Generic eVTOL Aircraft Preliminary Sizing Method for AAM/UAM Missions

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Abstract. Advanced Air Mobility (AAM) or Urban Air Mobility (UAM) presents many challenges to the aircraft design. The concept not only requires operations over urban airspace but also without the use of traditional airports with long runways. Additionally, the new aircraft designs must do so on electric power as much as possible with low chemical and noise emissions. Hence the term electric vertical takeoff and landing or eVTOL is popularized. This paper presents a novel method for preliminary sizing of eVTOL aircraft of arbitrary architecture. The methodology allows the conceptual analysis and initial trade-off studies independent of the aircraft configuration. Aircraft is considered as the sum of building blocks like rotors, propellers, wings, and several other subsystems contributing to mass, energy, power and drag estimates. Results from this study permit a quick evaluation of configurations and missions with an inevitable degree of approximation. Finally, the main features of the method are discussed in the paper with a relevant validation exercise for various eVTOL aircraft considering mass and other performance metrics.

1. INTRODUCTION

Aircraft have traditionally been used to bridge longer distances with higher speeds as compared to the ground transportation means. But now, under the broad umbrella of Advanced Air Mobility (AAM), innovative concepts are being proposed to operate in and connect urban, suburban and rural areas with either a scheduled or on-demand service [1]. Typical operational ranges are below 500 km and a subset term, Urban Air Mobility (UAM), deals with ranges of up to and around 100 km [1,2]. The new aircraft designs are envisaged to operate by exploiting smaller airstrips, helipads and vertiports, on electric power as much as possible, thus lowering the chemical and noise emissions. Moreover, the objective behind the use of this disruptive transformation is to avoid traffic congestion on roads, save time spent on daily commutes and to relieve the crowded ground transportation system. The addition of third dimension in transport system aims to bring a paradigm shift in a manner similar to the high-rise buildings, which exploit the vertical space in urban centres.

While traditional aircraft designs rely on historical regressions for initial takeoff mass, power, energy, and sizing estimates, these new concepts cannot fully benefit from such data for two main reasons. Firstly, there are not many operational examples of these aircraft in service and, secondly, many eVTOLs are under development and manufacturers maintain a certain degree of confidentiality [2,3].

Apart from the obvious benefits, AAM also presents many challenges spanning from aerial vehicle design to supporting infrastructure and from operations, regulations to integration and acceptance [4].

This paper tackles the fundamental problem of eVTOL vehicle initial design, including preliminary sizing, under the specific set of requirements applicable to AAM/UAM missions. Although modern helicopters partially fulfil similar requirements, they are considered too expensive, noisy, and polluting for the purposes of AAM [4]. There are, however, several other configurations for VTOL operations. These include vectored thrust and independent thrust designs for fixed-wing aircraft and multicopters in a wingless configuration, plus a wide range of concepts that mix the two approaches to lift generation. Vectored thrust is a more general term used for the aircraft like V22 Osprey or Sea Harrier which can use proprotors or jet exhaust for vertical lift and also for cruise phase simply by tilting the engines or entire wing with engines to 90 degrees. UAM examples of this design include Joby Aviation S4, Lilium Jet, Rolls-Royce EVTOL and Airbus Vahana [5]. On the other hand, independent thrust designs (also known as lift + cruise) rely on separate sets of propellers for vertical and for cruise flight phases. Wisk Aero Cora, Aurora PAV, EHang VT-30 and Pipistrel Nuuva V300 are examples of this design [5]. Wingless designs employ a number of rotors which are used for both vertical and forward flight by controlling the rotation speed and collective pitch of different sets of rotors for example EHang 216, CityAirbus, Kitty Hawk Flyer and Volocopter VoloCity are examples of this approach [5].

There are several pros and cons of these basic configurations of eVTOL aircraft depending on the type of sizing mission and given the current state of the art of battery and propulsion technologies. Several approaches have been considered to size specific types of eVTOL configurations, but a general methodology which could be used for any type of the configuration is still missing from the contemporary academic literature [4,6]. Although, methods applicable to a specific type or class of eVTOL aircraft do exist but these methods depend on additional tools for certain parameter calculation [3,7,8]. Hence these semi-autonomous methods require man-in-loop approach and cannot be adopted in an automated workflow scheme.

This paper presents the development of a methodology to predict takeoff weight and the corresponding weight breakdown, approximate size, power, and energy requirement for an eVTOL. This allows the conceptual analysis and initial trade-off studies independently from a specific, a-priori choice of the aircraft configuration. The aircraft is considered as the sum of building blocks such as rotors, propellers, wings, and several other subsystems contributing to the mass, energy, power and drag estimates. Thus, the method allows considering a wide range of vehicle architectures, while keeping the number of input data limited to the few parameters available in the conceptual design phase. Subsequently, the methodology is used to run various case studies to compare and contrast AAM missions, eVTOL configurations and their sensitivity to multiple technological parameters.

2. METHODOLOGY

This section presents the methodology which is a bottom-up procedure that consists of modelling the aircraft as an ensemble of objects or building blocks (BB), namely: Rotor(s), Propeller(s), Engine(s), Payload, Fuselage, Wings, Batteries, Landing Gear, and Subsystems. These objects, with their inherent weight, are addressing a specific function which is either producing or consuming power. Each Object possesses a set of input and output parameters, that are calculated with flight mechanics relations, statistical regressions, or technological assumptions. Figure 1 shows the process of individual sizing these objects or building blocks (BB) based on the performance requirements. The type of sizing method used to size these BBs is a combination of conventional fixed wing and rotorcraft sizing methods adopted, enhanced, and modified for eVTOL aircraft. The method has the flexibility to deal with very different configurations through many combinations of these objects, since it is possible to arbitrarily select the number of rotors, propellers, and tilting elements.

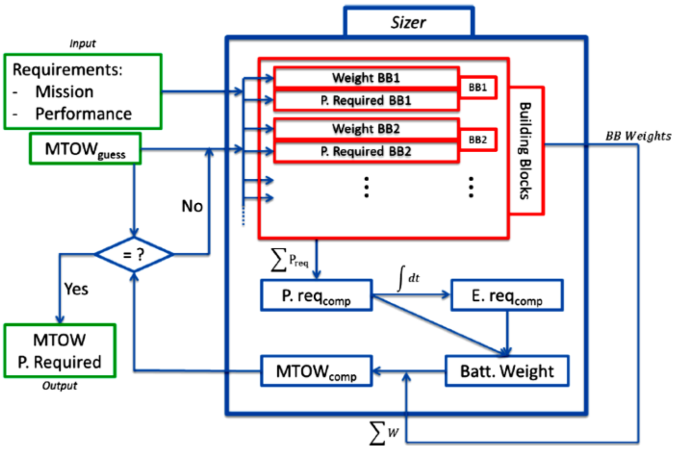

Figure 1: Component mass sizing and convergence cycle

Although, this approach considers a high degree of approximation in the start, but the results are sufficiently accurate for the preliminary phase of a conceptual design activity. Subsequently, this will be evident in a preliminary design validation exercise. Through this approach, it is possible to derive a complete weight breakdown structure for an eVTOL vehicle, its maximum installed power, its power required curve, and a few other basic parameters. This is obtained by starting with a limited number of input parameters drawn from the mission requirements, together with the following broad configuration and design choices or inputs, for example:

1. Number of wings if any.
2. Number of lifting rotors for takeoff.
3. Number of thrusting propellers for cruise.
4. Number of tilting rotors/propellers.
5. The percentage of lift provided by rotors, wings, and tilting propellers.

The complete list of input parameters is written to incorporate all possible innovative configurations which are currently under development. At this stage, no information is necessary on the actual geometry and general arrangement of the vehicle. Therefore, specifying the actual location of the rotors and wings, the shape of the fuselage and aerodynamic surfaces, and other configuration details is not needed. Figure 2 shows a broad overview of the sizing method in terms of inputs and outputs.

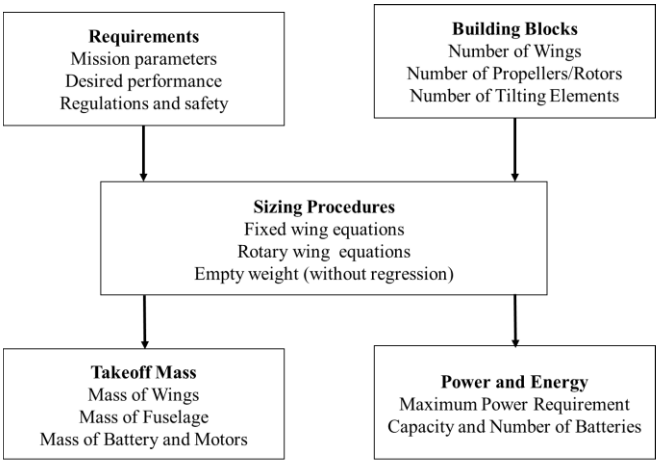

Figure 2: Broad overview of the methodology

2.1. Requirements and Sizing Mission

The general sizing mission profile is based on five flight phases. These phases include vertical take-off, transition to cruise, cruise phase, transition from cruise and vertical landing. The duration for both transition after take-off and before landing is assumed to be one minute each, while for the other phases it depends on the operational characteristics of the eVTOL aircraft under consideration. For compound and transformative configurations, two fundamental operational modes may be defined: "helicopter mode", which applies to vertical terminal phases and low-speed manoeuvring, and 'airplane mode', which applies to cruise. Although for these types, the details of transition phases are not general and clearly depend on the specific way devised to pass from helicopter to airplane mode and vice versa. But considering this transition to be happening in a fixed amount of time eliminates some complexity at this early stage of design.

Specific mission profile depends on the sizing mode being considered. The validation exercise, for example, considers the mission profile of the aircraft under study. On the other hand, when various configuration types are being compared, then Uber sizing mission is used as a baseline.

2.2. Structural and Component Masses

In the absence of historical regressions for empty mass calculations, an alternate rigorous approach is followed. In this approach, empty mass is estimated by carefully considering the constituent parts at a sufficient level of detail. Then the summation of empty mass and payload provides an estimate of total mass at takeoff. Unlike conventionally powered aircraft, no separate fuel mass fraction is considered but instead battery mass is included in the empty mass (M_e). Therefore, another parameter is defined as equivalent empty mass (M_{ee}). It is important to distinguish between these two parameters because in a conventionally powered aircraft empty mass is the structural mass. Equations 1 and 2 below clarify this difference.

$$M_e = M_{TO} - M_{PL} \tag{1}$$

$$M_{ee} = M_{TO} - M_{PL} - M_b \tag{2}$$

Here M_{PL} and M_b refers to payload mass and batter mass respectively. On a broad scale, empty mass for eVTOL aircraft consist of lift and power producing elements, fuselage and support structure, energy storage and conversion elements. Table 1 lists the further division of these elements along with references to size these components.

Table 1: Component Classification and references for sizing

Lift and Power Producing Elements [9–13]	**Fuselage and Support Structure** [11,14,15]	**Energy Storage and Conversion** [16,17]
Wings	Fuselage	Battery
Rotors	Tail Section	Electric Motors
Co-axial Rotors	Ducts	Cooling System
Ducted Fans	Nacelles	Actuators
Internal Combustion Engines	Flight Control	
	Landing Gear	

2.3. Power and Energy Estimates

Power and energy estimation process is split into three distinct phases based on vertical, transition and horizontal flight modes. Mass and power calculations are implicitly interconnected and require an iterative sizing loop. For the vertical flight phase, modified momentum theory is implemented to calculate the power required. This accounts for a pressure jump across the rotor disc to overcome the vehicle mass and to accelerate it to the transition height. The transition phase from vertical to horizontal or vice versa can be achieved through a number of configuration designs as discussed in the introduction.

In order to capture the effect of these individual designs in a unified framework, a contribution parameter is associated for every building block of the aircraft.

For example, consider Wisk Cora in a cruise flight and notice that the vertical thrust producing propellers are off and produce zero thrust in this phase. The entire mass of aircraft is supported by the aerodynamic lift created by the wings only. On the contrary, during a vertical ascent or descent, wings are not producing any lift and the vertical thrust producing propellers are supporting the mass of the aircraft. These contribution parameters (labelled as k_{lw} and k_{lp}) take values between 0 and 1 as defined by the user in the input file depending on the particular configuration. During the transition phases, these values indicate a lift split between the various elements of the aircraft.

3. VALIDATION AND RESULTS

Following the development of this sizing method (eVTOL code) and a test convergence of iterative procedure, it is important to benchmark or validate the results against the existing aircraft in this category. Although eVTOL aircraft are still a niche segment in aviation industry and not a lot of fully operational aircraft could be traced, but there exist a number of prototypes in the advance stages of development or in early production runs. A survey of such aircraft is conducted and a list these aircraft is compiled for a validation exercise. The list includes all major configuration types from tiltrotor/tilt-wings to lift-plus-cruise, multirotors and electric helicopter as presented in Table 2. The mass estimation methodology implemented in eVTOL code produces good results ranging from 2 to 8 percent of published takeoff mass of various aircraft as shown in Table 2.

Table 2: Results of Validation exercise

Aircraft	Published takeoff mass (kg)	Takeoff mass from the code (kg)	Percentage Difference
Wisk Cora	1224	1269	3.6
Joby S4	1814	1961	8.1
EHang 184	360	382	6.1
Vahana Alpha	726	711	2.0
Moog Surefly	680	647	4.8
Sikorsky Firefly	930	912	1.9

The next logical step in validation exercise is to compare the component wise mass of each eVTOL aircraft but for reason stated in the introduction such data is not readily available. Nevertheless, some component data for some of the aircraft is available. Therefore, a comparison of battery mass in table 3 for selected examples with available data points. The difference between actual and the estimated battery mass ranges from 3 to 13 percent. This is an indicator that the technological assumptions about the battery technology are matching because in most cases battery specific mass and power are not mentioned in the specification sheets.

Table 3: Comparison of battery mass

Aircraft	Published battery mass (kg)	Battery mass from the code (kg)	Percentage Difference
EHang 184	85	96	12.9
Moog Surefly	48	50	4.2
Tier 1 R44	498	484	2.8

The results from table 2 and 3 indicate the effectiveness of this method to estimate maximum takeoff mass and other component masses especially battery mass. As discussed earlier, the code works by estimating the power, energy, and component mass requirement for every phase of the flight and then sums up the total mass. Figure 3 shows the mass breakdown of Wisk Cora for each phase of flight and then at the end all the component masses are added to get the last column showing the maximum takeoff mass (MTOM). The MTOM for this aircraft 1224 kg and the last column shows a value of 1269 which is about 4% variation. In the first bar of Figure 3 the calculated wing mass is zero and this is because during this phase a vertical takeoff is performed with the need of fixed wings. During the transition phase, which is the second bar in Figure 3, wings partially provide the lift depending on the k_{lw} parameter defined in the previous section and the rest of the lift is generated by the set of 12 lift rotors. Similarly, during the cruise phase the rotor mass remains fixed as this is a lift-plus-cruise configuration and the mass of motor calculated in this phase is only for the pusher propeller for the forward flight. The final mass of motors in the last column is the combination of vertical lifting motors and the motor required for the forward flight.

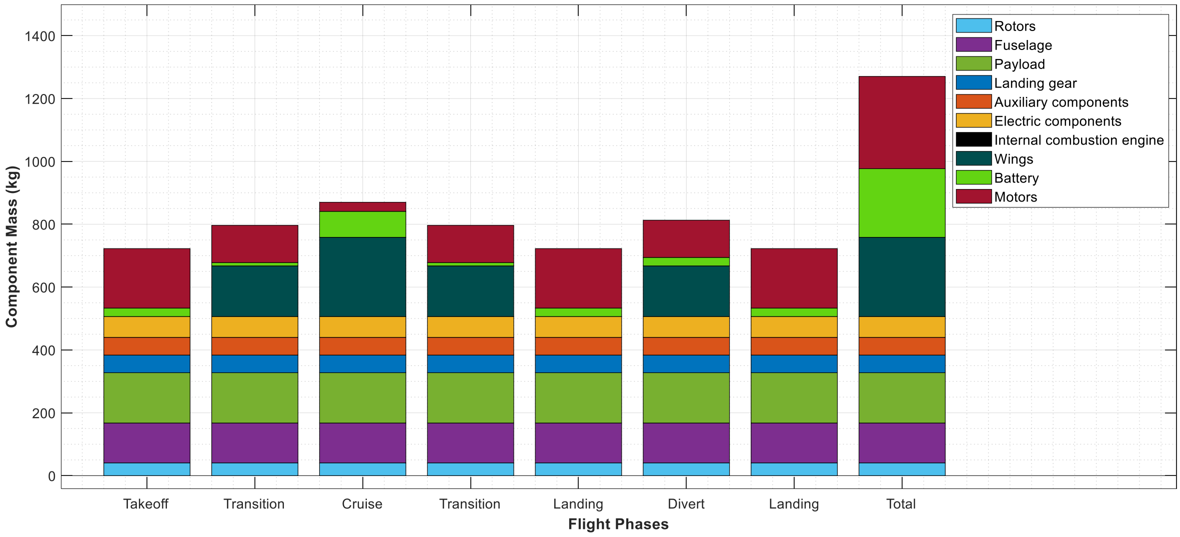

Figure 3: Component wise mass breakdown of Wisk Cora for each flight phase.

The next case study is Joby S4 which is essentially a tiltrotor by design with six tilting rotors. This study, as shown in Figure 4, presents a slightly different mass breakdown for each phase of the flight. As the same motors are used for the vertical takeoff and the forward flight therefore, during these phases the mass of motors is not much different from each other. The mass of motors is estimated based on the electric motor regression and the power demand of the flight phase. There are certain components which remain constant during all phases, these include payload, landing gear, rotors, auxiliary and electric component masses. Finally, the MTOM of 1961 kg in the last column corresponds well to the published value of 1814 kg.

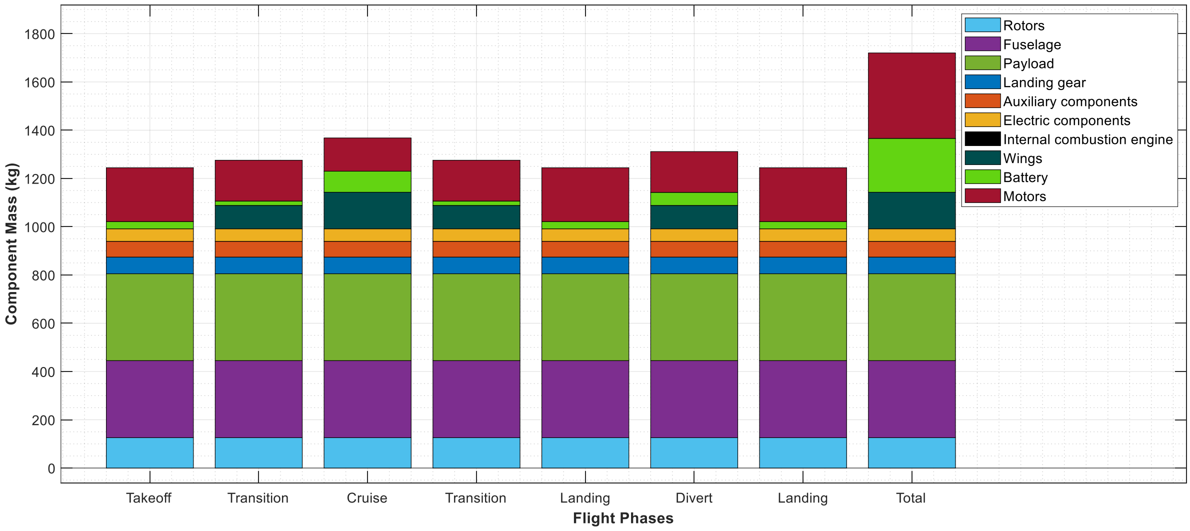

Figure 4: Component wise mass breakdown of Joby S4 for each flight phase.

4. Conclusion

The present paper described a bottom-up method to approach the preliminary sizing of an eVTOL of a general configuration, ranging from multicopters to winged vehicles, with all possible combinations of tilting propulsive elements and other options employed in transformative configurations. The proposed methodology, although capable of including a significant number of design variables, relies on relatively simple estimation procedures. Virtually arbitrary architectural topology of the vehicle can be considered, combining subsystems without substantial constraints in size and numbers. This feature, together with the inherent conceptual simplicity is clearly prone to uncertainties but allows analysing any UAM concept currently being considered.

The consistency of the method has been assessed by comparing its results with existing vehicles of known specifications, within the UAM class, yielding satisfactory results. Also, the method allows performing cost-affordable trade-off studies in order to determine the sensitivity of a design with respect to input data. Examples of this validation have been given, along with some qualitative results emerging from sensitivity analysis.

5. ACKNOWLEDGMENT

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6. REFERENCES

[1] Johnson W and Silva C 2022 NASA concept vehicles and the engineering of advanced air mobility aircraft *Aeronautical Journal* **126** 59–91

[2] Ugwueze O N, Statheros T, Horri N, Innocente M S and Bromfield M A 2022 Investigation of a Mission-based Sizing Method for Electric VTOL Aircraft Preliminary Design AIAA Science and Technology Forum and Exposition, AIAA SciTech Forum 2022

[3] Winter T F, Robinson J H, Sutton M, Chua J, Gamez A and Nascenzi T 2020 Structural Weight Prediction for an Urban Air Mobility Concept *AIAA AVIATION 2020 FORUM* AIAA AVIATION 2020 FORUM (VIRTUAL EVENT: American Institute of Aeronautics and Astronautics)

[4] Garrow L A, German B J and Leonard C E 2021 Urban air mobility: A comprehensive review and comparative analysis with autonomous and electric ground transportation for informing future research *Transportation Research Part C: Emerging Technologies* 132

[5] Anon eVTOL Aircraft Directory *Electric VTOL News*

[6] Ugwueze O, Statheros T, Horri N, Innocente M and Bromfield M 2022 Investigation of a Mission-based Sizing Method for Electric VTOL Aircraft Preliminary Design *AIAA SCITECH 2022 Forum* AIAA SCITECH 2022 Forum (San Diego, CA & Virtual: American Institute of Aeronautics and Astronautics)

[7] Hascaryo R W and Merret J M 2020 Configuration-Independent Initial Sizing Method for UAM/eVTOL Vehicles *AIAA AVIATION 2020 FORUM* AIAA AVIATION 2020 FORUM (VIRTUAL EVENT: American Institute of Aeronautics and Astronautics)

[8] Smart J T and Alonso J J 2019 Primary Weight Estimation for eVTOLs via Explicit Analysis and Surrogate Regression *AIAA Aviation 2019 Forum* AIAA Aviation 2019 Forum (Dallas, Texas: American Institute of Aeronautics and Astronautics)

[9] Gur O, Mason W and Schetz J 2010 Full-Configuration Drag Estimation *Journal of Aircraft - J AIRCRAFT* **47** 1356–67

[10] Leishman G J 2006 *Principles of Helicopter Aerodynamics with CD Extra* (Cambridge University Press)

[11] Nicolai L M and Carichner G 2010 *Fundamentals of Aircraft and Airship Design* (American Institute of Aeronautics and Astronautics)

[12] Stepniewski W Z, Shinn R A, Associates I T, Branch U S N A and S A S and T I and Laboratory A 1983 *A Comparative Study of Soviet Vs. Western Helicopters* (National Aeronautics and Space Administration, Scientific and Technical Information Branch)

[13] Schenderlein J and Clayton T Comparison of Helicopter Turboshaft Engines 14

[14] Raymer D P 2018 *Aircraft design: a conceptual approach* (Reston, VA: American Institute of Aeronautics and Astronautics, Inc)

[15] Jenkinson L R, Rhodes D and Simpkin P 1999 *Civil Jet Aircraft Design* (Arnold)

[16] Ulvestad A 2018 A Brief Review of Current Lithium Ion Battery Technology and Potential Solid State Battery Technologies

[17] Emadi A 2014 *Advanced Electric Drive Vehicles* (Taylor & Francis)