimation Methodology

	NDARC	CREATION	HYDRA
Rotor Performance	Profile, parasite, and induced power surrrogates calibrated to CAMRAD II results	Combined assessment from DynaPyVTOL a flight dynamics code for trim and AMB† for aerodynamics	Momentum theory with profile power correction, or BEMT.
Wing Aerodynamics	Finite wing theory with calibratable parametric models and multiple panels. Profile drag calibrated to RVLT assumptions, lift and induced drag using AVL	Lift and drag polars calculated based on aspect ratio and airfoil with flap deflection for trim in DynaPyVTOL	Numerical lifting-line theory
Battery Discharge	Empirical resistive losses with C-rate and state of charge	Analytical model calibrated to current known battery performance	Semi-empirical motor/battery model with voltage a constant function of state-of-charge

6.C Tool Specific Results

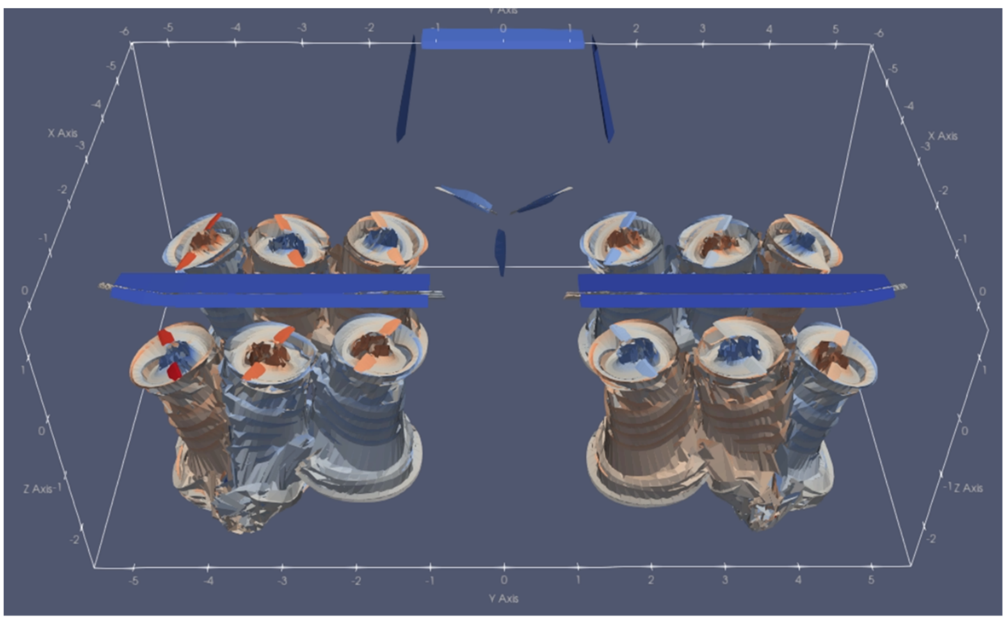

Figure 11: Hover Simulation with the CREATION Aero-Multi-Body Tool

†AMB: Aero-Multi-Body code: see Ref. 9

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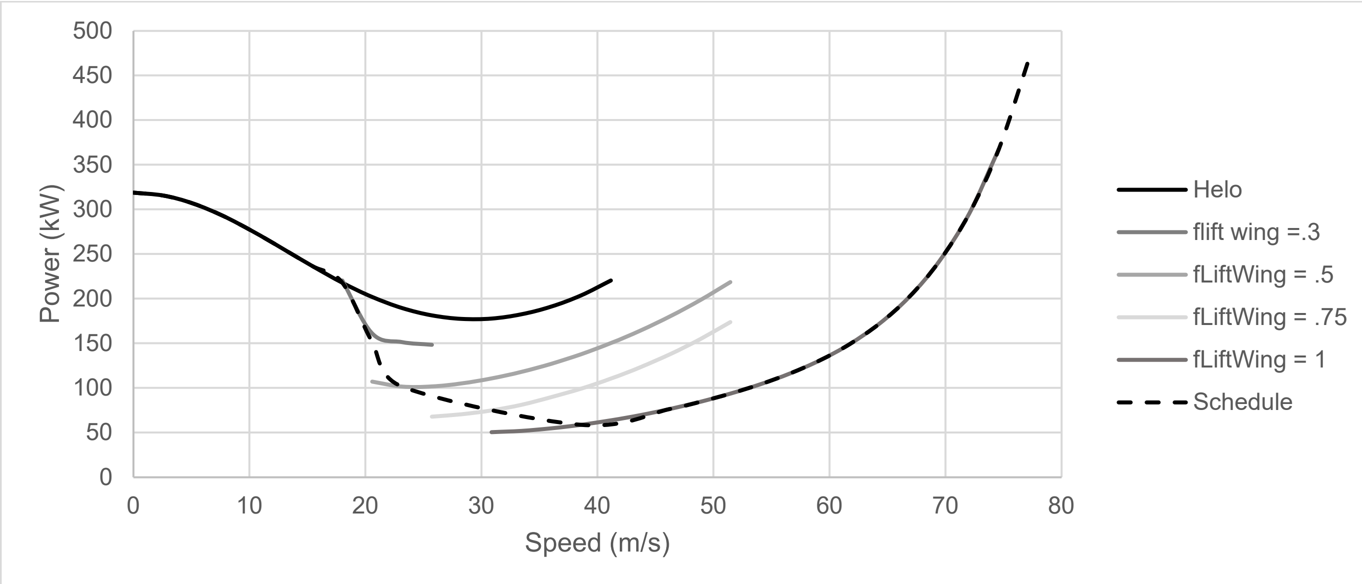

Figure 12: NDARC Wing Lift Schedule

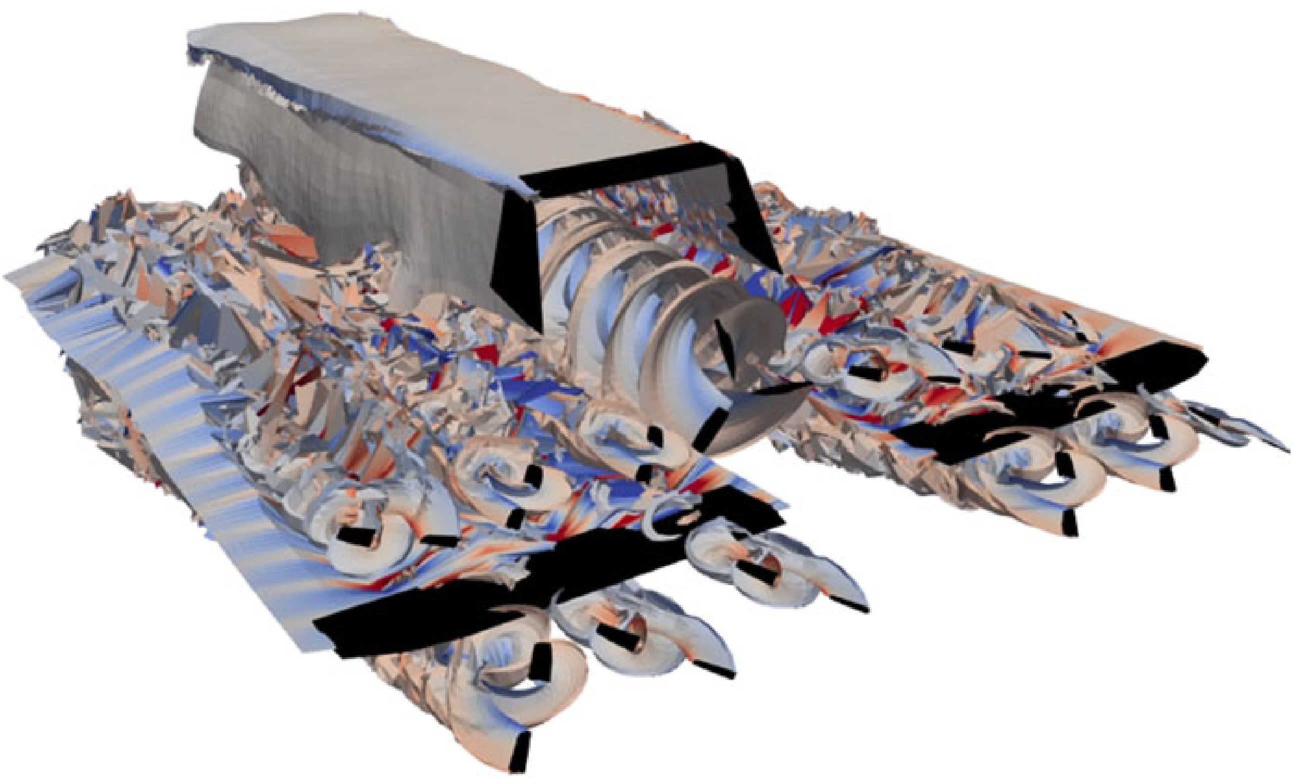

Figure 13: Example of Computational Challenges Within the Conversion Corridor (CREATION Output)

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