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Exploration of Design Drivers for the RVLT Lift+Cruise Reference Aircraft

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September 2023

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Abstract

A trade study was performed on an all-electric version of the Lift+Cruise urban air mobility reference aircraft developed under the Revolutionary Vertical Lift Technology Project. The trade study varied the input parameters of mission range, takeoff altitude, mission reserve time, cell specific energy, disk loading, and payload weight. A step-by-step incremental change in the input parameters was also examined. Analyses were performed using the NASA Design and Analysis of Rotorcraft tool and a Rapid Sizing Tool for electric vertical takeoff and landing aircraft. A comparison of the analysis results between the two tools shows good agreement in trends with differences in slope. Overall, the analysis shows that the Lift+Cruise configuration performs poorly on a NASA-defined, energy-dominated mission due to poor aerodynamic efficiency in forward flight. This poor cruise-flight efficiency results in a large energy requirement, which increases the required battery sizing and corresponding aircraft gross weight. As such, continued conceptual design and refinement of the Lift+Cruise reference aircraft by the RVLT Concepts Team will likely be limited.

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1 Introduction

A trade study was performed on an all-electric version of the Lift+Cruise reference aircraft, an urban air mobility (UAM) aircraft concept designed as part of the Revolutionary Vertical Lift Technology (RVLT) Project's family of reference aircraft. The reference aircraft were designed to provide an open aircraft architecture for tool development and noise assessment, and they were intended to contain many of the configuration and technology attributes proposed by industry. A turboelectric Lift+Cruise reference aircraft was developed by the RVLT Concepts Team and the design details for that aircraft are published in Ref. [1]. Figure 1 shows a rendering of the baseline Lift+Cruise reference aircraft. This trade study examines aircraft-level sensitivities to excursions in technology assumptions, mission requirements, and high-level design parameters in order to quantify the impacts of mission requirements and technology assumptions on the all-electric Lift+Cruise aircraft design.

Figure 1: Rendering of the six-passenger Lift+Cruise reference aircraft.

Aircraft trades were performed in the NASA Design and Analysis of Rotorcraft (NDARC) tool, and a Rapid Sizing Tool (RST) was used as a point of comparison. Descriptions of NDARC and RST are provided in Section 2, and modifications to convert the baseline Lift+Cruise reference aircraft to an all-electric aircraft are described in Section 3. The Lift+Cruise models from NDARC and RST were compared, and the results are summarized in Section 4. Trade explorations are described in Section 5, analysis results from the trade explorations are provided in Section 6, and Section 7 provides conclusions from the described study.

2 Tools

Two analysis tools were used to perform the trade explorations described in this study: the NASA Design and Analysis of Rotorcraft (NDARC) tool and an in-house Rapid Sizing Tool (RST). The tools are described in more detail below.

2.1 NASA Design and Analysis of Rotorcraft (NDARC)

The baseline, turboelectric Lift+Cruise model was developed in NDARC release 1.15 [2–6]. As described in Ref. [7]:

> NDARC is an aircraft system analysis tool intended to support both conceptual design efforts and technology impact assessments. The principal NDARC was first written incorporating low-fidelity models appropriate for general rotorcraft conceptual design, but was designed to be broadly adaptable to conventional and unconventional aircraft concepts; the architecture of the NDARC code accommodates configuration flexibility, a hierarchy of models, and ultimately, multidisciplinary design, analysis, and optimization.

NDARC was used to model the Lift+Cruise aircraft because of its flexible modeling capability and ability to handle aircraft with attributes of both rotorcraft and fixed-wing aircraft. NDARC enables the sizing and performance analysis of an aircraft by leveraging component-level models and applying a set of sizing missions and/or point performance requirements. This process ensures each component in the final design is appropriately sized for the most constraining condition required. Generally speaking, a set of well-tuned component models will result in a well-behaved, representative aircraft model.

NDARC is well suited to perform trade space explorations. The computational time, even for a design optimization, is relatively short. With each analysis, all components are appropriately sized to ensure they meet the requirements. The NDARC analysis capabilities enable complex trades with highly coupled physics to be performed. For example, an aircraft sizing trade can be performed to determine whether it is better to shut down a second proprotor to achieve torque balance following a rotor failure or to utilize all remaining proprotors coupled with a control effector schedule. This trade has significant coupling between the powertrain component sizing, the control scheme to achieve trim, and the aircraft performance, all of which are well captured by NDARC.

A challenge with NDARC is the significant number of inputs required to generate a converged solution. The component models must be populated with valid data inputs such that the entire aircraft can be analyzed, which can be quite burdensome. Generally, a user has a previous working model that can be modified to meet the new analysis requirements, and this reduces the burden. However, if the configuration to be analyzed is sufficiently different in architecture, then the model setup can still be a significant challenge. If a novel configuration is in its early design stage, there could be poorly defined inputs that result in poor convergence of the model, resulting in significant time spent debugging the solution instead of exploring the design space. There are benefits to having as a starting point a companion tool that leverages simplifying assumptions to reduce the analysis complexity. Utilizing a simplified analysis tool to generate the inputs for the NDARC model can improve the initial inputs, reducing model setup time.

2.2 Rapid Sizing Tool (RST)

The Rapid Sizing Tool is a custom, in-house Python package that utilizes first principles to enable fast design and analysis of electric vertical takeoff and landing (eVTOL) aircraft. Designed as a companion tool to NDARC, the RST is intended to act as a first-look tool to quickly evaluate an eVTOL concept or explore input sensitivities. RST is a simplified model that assumes the configuration can be designed to achieve certain performance targets.

RST uses high-level aircraft parameters to describe an aircraft, and the modeled physics include momentum theory to calculate power in vertical flight and basic force balance equations for forward flight. The analysis can either assume a fixed aircraft gross weight or a fixed empty weight fraction. In the RST, battery mass is treated like fuel mass in a traditional fuel-burning aircraft: battery mass is not included in the empty weight fraction. The unique constant-weight aspect of eVTOL aircraft (no fuel is burned) is leveraged in that it enables a simplification of the analysis. The mission is defined as a series of hover and cruise segments. Climb and descent segments are not explicitly modeled because the time spent in those segments for UAM missions is relatively short, and the increase in energy usage in the climb segment is somewhat offset by the energy savings in the descent segment.

In the RST, an aircraft is defined by a high-level set of parameters that drive the design characteristics and estimated performance of the aircraft. The accuracy of the results is directly tied to the quality of the inputs and associated assumptions. The value of this approach is that, with sound engineering assumptions, a rapid solution can be generated that provides valuable engineering insight with very few inputs. The aircraft parameter inputs are cruise lift-to-drag ratio (L/D), figure of merit (M), disk loading (w), empty weight fraction or fixed gross weight, payload weight, cruise efficiency (η_p), and powertrain efficiency (η_ϵ). A power factor input is also utilized to account for a failure scenario that requires an increase in power output. This power factor is a function of the aircraft configuration; increasing the number of propellers/rotors reduces the power factor required because the impact of a failed rotor (and the shutting down of its matching pair as appropriate) is decreased. Power factors typically range from 1.3 to 1.8.

The battery is modeled as a "box of energy" with energy and power limits, a state-of-charge range, packaging overhead, end-of-life characteristics, and a battery efficiency parameter. The energy and power limits are defined by cell-level specific energy and specific power[1]. Both the RST specific energy and specific power inputs are specified at cell beginning-of-life, such as 200 Wh/kg and 1.5 kW/kg, respectively.

The state-of-charge range is a constant multiplier on the total energy relative to the allowed usable energy, typically 80 to 85%. This limited allowable range in the battery usage is to extend the usable life of the battery. The packaging overhead is simply a multiplier on the weight, typically between 1.2 and 1.3, which represents the packaging inefficiency going from cell weight to pack weight, including the battery management system and safety components.

Battery end-of-life characteristics are important to model for eVTOL aircraft. It is assumed that UAM aircraft will be heavily utilized, which will result in the quick accumulation of charge-discharge cycles on the battery. With each cycle on the battery, the battery capacity is reduced, resulting in capacity fade, and the internal resistance grows, resulting in power fade; both of these characteristics act independently and can be nonlinear [8]. The end-of-life behavior of a cell is dependent on the cell characteristics, the environment in which it operates, and how it was used (e.g., high or low discharge and/or charge rate). Experimental cell testing can determine the capacity fade and

[1] The specific power limitation is the capability of a cell to produce power at low state-of-charge where the voltage, under load, will drop below a minimum voltage cutoff.

internal resistance growth as a function of cumulative cell cycles[2]. The cell end-of-life is established by determining a capacity fade cutoff value, which typically ranges from 70–90%. The RST models the capacity fade and internal resistance growth as multiplicative factors on the battery specific energy and power, and the multiplicative factors typically range from 0.5 (significant battery degradation) to 1.0 (new battery).

A final parameter included in the battery model is a battery efficiency term that is applied during a high-power demand state. Under a high-power demand, such as a vertical flight state (hover or vertical climb/descent), the voltage drop is more significant, requiring greater current to maintain a fixed power level. This increase in current, and therefore energy usage, during vertical flight segments is accounted for by the battery efficiency term. The battery efficiency term is not applied during forward or edgewise flight segments in RST. The default value for the battery efficiency term in RST is 90%.

3 Modifications to the Turboelectric Lift+Cruise Model

It was desired to explore aircraft system sensitivities of an all-electric version of the Lift+Cruise UAM reference aircraft as several industry proposed UAM concepts utilize all-electric powertrains. A turboelectric version of the Lift+Cruise configuration was readily available[3] and described in Ref. [1], and the model architecture was designed to easily convert to an all-electric version. Through some simple modifications, an all-electric Lift+Cruise NDARC model was then available on which to perform the mission and aircraft technology trades and quantify their impact on the aircraft sizing.

To convert from the turboelectric to the all-electric Lift+Cruise configuration, the aircraft component inputs were modified by reducing the number of propulsion components (`nPropulsion`) from 10 to 9 to eliminate the turboelectric engine/generator; reducing the number of engine groups (`nEngineGroup`) from 11 to 9 to account for the elimination of the turbine engine system and the associated generator system; changing the of number fuel tanks/batteries (`nTank`) from 2 to 1 as there was only a battery system and no hydrocarbon fuel tank; setting the number of engine models (`nEngineModel`) to zero because a turbine engine model was no longer required; and reducing the number of motor models (`nMotorModel`) from 2 to 1 as the generator motor model was no longer required. Changing `nMotorModel` to 1 does imply that the motor model for the lifting rotors was the same as for the pusher propeller, which may not always be true. However, for this analysis it was assumed to be the same. Lastly, there was no trim requirement for the turbine and generator to be synced, and so the number of trim variables was reduced in both the hover and forward flight modes.

The battery model component was reused from the turboelectric Lift+Cruise model with no changes. It leverages a Li-ion battery model with an allowable state of charge (SoC) range of 80% (5% minimum depth of discharge and 85% maximum depth of discharge). The assumed cell-level specific energy was 650 Wh/kg, which is well beyond the current 150–260 Wh/kg technology available today [9].

The turboelectric version of the Lift+Cruise aircraft has two sizing missions. The first is the "Mission 3: Most Constraining Mission" sizing mission from Ref. [10] and the second is the sizing of an emergency battery in the event of a turbogenerator failure.

[2]The cell cycles are accumulated by subjecting the cell to a representative power (current) profile from an aircraft mission. Note, there is not a one-to-one correlation from an aircraft mission to a cell cycle. For example, a short mission does not result in a full cell cycle.

[3]`http://sacd.larc.nasa.gov/uam`

The all-electric Lift+Cruise aircraft has no turbogenerator making the second sizing mission unnecessary. The only sizing inputs that are updated for the all-electric version are reducing the array lengths to nine (to match the number of propulsion groups, in this case 9) and reducing the number of missions from 2 to 1. The single sizing mission is identical between the previous turboelectric version and the all-electric version.

Reference [10] provides details for the “Mission 3” sizing mission utilized in this study. The mission specifies a 1200 lb payload flown for two hops of 37.5 nautical miles each into a 10 knot headwind at a cruise altitude of 4000 ft above ground level (AGL). The aircraft does not charge when on the ground after completing the first 37.5 nmi hop. A 20-minute cruise reserve is the final segment of the mission. This mission is an energy-dominated mission (as opposed to a power-dominated mission), meaning that the mission is much more demanding on the energy storage capabilities of the battery, due to the significant portion of the total mission being in cruise, than the power producing capabilities, such as would be demanded by hover. Advanced battery technology assumptions are required for the all-electric aircraft to be sized in the vicinity of 7000 to 9000 lb takeoff gross weight. It is not implied that this battery technology level is feasible in the near future, but rather this is the level required for a closed aircraft design at that gross weight. A packaging overhead factor of 1.3 was assumed to account for the battery management system, packaging inefficiencies, and safety systems.

4 NDARC and RST Model Comparison

NDARC and RST were both utilized in this trade exploration study. As a starting point, the inputs and outputs between the two tools were compared and any discrepancies that might impact the results were identified. To ensure consistency between the results of the two tools, the high-level vehicle parameters required for the RST model, such as cruise lift-to-drag ratio and figure of merit, were taken from the NDARC solution where possible. It was desired to have a consistent starting point between the analyses and verify that the simplifying assumptions utilized in RST were not skewing the results. A summary of the all-electric Lift+Cruise RST model inputs is provided in Table 1. All RST input values used in Table 1 came from the NDARC output except the battery high-power efficiency term.

Table 1: RST Inputs for the All-Electric Lift+Cruise Reference Aircraft

Parameter	Unit	Value
Lift-to-drag ratio	-	9.90
Disk loading	lb/ft^2	14
Figure of merit	-	0.70
Cruise propeller efficiency	-	0.80
Empty weight fraction	-	0.62
Powertrain efficiency	-	93%
Cell specific energy	Wh/kg	650
State-of-charge range	-	80%
Battery pack mass overhead	-	1.30
Battery high-power efficiency	-	90%

For this study, the battery end-of-life was not utilized in the RST model because the NDARC model results were generated with beginning-of-life batteries. The reserve segment L/D was 9.7 in the NDARC model, which was slightly lower than the cruise segment value of 9.9. The RST model currently utilizes a single cruise L/D, and so there was a slight discrepancy in the two models. A lift-to-drag ratio of 9.7 compared to 9.9 for the complete mission results in a 3% change in the RST estimated gross weight. Only the reserve segment has the reduced lift-to-drag ratio instead of the complete mission, so the 3% error is a conservative estimate. This error is considered sufficiently small to ignore.

Sizing results for the baseline, all-electric Lift+Cruise configuration aligned extremely well between NDARC and RST. The NDARC sized aircraft gross weight was 8810 lb and the RST gross weight was 8820 lb, a 0.1% error. Perhaps this should not be unexpected given the inputs to RST came from NDARC, but it does show consistency between the two models even with significantly reduced inputs for RST. Nearly all the RST inputs were identical to, or derived from, the NDARC model, so it should be noted that the only RST input available to tune the model would be the battery high-power efficiency. However, a default battery high-power efficiency of 90% yielded close agreement with the NDARC result, so adjusting this input to better match the NDARC result was not necessary.

As a sanity check on the empty weight fraction and estimated gross weight (by both NDARC and RST), the Lift+Cruise sized aircraft result was compared to a historical trend provided by Nicolai [11]. Figure 2 shows that the baseline, all-electric Lift+Cruise configuration aligns well on the upper side of the trend line. It should be noted that the tiltrotor aircraft are also above this trend line, so the Lift+Cruise model appears aligned with historical data.

5 Summary of Aircraft Trade Explorations

Two sets of trades were explored as part of this study with the intent of understanding the key drivers for aircraft sizing. One set of three trades focused on the aircraft design parameters, and the other set of three trades focused on the mission parameters. Table 2 shows the parameters varied for the trade study along with the minimum, baseline, and maximum values used. The minimum and maximum inputs were chosen to capture representative values that have been utilized by the UAM ecosystem for a range of aircraft configuration types, mission definitions, and technology assumptions.

Table 2: Variation in Aircraft Assumptions and Mission Parameters

Trade Type	Parameter	Unit	Min	Baseline	Max
Aircraft	Disk Loading	lb/ft^2	10	14	30
	Payload Weight	lb	880	1200	1240
	Cell Specific Energy	Wh/kg	550	650	700
Mission	Total Mission Range	nmi	50	75	90
	Takeoff Altitude	ft	2000	6000	8000
	Reserve Time	min	0	20	20

Trades of the aircraft parameters provide insight into main the drivers for aircraft sizing. Disk loading and payload weight are known drivers of aircraft design and gross

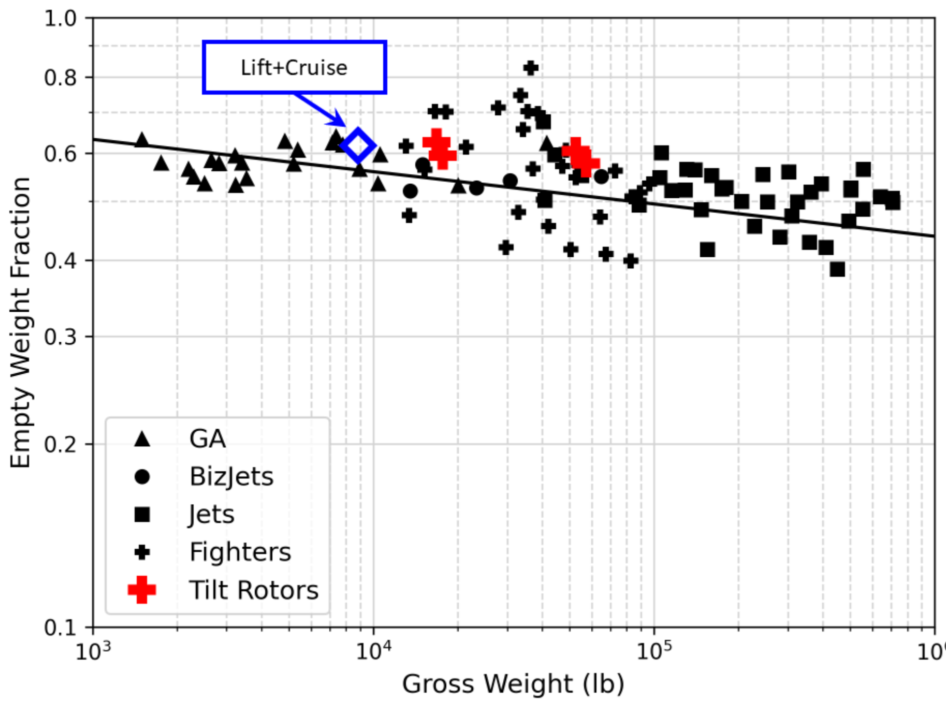


Figure 2: Comparison of Lift+Cruise empty weight fraction to historical data from Ref. [11]. The blue diamond shows the baseline, all-electric Lift+Cruise aircraft.

weight, but their exact impact on the Lift+Cruise sizing was unknown. The baseline, all-electric design required advanced battery technology assumptions in terms of specific energy to reach gross weight parity with the turboelectric Lift+Cruise aircraft [1]. Understanding the sizing impacts of varying battery specific energy was also desired.

The mission trades were designed to capture the characteristics of multiple UAM-type missions that have been proposed. Relative to the NASA sizing mission, some proposed industry missions have reduced range, payload, and reserve time requirements, and so it was desired to better understand how these variations in requirements affected the aircraft sizing. In this trade study, the reserve time was varied down to zero. It is acknowledged that having zero reserve time is not a viable solution, but understanding the full impact of the reserve segment on the aircraft sizing was insightful. The reserve time upper limit used here is the current rotorcraft operations requirement for reserve in visual flight rules, per 14 CFR §91.151. Mission range and takeoff altitude minimum and maximum values were selected to encompass the broad set of missions that have been proposed.

By varying each parameter, the requirements that are driving the design feasibility can be understood. While no single requirement may be over-constraining, an unintended "stacking" of requirements can occur when the combination of multiple requirements taken together results in the entire aircraft design space becoming infeasible. Careful consideration of aircraft design requirements for any mission should always be given, and simple trades can inform design space feasibility and system requirements.

6 Trade Study Results

Results from the aircraft trades sensitivities are discussed in Section 6.1, followed by results from the mission trades sensitivities in Section 6.2. Section 6.3 contains an exploration of a step-by-step change in aircraft and mission parameters to understand how modest, incremental changes to the inputs impact the final aircraft gross weight.

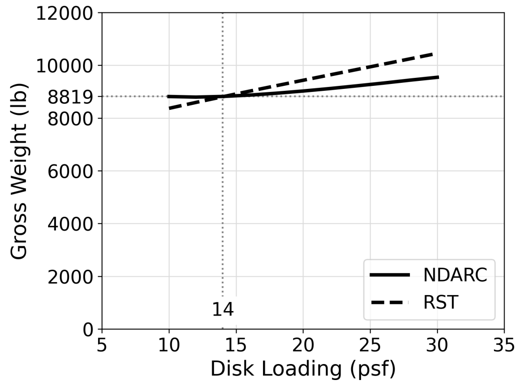
6.1 Aircraft-Level Parameter Trades

The gross weight sensitivities to variations in the aircraft-level parameters are shown in Fig. 3. The gross weight output from RST is shown to be more sensitive than the output from NDARC for all the aircraft-level parameters, but the trends are similar. The close agreement between the NDARC and RST gross weight predictions can be clearly observed in Fig. 3a. The NDARC and RST trend lines converge on gross weight at the baseline disk loading of 14. The changes in disk loading show that the RST results are linear, as somewhat expected due to the simplifying modeling assumptions in RST, while the NDARC results are nonlinear. As the disk loading continues to decrease, there appears to be an asymptotic behavior in the NDARC model. This nonlinear behavior highlights some of the secondary effects, such as changes in figure of merit, powertrain component sizing weights, and trim state, that are captured by NDARC in the aircraft resizing.

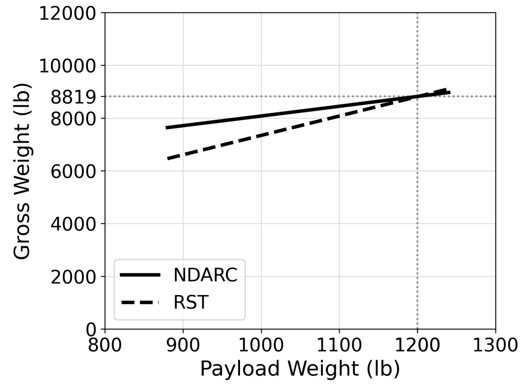
Although RST does not capture the secondary effects captured by NDARC, there are some advantages of the simplified RST analysis. The analysis performed here utilized a single-parameter sweep to characterize the aircraft sizing sensitivities to a single input change. As the disk loading is decreased, the powertrain efficiency, subsystem weights as a fraction of gross weight, and the figure of merit are all constant. These simplifying assumptions within RST enable the analysis of an aircraft configuration using a reduced set of inputs. The reduced set of required inputs accelerates the early conceptual design trades with RST capturing the dominant physical effects.

NDARC resizes the aircraft with any updated input but will always use the same model architecture, such as the number of motors, proprotors, etc. As the disk loading is decreased, the rotor diameter increases. There are no checks within NDARC to ensure blade tip clearance from the airframe or other rotors (note, RST does not contain these checks either), and so, for lower disk loadings, a better design solution may be to reduce the number of propulsors and rotors. Furthermore, as the rotor diameter continues to increase, the rotor performance changes and will require a redesign, which was beyond the scope of this work. The motor torque requirements also increase with reduced rotor efficiency and increased rotor diameter, which drives motor size and weight. Any results based on large deviations from the baseline design should be treated with caution as significant component redesign may be required, and changing the configuration architecture (e.g., number of rotors) may be a better solution. While NDARC captures many secondary effects, the impacts of these secondary effects may be overly optimistic or pessimistic. Evaluating the impact of the secondary effects on the resized aircraft requires sound engineering judgement.

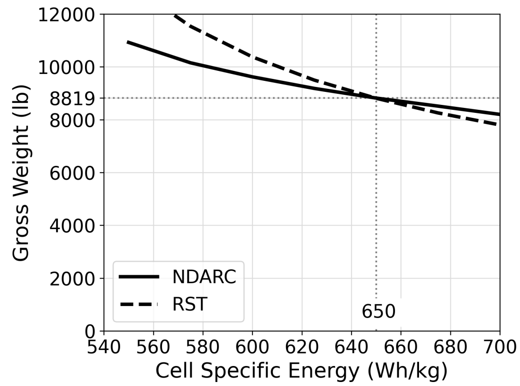
From an aircraft design perspective, all three aircraft parameters varied in Fig. 3 result in gross weight sizing impacts on the design. NDARC and RST both show a sizing sensitivity to disk loading, but the payload weight and cell-level specific energy are both more significant drivers for the sized aircraft gross weight. The allowable disk loading is somewhat tied to the configuration, and the cell specific energy is a technology



(a)



(b)



(c)

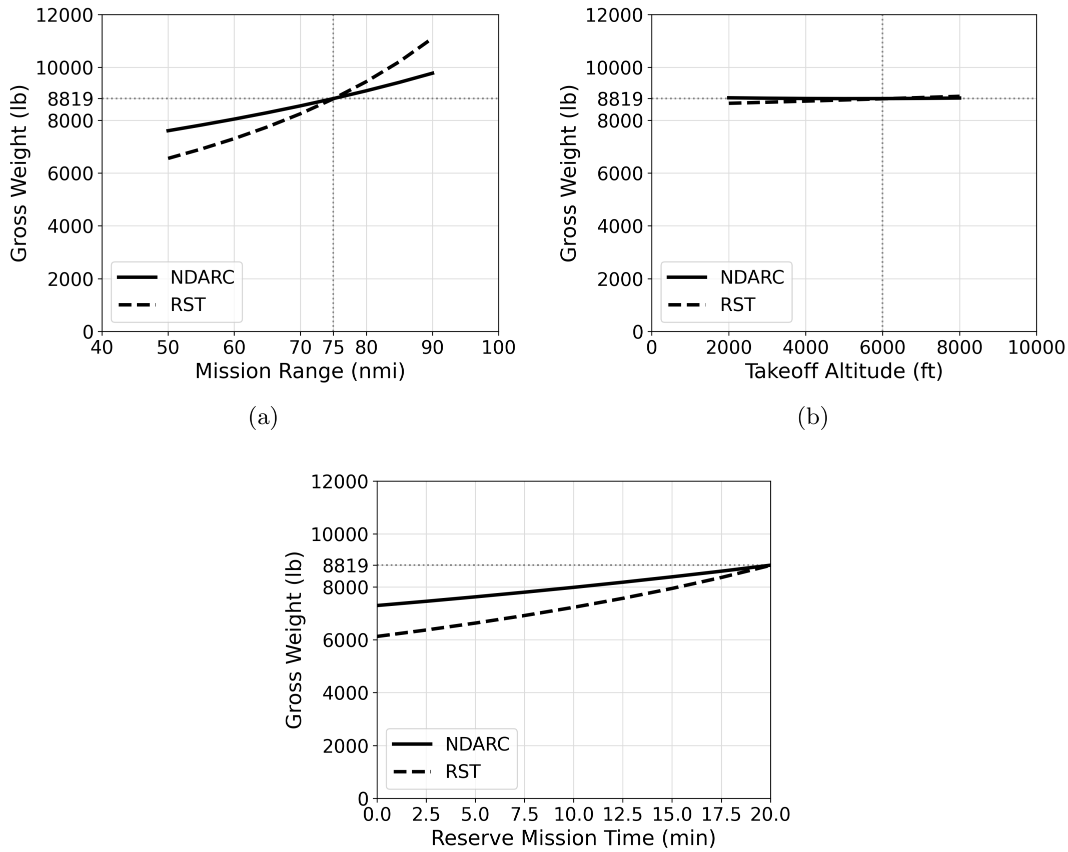
Figure 3: Influence of the aircraft-level input parameters of disk loading (a), payload weight (b), and cell specific energy (c) on aircraft gross weight for NDARC and RST models. Baseline input values are indicated by the vertical dashed line, and the baseline NDARC gross is weight shown by the dashed horizontal line.

assumption. The payload weight is solely driven by the aircraft requirements. As the design is strongly driven by the payload weight, careful consideration must be given when specifying a payload weight requirement. This single requirement can quickly drive a design from being feasible to being infeasible.

6.2 Mission-Level Parameter Trades

Trades on the mission-level parameters in Fig. 4 show trends similar to the aircraft-level trades of Fig. 3. The RST results show a larger sensitivity to mission range and reserve time than NDARC, which is similar to the results seen in the aircraft-level trades. For example, RST shows a strong advantage from reducing the mission range, whereas the results are more muted for the NDARC analysis. This mission range discrepancy stems for the changing efficiencies in NDARC as the aircraft is resized compared to the constant efficiencies in RST. As the range was reduced, the aircraft resizing in NDARC resulted in changes to cruise L/D and propeller efficiency, which reduced the sensitivity to changing mission range in NDARC when compared to RST.

Interestingly, RST and NDARC strongly agree on the limited impact of reducing



(a) (b) (c)

Figure 4: Influence of the mission-level input parameters of mission range (a), takeoff altitude (b), and reserve mission time (c) on aircraft gross weight for NDARC and RST models. Baseline input values are indicated by the vertical dashed line, and the baseline NDARC gross weight is shown by the dashed horizontal line.

the takeoff altitude. This result was unexpected because the air density impacts the power required for vertical flight. However, as a fraction of overall mission time, the vertical flight segments are quite small; therefore, the forward flight segments drive the overall mission energy consumption. A secondary sizing effect for eVTOL aircraft can be the power output ability of the battery. Given the large amount of energy required to complete the mission, the discharge rate was always well within any sizing constraints, such as a discharge rate limit to preserve battery life, and therefore was not an active constraint on the aircraft sizing. As such, for the Lift+Cruise configuration with the baseline advanced batteries, adjusting takeoff altitude has minimal effect. In industry configurations that leverage more near-term batteries for lower energy missions, the C-rate will be much higher, and, therefore, peak power in a vertical flight segment will likely be a sizing condition, especially at the end of the mission where battery SoC is low (i.e., at low battery voltage, a higher current is required for the same power demand).

Reducing the mission reserve time has the expected result of reducing the sized aircraft gross weight for both NDARC and RST, but RST continues to show a greater sensitivity. A slight discrepancy in the modeling exists as the reserve mission L/D

in NDARC was 9.7 compared to 9.9 for the cruise segment, whereas RST assumed a constant L/D. The results in Fig. 4c are very similar to the trends of Fig. 4a below 75 nmi, which is expected because reducing reserve time is similar to reducing mission range, especially at fixed gross weight. Both the mission range and reserve time have a strong sizing effect on the aircraft; the aircraft gross weight increases as mission range and reserve time grow. This strong sizing sensitivity highlights the importance of selecting requirements that maintain a feasible design space while also meeting market demand. Overly reducing the mission requirements to benefit the aircraft sizing can have a negative impact on the ability to achieve an economically viable solution. Likewise, having mission requirements that capture a large market but make the aircraft sizing infeasible is equally negative.

6.3 Step-by-Step Aircraft and Mission Parameter Changes

As previously shown in Figs. 3 and 4, the sized aircraft was sensitive to all input parameters explored except for the takeoff altitude. Next, to understand how the assumptions and mission requirements stack to drive the aircraft sizing, step-by-step input changes were applied to the NDARC model and the aircraft gross weight impact was quantified. The baseline battery cell specific energy assumption was extremely advanced, and it was desired to explore how much the battery technology assumption, in terms of specific energy, could be reduced with modest, incremental changes to the aircraft-level and mission-level parameter inputs discussed in Sections 6.1 and 6.2. Only modest changes to the inputs were utilized to determine if minimal changes to the aircraft and mission inputs could result in measurable changes to the final aircraft sizing. The target weight for the final sized aircraft was 7000 lb, which aligns with the 14 CFR Part 27 gross weight limits for rotorcraft. Table 3 summarizes the stepped input changes that were applied to the NDARC model. The L/D was not explicitly traded as part of this study because NDARC calculates the total aircraft aerodynamics using a component buildup approach. It was assumed that a well-designed aircraft would be able to maintain the baseline L/D as the step-by-step changes were made, and the NDARC aerodynamic model was tuned by adjusting the wing parasite drag such that the L/D was increased back to 10. This L/D change can be seen in the second-to-last step of Table 3.

The effect of the step-by-step changes on aircraft gross weight are shown in Fig. 5. As would be expected, the aircraft gross weight drops as the payload weight, mission range, and reserve requirements are all reduced. There is very little benefit from changing the

Table 3: Step-By-Step Change in Aircraft and Mission Inputs

Parameter	Unit	Initial Value	Final Value
Payload	lb	1200	1000
Segment Range	nmi	37.5	30.0
Reserve Time	min	20	10
Takeoff Altitude	ft	6000	2000
Disk Loading	ft	14	10
Cell Specific Energy	Wh/kg	650	608
Lift-to-Drag Ratio	-	9.5	10
Cell Specific Energy	Wh/kg	608	576

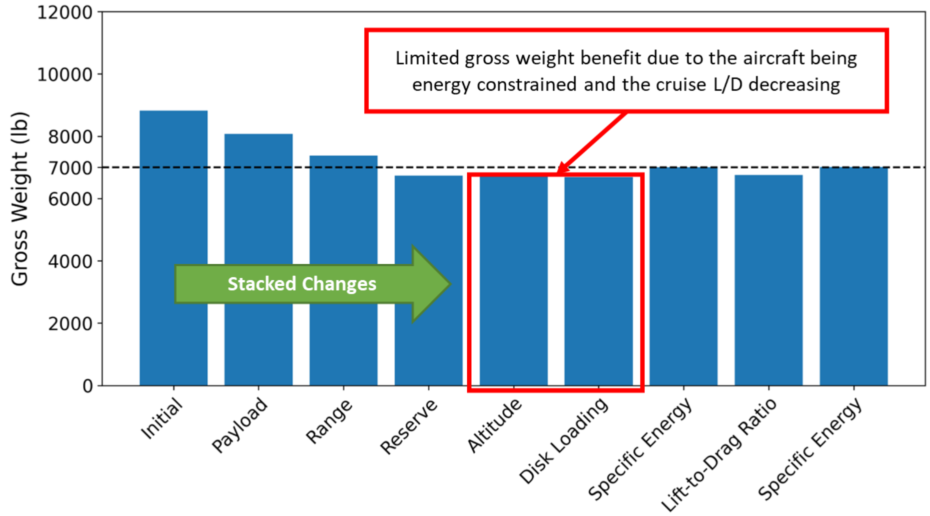


Figure 5: Gross weight changes resulting from step-by-step input parameter changes to the all-electric Lift+Cruise baseline. Target gross weight was 7000 lb while simultaneously reducing the battery specific energy technology assumptions from the 650 Wh/kg baseline.

density altitude and disk loading because the batteries are not power limited, and the L/D changes as the design deviates from the baseline. The cell specific energy was then decreased until the aircraft target weight reached 7000 lb. At this point, the NDARC aerodynamic inputs were adjusted from the baseline to achieve a target L/D of approximately 10, which it is assumed that a well-designed Lift+Cruise configuration could achieve. Since modifying a single parameter within NDARC results in changes to the aircraft sizing, this causes the cruise flight efficiency to deviate from the baseline. It is assumed that the cruise efficiency could be regained with more detailed design efforts, but achieving this cruise efficiency requires design effort beyond the scope of this work. The cell specific energy was adjusted a last time to 576 Wh/kg (355 Wh/kg pack level) to bring the aircraft weight back to 7000 lb[4]. This specific energy is still advanced battery technology beyond what is currently available today. The large energy requirement is driven by the energy-dominated mission and the aerodynamically "dirty" Lift+Cruise configuration, which has many components with interference (stopped rotors, pylons, etc.) and significant wetted area.

7 Summary and Conclusions

A trade study was performed on an all-electric RVLT UAM Lift+Cruise reference aircraft. Six parameters were explicitly explored to understand the aircraft sizing sensitivities to these inputs. The six parameters were mission range, reserve time, takeoff altitude, payload weight, disk loading, and battery technology assumptions. The study utilized two tools for comparison, NDARC and RST, which showed excellent agreement for the baseline, all-electric Lift+Cruise aircraft. After varying the described input parameters, the trends were shown to be similar in value and in direction, but RST generally showed greater sensitivity to changes in input parameters. The simplifying

[4]Note, final L/D was confirmed to still be 10.

assumptions of RST maintain constant performance efficiencies, such as figure of merit and cruise propeller efficiency, whereas the NDARC component buildup approach results in performance efficiencies changing as the aircraft is resized. These changes in efficiency imply either that a component redesign is required to regain the baseline component efficiencies in NDARC or that the constant component efficiencies assumed in the RST model are not achievable with the changes in input assumptions. RST has value when performing a quick aircraft design assessment, for independent analysis where insufficient details are available for an NDARC model, or to perform rapid trade studies.

Results from the trade studies explicitly show that extreme care must be taken in selecting the mission requirements for all-electric UAM aircraft. The energy constraints of batteries result in a Lift+Cruise aircraft configuration with strong sensitivity to payload weight and mission range changes. The results show disk loading and takeoff altitude have limited impact on aircraft sizing, which means the NASA UAM sizing mission is energy dominated. An energy-dominated mission means that the aircraft sizing is largely driven by the energy requirements of the mission, which are most impacted by the cruise performance of the aircraft. Because the mission is energy dominated, advanced battery technologies in terms of higher specific energy are required to obtain aircraft designs with reasonable gross weights. The energy required to complete the mission results in a battery with large capacity and so the discharge rate as a function of the battery capacity (C-rate) for each mission segment is never an active sizing constraint, even in vertical flight.

Unintentional "stacking" of requirements can be a challenge when developing aircraft and mission requirements. Requirement stacking is when no single requirement appears unreasonable, but the combination of multiple requirements taken together results in little to no feasible design space. A requirement stacking sensitivity was explored for the Lift+Cruise aircraft by sequentially adjusting the input parameters with the goal of achieving a target takeoff gross weight of 7000 lb. Only modest changes to the inputs were utilized since drastic changes, such as eliminating payload weight, reduce or eliminate the utility of the aircraft. The desire was to reduce aircraft sizing drivers through modest changes to the baseline input parameters, such as mission range and payload, to enable nearer term battery technology assumptions, in terms of cell specific energy. The findings were not favorable for the Lift+Cruise aircraft because even with the sequential change of requirements, the required cell specific energy assumption remained extremely high at 576 Wh/kg (355 Wh/kg pack), which would require a significant advancement in battery technology. Current cell technology for Li-ion batteries is in the 150 to 260 Wh/kg range, far short of the required specific energy assumption for a 7000 lb Lift+Cruise aircraft using the modified inputs shown in Table 3. This technology gap is driven by the mission being energy dominated and the generally aerodynamically "dirty" Lift+Cruise configuration. If the mission were to be more balanced between energy and power requirements or power dominated, then the Lift+Cruise configuration would likely encounter power limitations that would become active sizing constraints. Due to the poor performance of the Lift+Cruise configuration for the energy-dominated NASA sizing mission, continued development of the Lift+Cruise reference aircraft by the RVLT Concepts Team will likely be limited.

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