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Investigation of a Mission-based Sizing Method for Electric VTOL Aircraft Preliminary Design

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Future demands for Urban Air Mobility solutions has given rise to electrically powered vertical takeoff and landing aircraft, also known as eVTOLs. The apparent number of these concepts in development has rapidly grown to over 500. The race between eVTOL companies to push their concepts into commercial operation has produced a confidential aircraft development process amongst these manufacturers due to commercial sensitivity. This lack of existing data makes it difficult to carry out conceptual design analysis for eVTOL aircraft. This paper presents the results of the development of a comprehensive mass estimation method for battery-powered eVTOL aircraft in two main configurations, powered lift and wingless. Aircraft component mass estimation methods are adapted from literature on conventional aircraft design synthesis, augmented with rotorcraft power models, which are used to iteratively solve the forward-looking sizing problem using the numerical bisection method. A range sensitivity study showed that for ultra-short missions of 10 km or less, the wingless aircraft becomes more efficient in energy consumption due to its simpler and ultimately lighter airframe structure when sized for very short missions.

Nomenclature

A	=	area [m ²]	els	=	electrical system
AR	=	aspect ratio	fc	=	flight controls
D	=	drag [N]	feq	=	fixed equipment
DL	=	disk loading [N/m ²]	fur	=	furnishings
E	=	energy [kWh]	$fuse$	=	fuselage
L	=	lift [N]	i	=	ideal
N	=	number	iae	=	instrumentation and avionics system
P	=	power [W]	$motor$	=	motor
S	=	surface area [m ²]	pax	=	passengers
T	=	thrust [N]	pl	=	payload
V	=	velocity [m/s]	$prop$	=	propeller
W	=	weight [N]	pt	=	power train

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l	= length [m]	s	= aircraft structure
m	= mass [kg]	ult	= ultimate
η	= efficiency, design load factor	v	= vertical
ρ	= fluid density [kg/m ³]	DEP	= Distributed Electric Propulsion
h	= horizontal	$EASA$	= European Aviation Safety Agency
C	= climb, coefficient	$eVTOL$	= electric Vertical Take-Off and Landing
D	= descent	PAV	= Personal Aerial Vehicle
bat	= battery	SRW	= Slowed-Rotor Winged (eVTOL)
$contr$	= controller	UAM	= Urban Air Mobility
e	= empty		

I. Introduction

The aviation industry is currently witnessing a disruption in propulsion technologies. Forefront among the examples of this disruption is the electrically-powered vertical takeoff and landing aircraft, also known as the eVTOL. Towards the end of 2021, there were over 500 proposed eVTOL concepts, prototypes and production vehicles [1], some of which were being unveiled at the rate of more than one per week [2]. The vehicles being proposed are capable of vertical takeoff and landing (VTOL), fully electric or hybrid-powered propulsion and energy storage systems and are typically designed to carry under ten passengers with a maximum takeoff mass below 3175 kg [3]. A significant proportion of these aircraft is designed to provide urban air mobility (UAM) solutions. These UAM or air taxi missions are believed to be the next logical course for aviation progress. Improvements in battery technologies, distributed electric propulsion (DEP), and regulatory receptiveness have bolstered this belief.

Typical UAM missions may cover intra-city routes of about 50 km in the short term and then above 50 km in the medium term. This, for example, will be sufficient for a Reading to London Heathrow and Oxford to London Heathrow service, respectively. Inter-city missions that cover 100+ km are heavily dependent on battery density technology levels for fully-electric concepts. The use of hybrid-electric propulsion in some concepts is believed to be a stop-gap until the technological maturity and economic feasibility of fully-electric battery-powered concepts are realized [4]. Apart from UAM missions described earlier, there exists an ever-increasing possibility of use cases for eVTOL aircraft. Some of the use cases that are currently being evaluated include emergency services such as medical evacuation (medevac), humanitarian response and fighting wildfires [5, 6]. Further use cases include last-mile aerial delivery and law enforcement [5].

Table 1. eVTOL aircraft classification

	Primary Classification	Secondary Classification	Tertiary Classification
eVTOL Concepts, Prototypes & Production Vehicles	Powered Lift	Vectored Thrust (Same propulsion system for hover and forward flight)	Tilt Wing
			Tilt Fan
			Tilt Prop
		Tilt Body Tilt Frame	
		Independent Thrust (Separate propulsion system for hover)	Lift + Cruise
			Slowed-Rotor Winged
	Combined Thrust (Combined propulsion system for hover)		Tilt Wing
		Tilt Fan	
		Tilt Prop	
Wingless		Multicopter	
		Personal Aerial Vehicle	
		Electric Rotorcraft	

Two distinct features common to most unveiled concepts are vertical takeoff and landing (VTOL) capability and the use of a distributed propulsion system. The latter allows for a simplified and more efficient propulsion system for the vertical and forward lift when compared to conventional VTOLs' use of jet engines and the complex thrust vectoring schemes employed. The European Union Aviation Safety Agency (EASA), in its Special Condition for

Small-category Vertical Take-Off and Landing Aircraft (SC-VTOL-01), attempts to define an eVTOL aircraft as 'a person-carrying vertical takeoff and landing (VTOL) heavier-than-air aircraft in the small category, with lift/thrust units used to generate powered lift and control' [3]. EASA establishes that the VTOL capability of these aircraft sufficiently differentiates them from conventional airplanes. Likewise, the existence of distributed electric propulsion (above two lift/thrust units) sufficiently differentiates eVTOL aircraft from conventional rotorcraft.

A. eVTOL Aircraft Classification

eVTOL aircraft are split into two main categories: *powered lift* and *wingless aircraft* (Table 1). Powered lift aircraft are winged aircraft capable of VTOL and aerodynamic lift in forward flight. Wingless aircraft, on the other hand, are multirotor aircraft with two or more lift/thrust units with limited to no capabilities for wing borne forward flight. Powered lift eVTOLs are further decomposed into two main categories, depending on whether the concept uses a common powerplant or independent powerplants for lifting and forward flight.

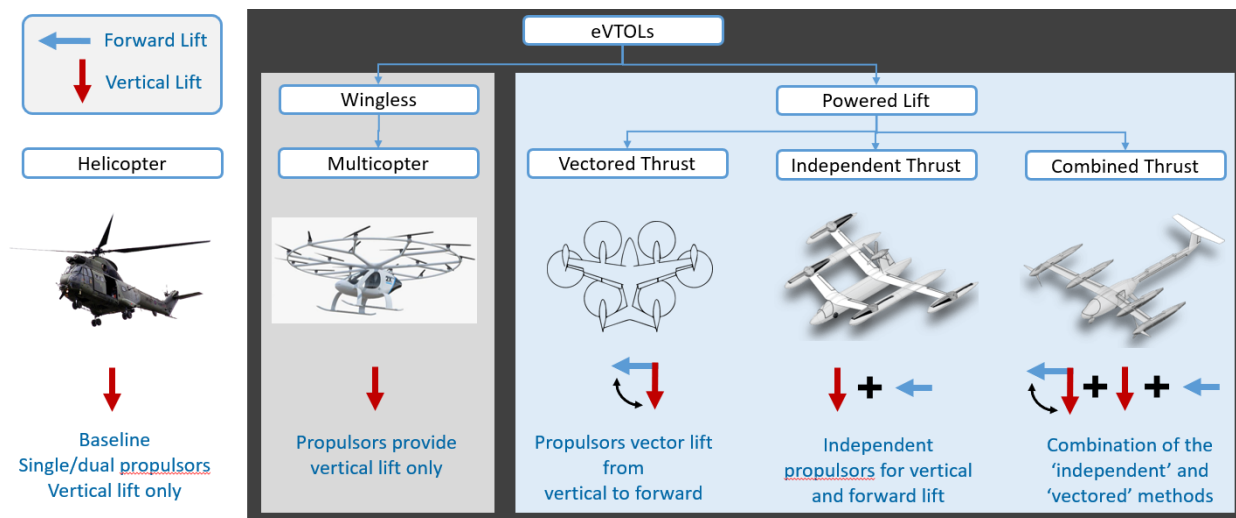


Figure 1. eVTOL Propulsion Configurations

1. Powered Lift

Vectored Thrust: These are powered lift eVTOLs that use all of their lift/thrust units for both vertical lift and cruise. This is achieved by rotating (vectoring) the resultant thrust points against the direction of motion. Vectoring the thrust points can be achieved by rotating the whole wing-propulsion assembly (Tilt Wing), by rotating the lift/thrust unit itself (Tilt Fan for ducted fans and Tilt Prop for propellers) or by rotating the whole aircraft frame pivoted about the fuselage (Tilt Body or Tilt Frame).

Independent Thrust: Independent thrust eVTOLs are a type of powered lift eVTOLs that use entirely different lift/thrust units for the vertical lift and forward flight regimes. None of the lift/thrust units are vectored as their thrust points remain fixed against the direction of flight. This class of eVTOL is also referred to as 'Lift + Cruise'. Slowed-Rotor Winged (SRW) eVTOLs, on the other hand, differ from Lift + Cruise eVTOLs because they possess a single large rotor akin to a helicopter. The rotational speed of the rotor is reduced during cruise to decrease drag. SRW eVTOLs are still classed as powered lift aircraft because they possess a fixed-wing responsible for a significant portion of aerodynamic lift generated in forward flight.

Combined Thrust: Combined Thrust eVTOLs are a fusion of Vectored Thrust and Independent Thrust eVTOLs. They use some but not all of their lift/thrust units for both vertical lift and cruise. This category of eVTOL is a compromise between the practicality of Lift + Cruise aircraft and the desired efficiency of Vectored Thrust aircraft. Combined Thrust eVTOLs only vector a portion of their lift/thrust units for vertical lift and forward flight while the other lift/thrust units remain in a fixed role of augmenting vertical lift.

2. Wingless

Wingless eVTOL aircraft rely solely on the thrust from their lift/thrust units for both vertical lift and forward flight. Multicopters are the dominant secondary classification of wingless architecture with a carrying capacity of two to five occupants. These aircraft are designed mainly for use in air taxi services and emergency services. Personal Aerial Vehicles (PAV), although technically possessing a multicopter architecture, distinguish themselves from the previous

subclass in carrying capacity. As the name suggests, PAVs are single-seat multicopter eVTOLs where the operator sits or stands to ride the aircraft. These aircraft are generally observed to be enthusiast vehicles with significantly lower utility when compared to multicopters. Due to the low cost of off-the-shelf electric motors required in powering this weight class, PAVs are generally the least expensive to manufacture. For this reason, larger and more complex eVTOL designs usually start as PAVs until the propulsion architecture can be proven.

B. Overview of Aircraft Design Methods

There is a lack of a unified conceptual design approach for electric vertical takeoff and landing vehicles (eVTOLs). This is due to the early stage of development and adoption of these aircraft. However, in line with the rapid development of these aircraft, research into the conceptual design of eVTOLs has grown recently. Sizing methods, which are methods for estimating the mass, size and power requirements to meet mission requirements, have been well established for conventional fixed-wing aircraft. However, these methods are partially inadequate for eVTOL aircraft sizing because of two main reasons; electric energy source and vertical takeoff and landing capability.

Sizing methods for conventional aircraft are based on the use of conventional liquid fuels whose mass reduces in-flight. Batteries, on the other hand, do not share this trait. The use of batteries as the energy source for eVTOLs is becoming widespread [7]. As such, it is expected that a sizing method proposed for eVTOL aircraft would account for this peculiarity. As the halfway point between fully-electric battery-powered aircraft and conventional aircraft, hybrid-electric aircraft utilize liquid fuels in generating electric power for the lift/thrust units. This allows for partial implementation of conventional sizing methods based on fuel fractions because of the decreasing aircraft mass during its mission. This is evident in literature focused on the conceptual design of hybrid-electric VTOL aircraft [8-11].

Literature on the initial sizing of fully-electric battery-powered eVTOL aircraft lacks in comparison to that of hybrid-electric aircraft. This may be attributed to the lower range performance of the battery-powered designs when compared to their hybrid-electric counterparts. However, at the end of 2021, average energy densities for Lithium-ion batteries are hovering at the 250 Wh/kg point [12]. Even other battery chemistries, such as Lithium-sulfur (Li-S) batteries, show a promising battery density of up to 560 Wh/kg in laboratory conditions [13]. Although, manufacturing challenges will need to be overcome before a commercial debut. As the technological limitations for battery-powered eVTOL aircraft design reduce, the need for a configuration-dependent rapid sizing method arises. This method can be used to quickly assess the suitability of an eVTOL configuration given a mission role. This is the focus of the paper.

Historically, the conceptual design of new aircraft followed defined syntheses set out in established texts. Roskam[14], Gudmundsson[15], and Raymer[16] provide exhaustive literature on conceptual aircraft design methods for fixed-wing aircraft with occasional accommodations for some experimental aircraft and general homebuilt aircraft. Literature on conventional rotorcraft aircraft design is observed to be less prevalent than its fixed-wing counterparts. However, Newman[17], Johnson[18] and Leishman[19] provide an in-depth look into the governing principles in rotorcraft aerodynamics and performance, with some treatments in rotorcraft design case studies. The design synthesis covered in the fixed-wing aircraft design books relies heavily on already existing aircraft data from established manufacturers. This approach would be ideal for eVTOL aircraft design in the future after there is a widespread adoption and comprehensive aircraft performance data from in-service eVTOL aircraft. However, there is an opportunity to apply parts of conventional aircraft mass estimation methods to eVTOL mass estimation.

The next sections of this paper focus on developing a comprehensive mass estimation method for rapid eVTOL sizing. This method is configuration-dependent with treatments to the powered lift and wingless classes. Aircraft component mass estimation methods are adapted from literature on conventional aircraft design synthesis. These are augmented with rotorcraft power models based on the momentum theory. All of which is used to estimate the power and energy required. This allows for the battery mass to be estimated. It is, however, not possible to obtain an exact solution to the sizing problem analytically. Thus, the numerical bisection method is employed to solve this forward-looking problem iteratively until the error between two concurrent final mass estimates is minimized within a given tolerance, resulting in the final aircraft mass.

II. Method

This section presents a hybrid technique for mass estimation of eVTOLs, drawn from established methods of sizing conventional fixed-wing and rotary-wing aircraft and electric-powered aircraft. This is then followed by the development of an iterative sizing process to achieve the final aircraft mass.

A. Mass Estimation

The total mass (m) for an eVTOL aircraft can be described as the sum of its empty mass (m_e) and the payload mass (m_{pl}).

$$m = m_e + m_{pl} \quad (1)$$

Where the empty mass (m_e) consists of component structure mass (m_s), power train mass (m_{pt}), fixed equipment mass (m_{feq}) and battery mass (m_{bat}).

$$m_e = m_s + m_{pt} + m_{feq} + m_{bat} \quad (2)$$

The components of the empty mass, structural components (m_s), powertrain system (m_{pt}) and fixed equipment mass (m_{feq}), are further decomposed into

$$m_e = (m_{wing} + m_{fuse} + m_{tail} + m_{lg} + m_{boom} + m_{tilt}) + (m_{motor} + m_{prop} + m_{contr}) + (m_{fc} + m_{els} + m_{iae} + m_{fur}) + m_{bat} \quad (3)$$

The following sub-sections develop approaches towards estimating the masses of the sub-components defined in Eqn (3). Furthermore, although the fixed equipment masses (m_{feq}) have been presented to the reader to provide a comprehensive component mass identification, the estimation of fixed equipment masses (m_{feq}) is not carried out in this paper due to difficulties in obtaining information on eVTOL aircraft system architecture.

1. Estimating battery mass

Power requirements for a given mission are determined through an evaluation of the aircraft physics during each mission phase. The mission phases, takeoff hover, climb, cruise, descent and landing hover, are illustrated in Figure 2. In order to accurately size the aircraft, the power required to complete each mission phase will be estimated with the methods below. In vertical flight, it can be reasonably assumed that both the powered lift and wingless aircraft are governed by the same physics. Both the powered lift and wingless types are treated as rotorcraft here. As such, the equations modelling the power required for all phases except cruise apply to both the powered lift and wingless. In the cruise phase, however, the powered lift type is treated as a fixed-winged aircraft, and the corresponding fixed-wing power models are applied, albeit with adaptations for a battery energy source.

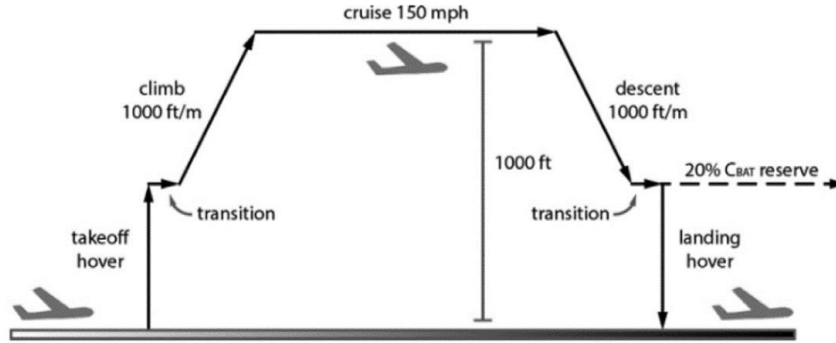


Figure 2. The flight mission profile for a typical UAM flight, adapted from Uber [20]

The power required in vertical mode can be modelled from conservation laws of aerodynamics, with the assumption that the flow through the rotor disk area (A) is one-dimensional, quasi-steady, incompressible and inviscid [19]. For a rotorcraft in a hover state, its weight is assumed to be equal to the thrust generated by the rotor disk. Thus the thrust can be expressed as a difference in momentum induced at the rotor disk plane (i) and a point far downstream in the flow. This is expressed as [17]

$$T = M_{FLOW}v_2 = \rho Av_i v_2 \quad (4)$$

Where v_i is the ideal induced velocity at the rotor disk plane and v_2 is the velocity far downstream in the flow. The induced velocity is shown to be double that of the downstream velocity. Hence Eqn (4) can be rewritten in terms of the induced velocity to produce [17]

$$v_i = \sqrt{\frac{T}{2\rho A}} \quad (5)$$

The ideal induced velocity is used to calculate the ideal power required to hover (P_i) as

$$P_i = T v_i = T \sqrt{\frac{T}{2\rho A}} \quad (6)$$

An example of the relationship between these parameters is the inverse of the induced velocity, which is the thrust generated per unit power required, an indication of the aircraft's hover efficiency. An important metric in eVTOL design, Figure 3 shows estimated hover efficiencies versus disk loadings for select eVTOLs.

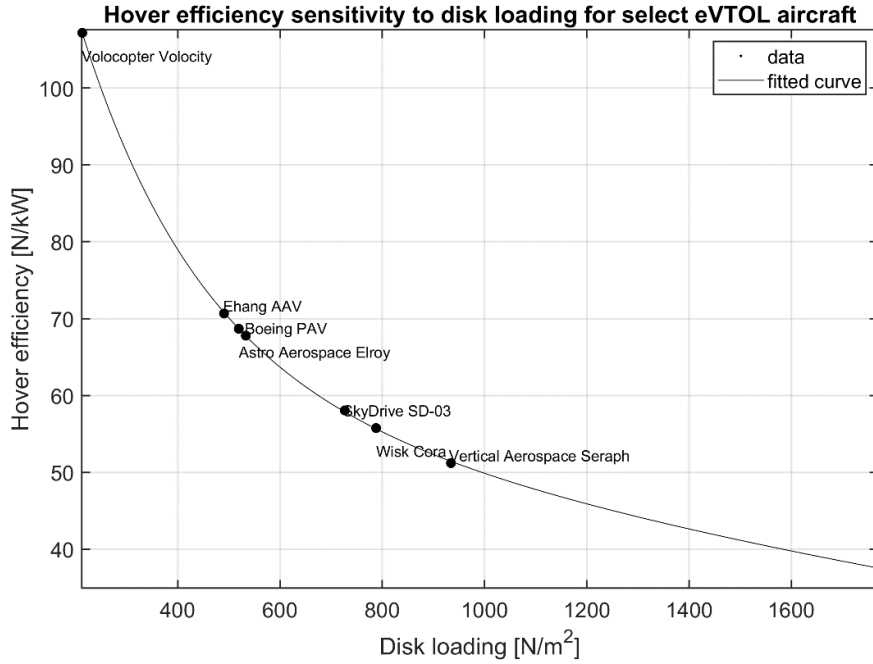


Figure 3. Trends in hover efficiency as a function of disk loading for select eVTOLs

The term *ideal* signifies that the thrust is generated at 100% efficiency. This is true for the assumption of an inviscid flow. However, for realistic estimations of hovering power, a *figure of merit* (FoM) is introduced to account for losses due to viscous effects. Typical values for FoM are between 0.7 and 0.8. $FoM = 0.75$ is selected for this study. Thus the actual power required to hover (P_{hov}) is given as [19]

$$\frac{P_{hov}}{FoM} = T \sqrt{\frac{T}{2\rho A}} = \sqrt{\frac{T^3}{2\rho A}} \quad (7)$$

The power required to climb (P_{clb}) and descend (P_{des}) are given as [19]

$$\frac{P_{clb}}{P_{hov}} = \frac{V_{clb}}{2v_h} + \sqrt{\left(\frac{V_{clb}}{2v_h}\right)^2 + 1} \quad (8)$$

$$\frac{P_{des}}{P_{hov}} = \frac{V_{clb}}{2v_h} - \sqrt{\left(\frac{V_{clb}}{2v_h}\right)^2 - 1} \quad (9)$$

Where V_c and V_d are the climb and descent velocities, respectively. Eqns (7), (8) and (9) complete the power models required rotorcraft in vertical flight. For rotorcraft, the power required to cruise in forward flight ($P_{cru,w}$) can be expressed as [19]

$$P_{cru,w} = T(V_{cru} \sin \alpha + v_i) \quad (10)$$

Where V_{cru} is the cruise velocity, and the angle of attack (α) is defined as a function on the aircraft's drag (D) [19].

$$\alpha = \tan^{-1} \left(\frac{D}{T} \right) \quad (11)$$

In the determination of cruise power for both aircraft types, the drag force experienced by the aircraft largely determines the power required. Hence the drag model is used [15]

$$C_D = C_{D_{min}} + \frac{C_L^2}{\pi A R e} \quad (12)$$

The second part of Eqn (12), the induced drag, can be easily estimated based on an assumed efficiency factor (e) of 0.8 and selected aerofoil characteristics. Methods to estimate the first part, parasitic drag, are presented in [14], [15] and [16]. For this study, however, the OpenVSP tool [21] was used to estimate the parasitic drag for both aircraft. The drag force on the aircraft can then be defined as

$$D = 0.5 \rho V_{cru}^2 S C_D \quad (13)$$

The power required in cruise ($P_{cru,pl}$) for the powered lift type is simply given as

$$P_{cru,pl} = \frac{D V_{cru}}{\eta_{propulsion}} \quad (14)$$

$\eta_{propulsion}$ represents the overall propulsion system efficiency.

The power required in cruise is obtained as a product of the aircraft's drag and cruise speed. Thus the entire power requirement for a given mission can be summarized in Table 2.

Table 2. Configuration-dependent power estimations for mission phases

Phase	Powered lift	Wingless
Hover	Eqn (7)	Eqn (7)
Climb	Eqn (8)	Eqn (8)
Cruise	Eqn (14)	Eqn (10)
Descent	Eqn (9)	Eqn (9)

The total energy consumed (E_{total}) is the product of the power required for each mission phase and the mission phase duration.

$$E_{total} = (P_{climb} t_{climb}) + (P_{cruise} t_{cruise}) + (P_{descent} t_{descent}) \quad (15)$$

The battery mass (m_{batt}) can now be calculated from the total energy consumed during the mission [10, 22]

$$m_{batt} = \frac{E_{total}}{E^* \eta_{batt}} \quad (16)$$

Typical Lithium-ion battery efficiencies (η_{batt}) are between 80% and 90% [12, 23]. While typical Lithium-ion battery densities are in the region of 170 Wh/kg to 350 Wh/kg [22]. A battery density of 250 Wh/kg was selected for this study as it is believed to be representative of the state-of-the-art in battery technology for 2021.

2. Estimating the airframe structure mass

The airframe component masses from Eqn (3) are estimated in this section based on established mass ratios for similar category aircraft. It is important to note that these mass ratios are based on the use of conventional aircraft-grade aluminium. This may not be ideal for eVTOL aircraft due to the added weight penalty of aluminium when compared to composite materials, a preferred option for eVTOLs. There is currently no existing data for mass ratios based on composite materials for comparable aircraft. For this reason, the mass ratios based on aluminium aircraft are used as a stop-gap, with the knowledge that the sized aircraft may be slightly overweight.

The fuselage mass is estimated using the 'Cessna class II method for fuselage mass estimation' [24]. This method is valid for an unpressurized fuselage and a maximum cruise speed of less than 200 kts.

$$m_{fuselage} = 14.86m^{0.144} \frac{l_{fuselage}^{0.778}}{p_{max}} l_{fuselage}^{0.383} N_{pax}^{0.455} \quad (17)$$

The wing mass is estimated using the 'Cessna class II method for wing mass estimation' [24]. This method is valid for a cantilever wing with a maximum cruise speed less than 200 kts.

$$m_{wing} = 0.04674m^{0.397} S^{0.360} n_{ult}^{0.397} AR^{1.712} \quad (18)$$

The empennage mass is estimated using the 'Cessna class II method for empennage mass estimation' [24]. This method is valid for a lightly-loaded empennage with no horizontal tail sweep. The horizontal tail mass estimate is given as

$$m_{tail,h} = \frac{3.184 m^{0.887} S_h^{0.101} AR_h^{0.101}}{174.04 t_{r,h}^{0.223}} \quad (19)$$

While the vertical tail mass estimate is given as

$$m_{tail,v} = \frac{1.68 m^{0.567} S_v^{1.249} AR_v^{0.482}}{639.95 t_{r,v}^{0.747} (\cos \Lambda_{0.25,v})^{0.882}} \quad (20)$$

The horizontal and vertical tail areas (S_h, S_v) are estimated based on the determination of the tail volume ratios [15, 25]. The thickness to chord ratios ($t_{r,h}, t_{r,v}$) were assumed as 10% for both horizontal and vertical tails.

Finally, the landing gear mass is estimated using the 'USAF method for landing gear mass estimation' [24]. This method is valid for a maximum cruise speed of 300 kts and provides mass estimates of both the nose and main landing gears.

$$m_{lg} = 0.054 l_{s,mlg}^{0.501} (m \eta_{ult})^{0.684} \quad (21)$$

3. Estimating the propulsion system mass

The propulsion system consists of electric motors and propellers. The motors are sized to the maximum instantaneous power requirement for the entire mission. This is usually in the climb phase as this is the phase where the power is required to overcome gravity. For this method, a power density regression model (Figure 4) is developed from available data on DC electric motors [7].

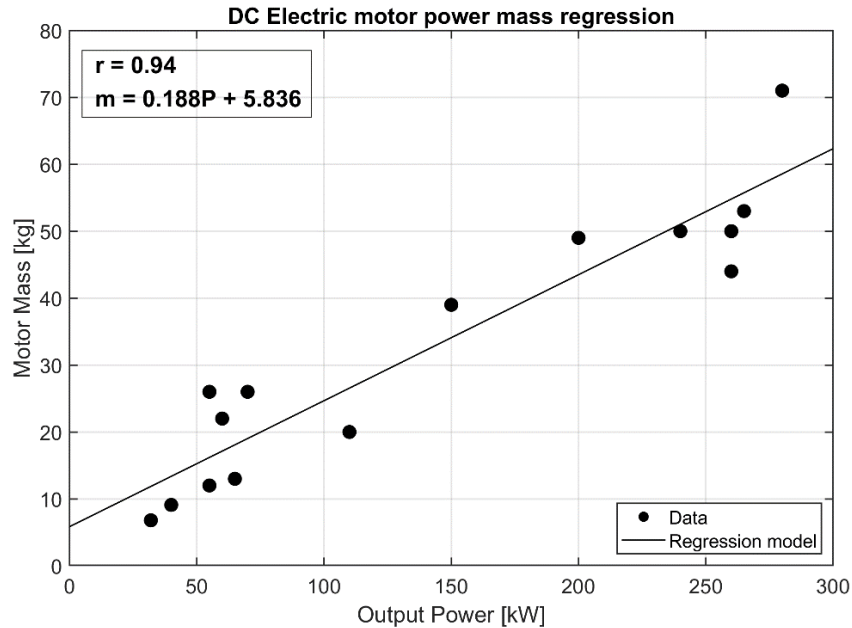


Figure 4. DC electric motor power density regression

Using a power density regression on DC electric motors (Figure 4), the motor mass (m_{motor}) can be represented as

$$m_{motor} = \frac{0.188 P_{climb} + 5.836}{N_{motors}} \quad (22)$$

If possible, the propeller mass should be obtained directly from manufacturer data. However, in the case where a propeller size is not yet known, then the propeller mass can be estimated using the 'Torenbeek propeller mass estimation' [24, 26]. This method is valid for motor shaft powers under 1100 kW.

$$m_{prop} = 0.144 \left(d \frac{P_{climb}}{N_{props}} N_{bl}^{0.5} \right)^{0.782} \quad (23)$$

B. Sizing Process

The equations governing the overall aircraft mass estimation are now defined. It is, however, not possible to obtain an exact solution to the sizing problem analytically. Thus, the numerical bisection method is employed to solve this forward-looking problem iteratively and predict the final mass estimate of the eVTOL aircraft based on the component mass estimations carried out in the previous sub-section. Given that the component masses in Eqn (3) have now been defined, the total aircraft mass defined in Eqn (1) can thus be rearranged to satisfy the fixed-point theorem such that

$$g(m) = f(m) - m \quad (24)$$

The fixed-point theorem implies that a value of m exists where

$$g(m) = f(m) - m = 0 \quad (25)$$

Thus, the solution is achieved. The bisection method is employed to find an approximate solution numerically where the total mass value (m) is obtained within the limits of the analytical solution, a set tolerance.

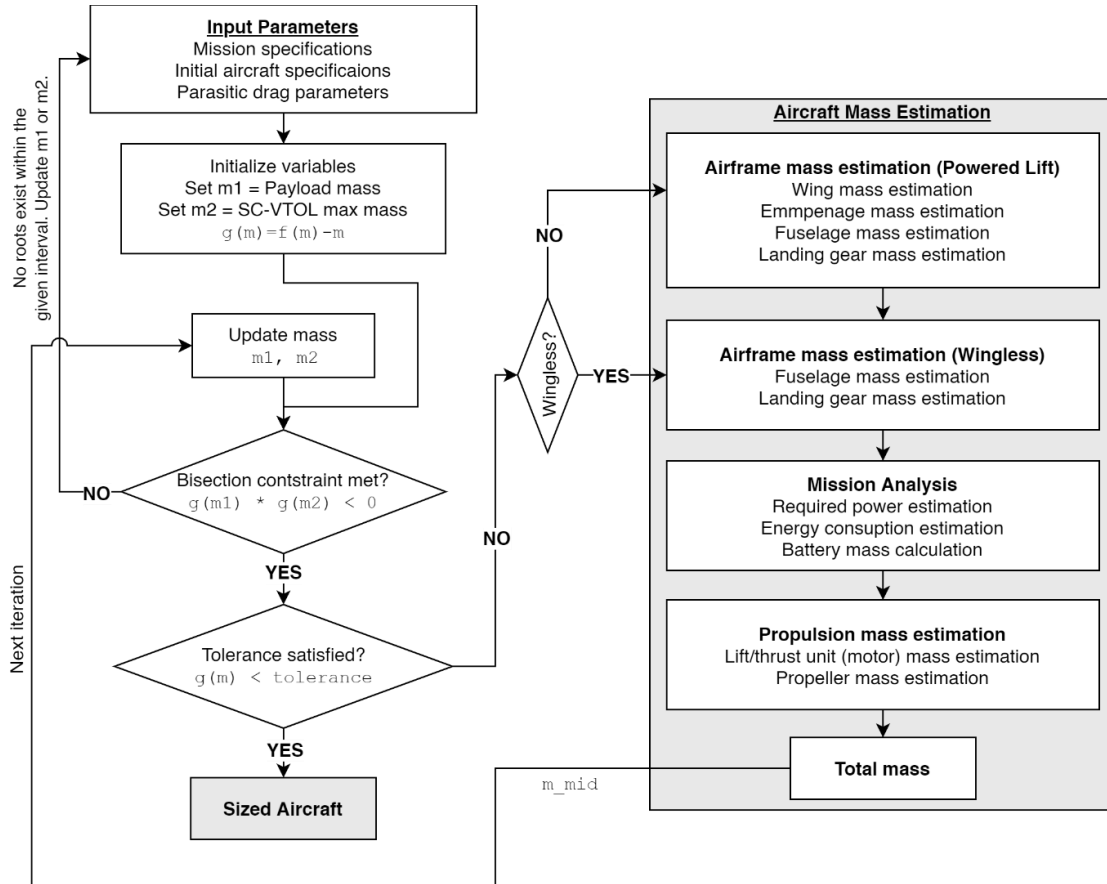


Figure 5. eVTOL Mission-based sizing process

In Figure 5, two initial guesses to the final mass are made (m_1, m_2). Such that they satisfy the condition

$$g(m_1) \times g(m_2) < 0 \quad (26)$$

Thus placing the eventual solution within the bounds of m_1 and m_2 . The interval is halved (bisected), and the new midpoint (m_{mid}) is reevaluated to satisfy the bisection condition at both the upper and lower bounds. Only one of these will satisfy the condition. Thus, m_{mid} replaces the previous bound. This process is carried out iteratively until m_{mid} approaches the analytical solution at a set level of tolerance. In each iteration, a configuration-dependent mass estimation process is carried out on m_{mid} and stored. The values obtained at the last successful iteration are the sized aircraft parameters.

III. Results

A sizing study was carried out on reference designs for both a powered lift and a wingless eVTOL. First, a mission profile was defined for the case study (Table 3). This mission profile was adapted from Uber[20] and Brown[27]. A mission range requirement of 100 km was specified. With a specified battery specific energy density (E^*) of 250 Wh/kg, both eVTOL types can be realistically evaluated for their comparative mission efficiencies. This is representative of typical UAM missions being planned. This allows for an investigation on the limits for the battery-powered eVTOL aircraft, especially the wingless eVTOL. A mission payload (m_{pl}) of 400 kg (3 passengers + 1 pilot) was specified, which is also typical for UAM missions.

Table 3. Case study mission profile for a typical UAM flight, adapted from Uber[20] and Brown[27]

Mission Phase	Duration (min)	Horizontal Speed (km/h)	Distance (km)	Vertical Speed (ft/min)	Ending Altitude (ft)
Takeoff Hover	0.17	0	0	0	5
Climb	2	0	0	500	1000
Cruise	25	240	100	0	1000
Descent	2	0	0	-500	5
Landing Hover	0.17	0	0	0	0

3D models of both the powered lift and wingless eVTOLs were created in OpenVSP for parasitic drag analysis, which was used to refine the drag model using in the sizing process. Both designs feature the exact same fuselage body to enable a fair comparison. A convergence check was performed for both sized aircraft. The sizing process converged to the same result for the range of initial guesses provided. However, a solution is achieved significantly faster for initial guesses closer to the final result.

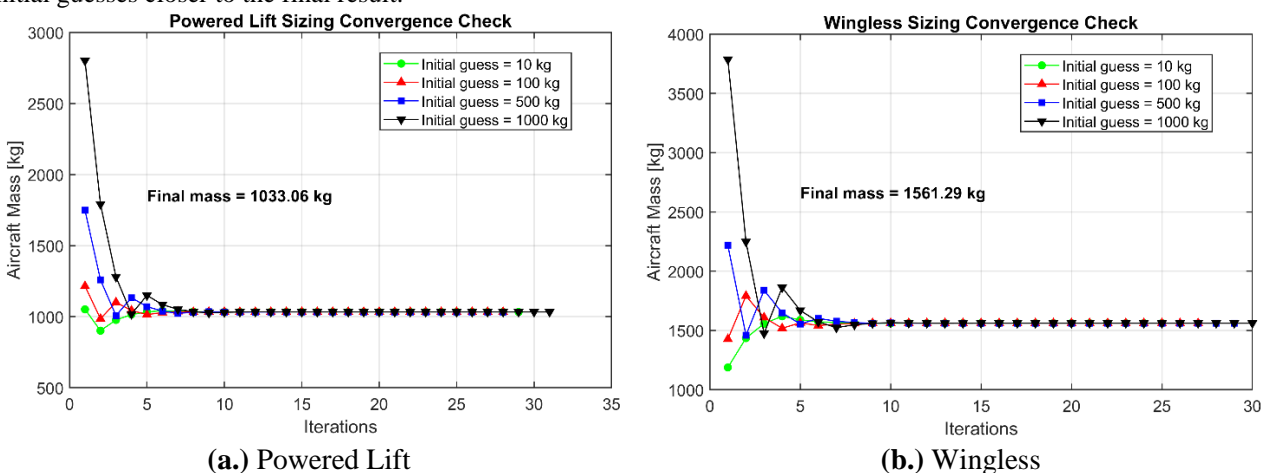


Figure 6. Convergence checks for both sizing results

Table 4 shows the results obtained from the sizing study for both the powered lift and wingless type. The final total mass difference can be observed. As expected, the lack of a wing significantly affects the cruise efficiency of the wingless type despite 36% in weight savings on the aircraft structure. The propulsion system and battery masses scale with the overall aircraft mass. Therefore, higher masses for the wingless type are expected. It is observed that the powered lift aircraft structures mass is significantly higher (35%) despite the wingless type being 33% heavier overall.

Table 4. Mass breakdown for powered lift and wingless types

Parameter	Powered Lift (kg)	Wingless (kg)
Fuselage mass	161.66	171.57
Wing mass	65.82	0.00
Horizontal stabilizer mass	14.55	0.00
Vertical stabilizer mass	1.93	0.00
Landing gear mass	13.69	18.16
Structures mass	257.65	189.73
Propulsion mass	88.29	123.42
Battery mass	287.12	848.13
Empty mass	633.06	1161.29
Payload	400.00	400.00
Total mass	1033.06	1561.29

Figure 7 provides a clearer picture of the mass fractions for the major systems. The payload fractions are the most significant metrics. Higher payload fractions signify better efficiency in carrying out the given mission. The powered lift type dedicates 39% of its total mass to a useful payload.

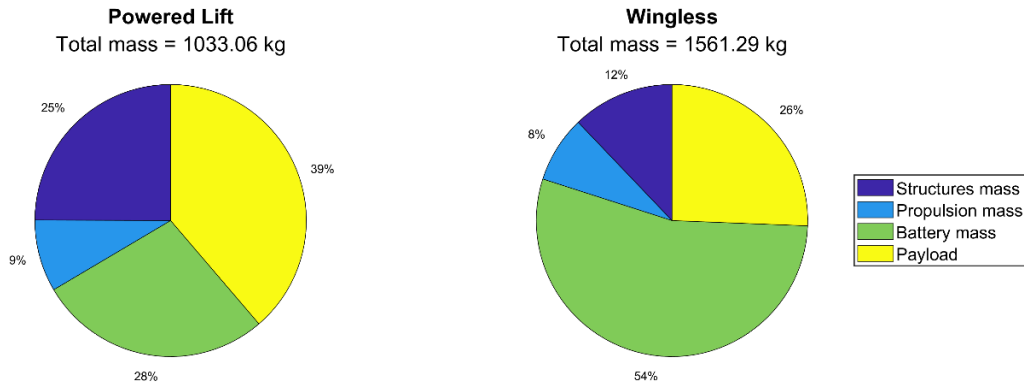


Figure 7. Mass breakdown fractions compared for powered lift and wingless types

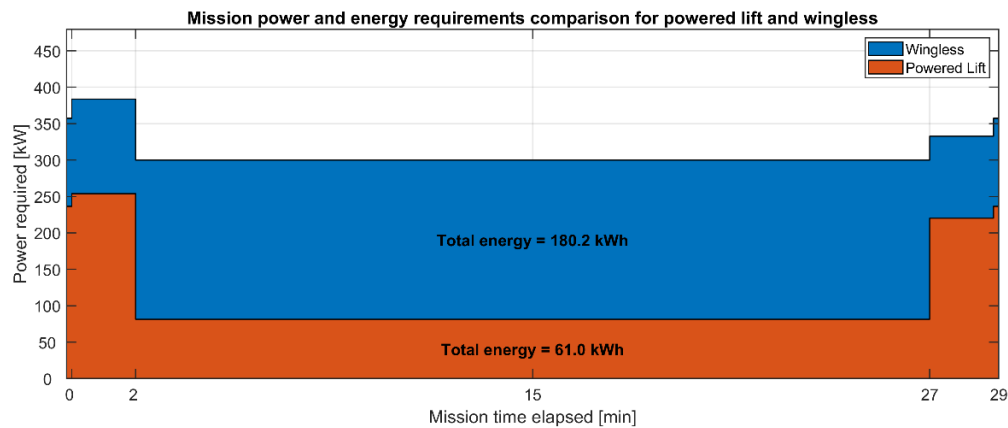


Figure 8. A comparison of power requirements and energy consumption for the given mission

A comparison of energy consumption is presented in Figure 8. In the cruise mission phase, the energy consumption for the wingless eVTOL type is three times greater than that of the powered lift aircraft. The power required in the vertical flight scaled with the overall aircraft mass even though both types used the same power modelling for vertical flight. A range sensitivity study was carried out to investigate the comparative advantages of both types. Energy consumption and power required scale exponentially with increasing range. These effects are by far more pronounced on the wingless type. For intra-city missions up to about 30 km, the difference in energy consumption is insignificant. However, as the mission range increases, the aerodynamic efficiencies of the powered lift type become more apparent. Due to the simpler architecture of the wingless type, for mission ranges, 30 km and below, the total mass of the wingless type becomes increasingly less than that of the powered lift type. However, its energy consumption still remains above the powered lift type. For ultra-short missions of 10km or less, the wingless eVTOL becomes a more efficient choice.

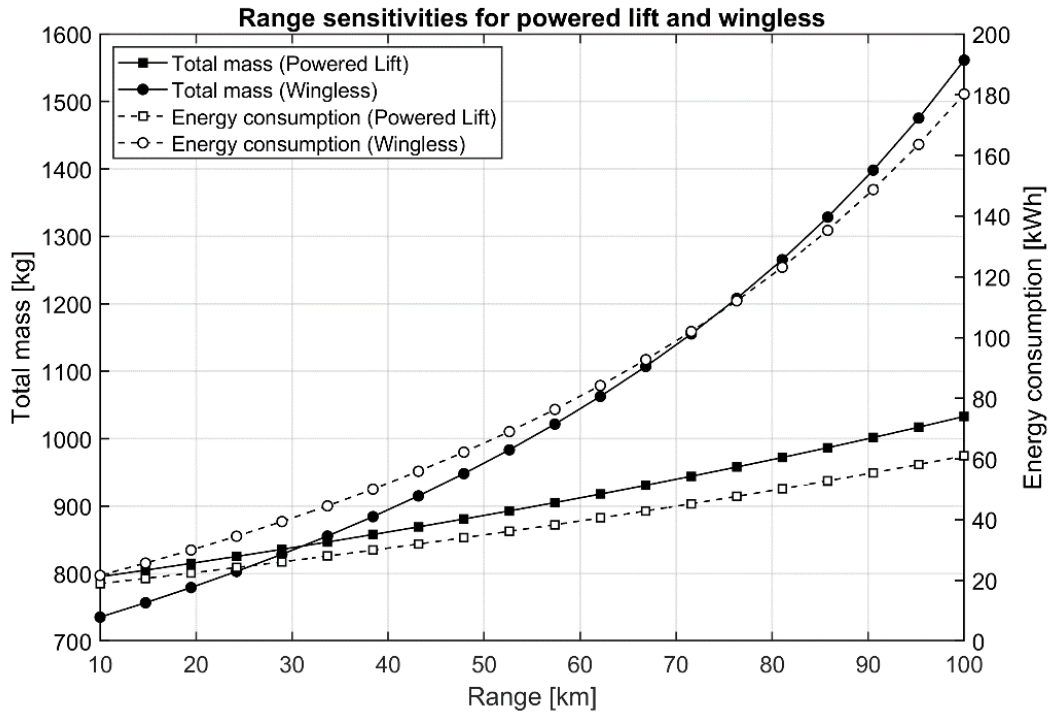


Figure 9. Range sensitivities for the powered lift and wingless types

IV. Conclusion

The initial results for the powered lift and wingless configuration serve as a proof-of-concept for the proposed mass estimation and sizing method. This presented work offers a hybrid technique for component mass estimation for battery-powered eVTOL aircraft. This is then followed by the development of an iterative sizing process to achieve the final aircraft mass. For a given payload of four occupants (400 kg) and defined mission specification, the component masses and final aircraft masses required for both the powered lift and wingless configurations are rapidly estimated. A range sensitivity study showed that for ultra-short missions of 10 km or less, the wingless aircraft becomes more efficient in energy consumption due to its simpler and ultimately lighter airframe structure sized for the given mission.

The methods presented in this paper are drawn from established design synthesis of conventional fixed-wing and rotary-wing aircraft and can serve as a stop-gap for sizing battery-powered eVTOL aircraft until widespread adoption is achieved, ultimately leading to better availability of eVTOL aircraft performance data. Further work will investigate the comparative mass sensitivities of the eVTOL configurations to other mission parameters such as payload, cruise speed and manoeuvrability.

References

- [1] The Electric VTOL News. "eVTOL Aircraft Directory." Vol. 2020, Vertical Flight Society, 2020.
- [2] Bromfield, M. A. "Urban Air Mobility," *Future Transport Conference, Chartered Institute for Ergonomics and Human Factors*. Birmingham, UK, 2018.
- [3] EASA. "Special Condition for Small-category Vertical Take-Off and Landing (VTOL) Aircraft." Vol. SC-VTOL-01, European Aviation Safety Agency, Brussels, 2019.
- [4] Bacchini, A., and Cestino, E. "Electric VTOL Configurations Comparison," *Aerospace* Vol. 6, No. 3, 2019, p. 26.
- [5] Doo, J. T., Pavel, M. D., Didey, A., Hange, C., Diller, N. P., Tsairides, M. A., Smith, M., Bennet, E., Bromfield, M., and Mooberry, J. "NASA Electric Vertical Takeoff and Landing (eVTOL) Aircraft Technology for Public Services – A White Paper," *NASA Transformative Vertical Flight Working Group 4 (TVF4)*. National Aeronautics and Space Administration, Washington, D.C., 2021.
- [6] Innocente, M. S., and Grasso, P. "Self-organising swarms of firefighting drones: Harnessing the power of collective intelligence in decentralised multi-robot systems," *Journal of Computational Science* Vol. 34, 2019, pp. 80-101. <https://doi.org/10.1016/j.jocs.2019.04.009>
- [7] Hascaryo, R. W., and Merret, J. M. "Configuration-Independent Initial Sizing Method for UAM/eVTOL Vehicles," *AIAA AVIATION 2020 FORUM*.
- [8] Kamal, A. M. R.-S., Alex,;. "Design methodology for hybrid (VTOL + Fixed Wing) unmanned aerial vehicles," *Aeron Aero Open Access J* Vol. 2, No. 3, 2018, pp. 165-176. <https://doi.org/10.15406/aaaj.2018.02.00047>
- [9] Barra, F., Capone, P., and Guglieri, G. "A Methodology for Preliminary Performance Estimation of a Hybrid-Electric Tilt-Wing Aircraft for Emergency Medical Services," *2020 International Conference on Unmanned Aircraft Systems (ICUAS)*. 2020, pp. 1636-1643.
- [10] Finger, D. F., Bil, C., and Braun, C. "Initial Sizing Methodology for Hybrid-Electric General Aviation Aircraft," *Journal of Aircraft* Vol. 57, No. 2, 2020, pp. 245-255. <https://doi.org/10.2514/1.C035428>
- [11] Vries, R. d., Brown, M. T., and Vos, R. "A Preliminary Sizing Method for Hybrid-Electric Aircraft Including Aero-Propulsive Interaction Effects," *2018 Aviation Technology, Integration, and Operations Conference*.
- [12] Yu, X., Sandhu, N. S., Yang, Z., and Zheng, M. "Suitability of energy sources for automotive application – A review," *Applied Energy* Vol. 271, 2020, p. 115169. <https://doi.org/10.1016/j.apenergy.2020.115169>
- [13] Yin, F., Jin, Q., Gao, H., Zhang, X., and Zhang, Z. "A strategy to achieve high loading and high energy density Li-S batteries," *Journal of Energy Chemistry* Vol. 53, 2021, pp. 340-346. <https://doi.org/10.1016/j.jechem.2020.05.014>
- [14] Roskam, J. *Airplane Design - Part I: Preliminary Sizing of Airplanes*. Lawrence, Kansas: Analysis and Research Corporation, 2005.
- [15] Gudmundsson, S. *General Aviation Aircraft Design : Applied Methods and Procedures*. Oxford: Elsevier Inc., 2014.
- [16] Raymer, D. P. *Aircraft Design: A Conceptual Approach*. Reston, Virginia: American Institute of Aeronautics and Astronautics, Inc., 2006.
- [17] Newman, S. *The foundations of helicopter flight*. Oxford; Burlington, Mass.: Butterworth Heinemann, 2003.
- [18] Johnson, W. *Helicopter Theory*. New York: Dover Publications, Inc, 1980.
- [19] Leishman, J. G. *Principles of Helicopter Aerodynamics*. New York: Cambridge University Press, 2006.
- [20] Uber Elevate. "Uber Elevate Mission and Vehicle Requirements." Vol. 2018, 2018.
- [21] NASA. "OpenVSP." Vol. 2021, 2021.
- [22] Hepperle, M. *Electric Flight - Potential and Limitations*, 2012.
- [23] Zhao, S., Guo, Z., Yan, K., Wan, S., He, F., Sun, B., and Wang, G. "Towards high-energy-density lithium-ion batteries: Strategies for developing high-capacity lithium-rich cathode materials," *Energy Storage Materials* Vol. 34, 2021, pp. 716-734. <https://doi.org/10.1016/j.ensm.2020.11.008>
- [24] Roskam, J. *Airplane Design - Part V: Component Weight Estimation*. Lawrence, Kansas: Analysis and Research Corporation, 2003.
- [25] Sholz, D. "Empennage sizing with the tail volume complemented with a method for dorsal fin layout," *INCAS Bulletin* Vol. 13, No. 3, 2021, pp. 149-164. <https://doi.org/10.13111/2066-8201.2021.13.3.13>
- [26] Torenbeek, E. *Synthesis of Subsonic Airplane Design*. Dordrecht: Springer, 1982.
- [27] Brown, A., and Harris, W. "A Vehicle Design and Optimization Model for On-Demand Aviation," *2018 AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*.