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Generating Structural Weight Estimation Equations for a Category of UAM Aircraft

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Weight estimation is an important aspect of the aircraft conceptual design process. Due to the inherent cascading and interdisciplinary effects associated with variations in vehicle structural weight, accurate weight estimation is needed. For conventional aircraft configurations, empirical and semi-empirical weight equations can be utilized during the weights buildup process. However, these equations are often not applicable to novel aircraft configurations such as urban air mobility (UAM) vehicles. Many UAM aircraft have been designed but very few have been built, and the weight statements have been kept as proprietary information. This lack of available data has prevented the wider UAM community from creating empirical-based relations for UAM structural weight prediction. In this effort, a physics-based approach for structural weight estimation has been developed for the category of Lift+Cruise UAM vehicles. Through the research of aircraft that have been designed in this category, we can determine the most common configurations. Utilizing the M4 Structures Studio (M4SS) toolset, estimates of the structural weight of these classifications of UAM can be generated. By feeding hundreds of design sets into M4 Structures Studio's parametric structural model, numerous structural analysis models can be generated and utilized for a loads-based sizing optimization. Once the structural weight is calculated for each variant, an appropriate surrogate model can be generated for the dataset. These equations can then be used during conceptual aircraft design as a weight estimate for Lift+Cruise UAM aircraft.

I. Introduction

Typically, estimating the weight of an aircraft during conceptual design relies heavily on empirical methods. In the statistical equations proposed in Raymer's book [1], each component of the aircraft has its own formulation to estimate the weight of that component, and the summation of those weights will give the full aircraft weight. These equations are based on a regression analysis of a comprehensive and historical set of available aircraft weight statements and aircraft drawings. Unfortunately, these equations are largely not applicable to urban air mobility (UAM) configurations, and no such relations exist for this new category of aircraft.

In NASA's more recent paper on the Flight Optimization System [2], they developed new weight equations that are based on aircraft data as well, but this method may be more useful for newer aircraft designs. Data from only 42 aircraft were taken for this development, but the curve fitting technique used here can more accurately predict the weight of vehicles that do not fit within their database of aircraft because this type of curve fitting is based on physical characteristics and is also optimized to fit the data more accurately. Weight equations were developed for

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"transport, fighter/attack, general aviation, and hybrid wing body (HWB)." Since UAM vehicles have unique features, like booms and lift rotors, this method still may not be very accurate for the weight prediction of these configurations.

The method described in Torenbeek's book [3] utilizes a quasi-analytical approach. This is made for weight prediction of structural elements during the conceptual design stage when the basic geometry and performance are already determined. The functional considerations, the structural layout of the aircraft, and a load case for the component were used to derive the weight estimation equations which were made more accurate by linearization using regression analysis and empirical data. These equations primarily apply to metal wings and fuselages for transport aircraft. Like NASA's Flight Optimization System, this method does not account for structural characteristics specific to UAM aircraft and therefore would not be accurate at estimating UAM weights.

Kowalski et al. utilize Torenbeek's equations alongside Finite Element Model (FEM) analysis to generate weight estimations for the propulsive fuselage concept (PFC) [4]. The methodology proposed here is more accurate than only using empirical equations for estimating aircraft weight in the conceptual design stage. It is also more useful when unconventional structures are being used since empirical equations work only with structures that fit within their database. We will expand greatly on this idea of using finite element models to estimate aircraft weight in our research. We will generate hundreds of models to establish a database of weights that can be used to estimate the weight of other similar vehicles without going through the process of building the full FEM.

Most of the methods mentioned above utilize weight information that is available on several aircraft. Unfortunately, there is not much weight information available on UAM aircraft because it is a newer type of vehicle, and most are still in the design or testing phase. Therefore, the weight of these aircraft in conceptual design needs to be estimated using a different method until sufficient empirical data is available. The physics-based method to estimate the weight is an alternative when empirical data is unavailable, but it requires more detailed information about the aircraft and can be labor and time-intensive. In this study, we will generate our own simulated dataset of aircraft weight for several variations of some of the most common configurations of Lift+Cruise UAM aircraft using M4 Structures Studio (M4SS) which is a parameterized structural modeling tool that utilizes a physics-based approach to optimize aircraft structural weight. Finally, this data will be fitted to a polynomial that can be used to quickly estimate the weight of a Lift+Cruise UAM aircraft.

II. Methodology

A. Categorization of Urban Air Mobility

To determine the most common UAM Lift+Cruise configurations, we gathered information on as many electric vertical takeoff and landing (eVTOL) vehicles as possible. Our data set will be based on eVTOL vehicles since UAM aims to make air transportation in urban and suburban areas more convenient. Because VTOLs can land and take off from virtually anywhere, it makes it ideal for urban and suburban areas where not much land is available. Conveniently, the Vertical Flight Society publishes an up-to-date directory of all eVTOL aircraft around the world that have been designed and shared with the public [5]. There are over 700 aircraft listed on the site and they are primarily categorized by their thrust mechanisms. The categories are Vectored Thrust, Lift+Cruise, Wingless (Multicopter), Hover Bikes/Personal Flying Devices, and Electric Rotorcraft. This effort is focused on the Lift+Cruise category which defines eVTOLs that have rotors that are used only for hover and rotors that are used only for forward thrust. Therefore, this study does not encompass information on aircraft with a tiltwing or tiltrotor which have rotors that are used for both hover and forward thrust. The vectored thrust configurations may be very similar to those in Lift+Cruise, but in this study, we did not account for the extra mechanical weight that may be needed to allow for thrust vectoring.

When researching the Lift+Cruise proposed concepts, we noted features that would most likely impact the structural weight of the aircraft significantly. One of the attributes that we included was the number of rotors for hover and cruise and whether they are ducted. The number of booms was an important component that is common for eVTOL aircraft as in many cases, the booms provide structure to hold the propellers. Many of the concepts utilized canards or tandem wings rather than the typical main wing and empennage. The information that we collected was organized into a spreadsheet but we also laid out images of the aircraft from the database so we could more easily distinguish similar characteristics between the vehicles.

B. Process Overview for Generation of Weight Data

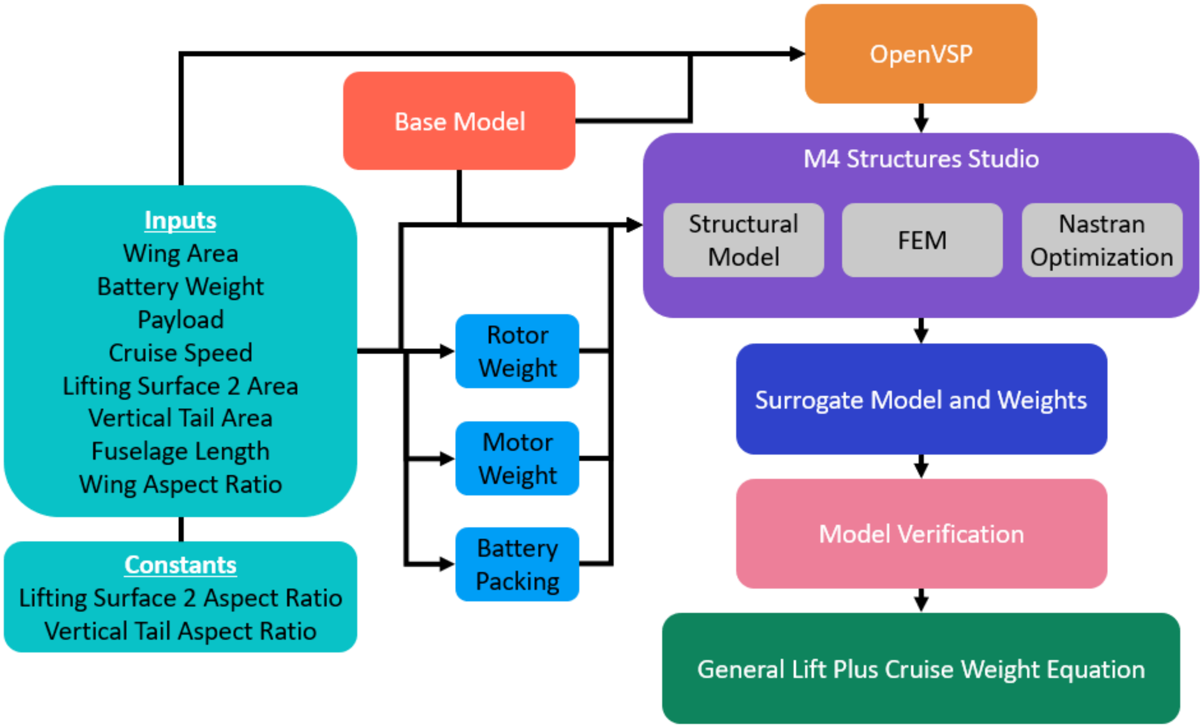

Figure 1: Overview of the process for obtaining weights for many design variants.

An automated process was developed to generate simulated weight data. There are several parameter inputs that are required to build the structural models, and hundreds of these parameter input sets are generated using the Latin hypercube sampling method [6]. A base model is first created for each category of UAM. For this base model, an outer model line (OML) was built up in OpenVSP. It is then loaded into M4 Structures Studio where the structural layout, material properties, nonstructural masses, and load cases are defined. For each of the generated input parameter sets, aspects such as geometry sizing in the base OpenVSP model are updated. This OpenVSP model will then be loaded into the base parameterized structural model in M4SS where the nonstructural masses are updated and flight conditions are changed for the load cases according to the generated input parameters. In M4SS, the FEMs are created and then the structural weight is obtained by sizing the FEM against critical load cases using NASTRAN's Design Optimization subroutine. This process is outlined in Figure 1 and a more thorough explanation of this process is explained in the paper by Nascenzi et al [7].

Once weights of variations of a single configuration are obtained, we do a model verification. We ensure that the NASTRAN optimization of the model was able to converge to a feasible solution, and we ensure that all vehicles created have a reasonable static margin. Once we have ensured that the generated aircraft are feasible, the weight data can then be curve fit to obtain surrogate models. This model can then be used to quickly estimate the weight of Lift+Cruise configurations.

III. Base Structural Models

There are several assumptions to be made before the full base structural model for each of the classifications can be developed. Some of these assumptions include what materials will be used, what nonstructural masses are needed, and what load cases the vehicle will be sized to. Assumptions made are all informed by industry experts.

A. Materials

For all the models, we will be using a common materials library of a unidirectional (UD) carbon, a plain weave (PW) fabric, and aluminum 2024 T6. The UD carbon is Cytec MTM45-1/ 12K HTS5632 and the PW fabric is Cytec

MTM45-1 PW C2 3K PW G30-500. These selections were based on materials previously used in a study of NASA's Lift + Cruise configuration [8].

B. Material Properties
This section provides an overview of the material properties and associated design variables used within the sizing optimization. These consist of aluminum shell thicknesses, beam cross-section profile dimensions, and composite ply thicknesses. These profiles and layups permit the optimization of several design variables.

Table 1: Composite skin shell element layup and thickness bounds for material sizing optimization.

Ply	Material	Orientation	Baseline (ft)	Lower Bounds (ft)	Upper Bounds (ft)
1	UD Carbon	0	0.00158	0.00144	0.0055
2	PW Fabric	0/90	0.00198	0.00144	0.0055
3	PW Fabric	-45/45	0.00198	0.00144	0.0055
4	PW Fabric	0/90	0.00198	0.00144	0.0055
5	UD Carbon	0	0.00158	0.00144	0.0055

Table 2: Aluminum internal structure shell elements thickness bounds for material sizing optimization.

Material	Baseline (ft)	Lower Bounds (ft)	Upper Bounds (ft)
Aluminum	0.0075	0.0075	0.1

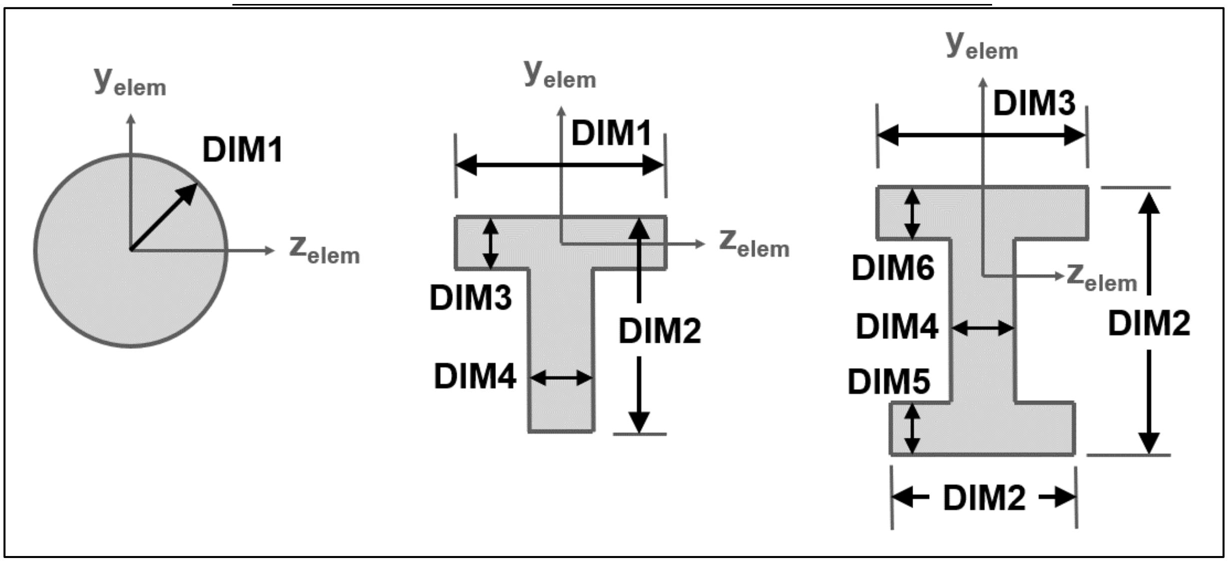

Figure 2: Rod, T-cross, & I-beam section dimension visualization.

Table 3: Aluminum rod cross-section dimension bounds for material sizing optimization.

Dimension	Baseline (ft)	Lower Bounds (ft)	Upper Bounds (ft)
D1	0.10	0.050	0.50

Table 4: Aluminum T cross-section dimension bounds for material sizing optimization.

Ply	Baseline (ft)	Lower Bounds (ft)	Upper Bounds (ft)
D1	0.25	0.0083	0.50
D2	0.25	0.0083	0.50
D3	0.0083	0.0083	0.0083
D4	0.0083	0.0083	0.0083

Table 5: Aluminum I cross-section dimension bounds for material sizing optimization.

Ply	Baseline (ft)	Lower Bounds (ft)	Upper Bounds (ft)
D1	0.30	0.15	0.45
D2	0.20	0.10	0.30
D3	0.20	0.10	0.30
D4	0.032	0.032	0.20
D5	0.032	0.032	0.10
D6	0.032	0.032	0.10

All skin elements will use the ply layup outlined in Table 1. They are sized independently of the models' defined property regions. The aluminum internal structure was defined using both shell and bar elements. The shell element starting thickness and optimization bounds are shown in Table 2. The bar element cross sections are shown in Figure 2 and the starting thickness and optimization bounds are shown in Table 3, Table 4, and

Table 5.

To the skin elements, additional material is added for lightning strike protection. A standard metal mesh is assumed to be the material added, but there are a variety of products for lightning protection available ranging from 0.010 lb/ft^2 to a more typical area weight of 0.040 lb/ft^2 [9]. In this study, we utilize the copper mesh CU195F which has an area weight of 195 g/m^2 which is approximately equal to 0.040 lb/ft^2, and this weight is added to all skin elements [10].

C. Calculation of Non-Structural Masses

Batteries

An input parameter for the generation of this weight database is battery weight. For this study, we added a step to determine battery packing. This step seemed to be necessary to accurately determine the sizing, placement, and weight of the battery packs in the aircraft because we are limited by things like the volume available and current battery technology available. To make this simulated weight data as realistic as possible we needed to find out whether an aircraft would be able to complete a typical mission with the amount of battery/energy that can fit in the vehicles. A typical mission for UAM can vary from a long-range and small payload mission, or a short-range and large payload mission to a more constraining long-range and large payload mission as described in this paper outlining potential UAM mission requirements [11]. These mission requirements were used to do a rough calculation of how much energy, and in turn how much battery, would be needed.

When determining how much volume there is within the vehicle to place batteries, we considered the placement and sizing of other nonstructural masses, the safety of the vehicle, and the static margin of the aircraft. Some of the nonstructural masses that were considered include rotors and motors attached to the booms, drive systems, mechanical systems, and other miscellaneous masses. For safety, we decided against placing the battery in the wings where the typical fuel source for tube and wing transport aircraft places fuel. The crash test that was done on NASA's Lift+Cruise UAM, made it clear that adding weight above the passenger cabin would be a safety hazard [12]. For some of the concepts, more weight was needed forward while others needed more weight aft to have a reasonable static margin. So, for some vehicles, the majority of the battery placement is in front of the passengers while for others it is aft of the passenger cabin. For all the vehicles, we decided to place batteries in the booms while still leaving a good amount of space for motors and rotors to be placed. We utilized the OpenVSP models to fit boxes within the free space to get the volume available for batteries as exemplified in Figure 3.

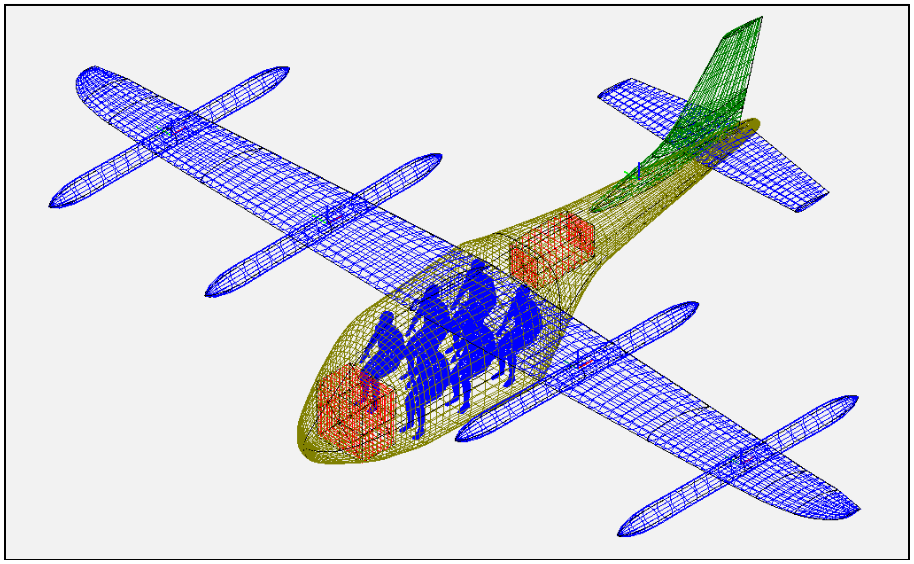

Figure 3: Example of how battery volume estimation was executed.

For battery cells, we wanted to incorporate the current best battery technology. A company called Amprius Technologies seemed to have the most advanced battery cells for eVTOLs that are currently available. They recently announced in a press release that they have created a 500 Wh/kg battery cell, but for the purposes of this study, we decided against using this specific energy because there is not enough information released to size the battery pack [13]. Instead, to size and get the weight of the battery packs for this study, an older battery cell from Amprius is used which has a specific energy of 416 Wh/kg. In NASA's battery technology workshop in 2017, they shared specifications on this battery cell which we utilized to determine how much battery can fit within each vehicle. The cell dimensions are 4.6 mm by 50 mm by 55 mm. Each of these cells contains 13.2 Wh of energy and weighs 31.7 g [14].

In Rob McDonald's lecture on batteries for electric aircraft, he lists equations that can be used to calculate battery packing volumetric efficiency for cylindrical battery cells. To calculate battery packing efficiency for Amprius's battery cell, we used the same methodology but adjusted it for prismatic cells. We are still considering the added volume for the module boundary and including coolant gaps between cells, but we have ignored any circle packing inefficiencies. For the battery packing material density, we utilized the information given in this lecture on Tesla's Model S battery module which has a packing material density of 428.9 g/L [15].

To the preprocessing step of the automated process, a tool was added that takes in the volume available and the total battery weight, then calculates the battery packing weights. It is currently set up to calculate battery packing for the aforementioned cells and battery packing material specifications but could easily be updated for different battery cells and packing material if desired in future studies. In the second category of Lift+Cruise vehicles, for example, the battery can be held in the booms, in the nose of the fuselage, and aft of the passenger cabin as shown in Figure 3. For the boom batteries, one would input the length and the diameter of the booms that the battery can fit within, then this tool calculates the weight of the sized boom battery pack. Similarly, for the battery in the fuselage, we assumed the battery pack would be box-shaped so the user just needs to input the height, length, and width of the volume available.

Rotors/Motors

Rotor weights typically vary based on inputs like the shaft power, the tip speed, and rotor diameter, but these inputs are unknown. Instead, for this study we estimated the shaft power and rotor diameter to calculate an estimated rotor weight which was then validated against the weights given for NASA's Lift+Cruise UAM concept. Motor weights are estimated using the empirical formula for permanent magnet AC motors which is referenced in the paper by Silva et al. [8]. In general, for the estimation we had the hover rotor weights increase for increases in wing area, battery weight, payload, and wing aspect ratio. This is because we assumed rotor diameters increased with wing size, and that the power required increased with increases in weight of the vehicle, in this case weight of the nonstructural masses. Cruise rotors weights we assumed increased with increases in component outer model line areas since that would essentially correspond to increases in drag or thrust in cruise. It also increases with an increase in cruise speed because higher power is required to fly at higher speeds.

D. Load Cases

The load cases for each vehicle will be the same. Table 6 summarizes the eight load cases and **Error! Reference source not found.** gives a visual of some of the load cases.

Table 6: The eight load cases used to size the aircraft.

Load Case Description	Factor	Limit/Ultimate	Location
Transition Mode	1.5g	Limit	Rotor Hubs
Hover Mode	2.0g	Limit	Rotor Hubs
One Engine Out	2.0g	Limit	7/8 Rotor Hubs
Pullup maneuver	3.0g	Limit	Aero Model (Wing + H-Tail)
Flutter	NA	NA	Aero Model (Wing + H-Tail)
Landing Load	2.0g	Limit	Landing Gear Attachments
Forward Crash	12.0g	Ultimate	Nose
Downward Crash	12.0g	Ultimate	Fuselage Bottom Skin

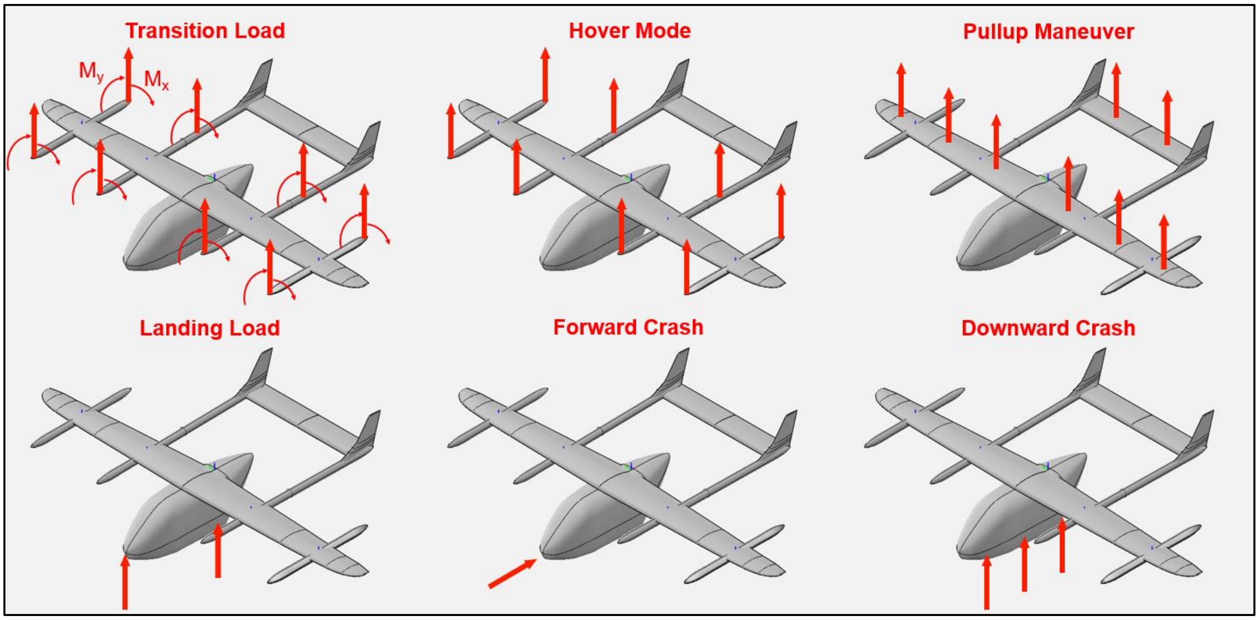

Figure 4: Six of the weight load cases.

E. Parameter Set

Table 7: Parameterization.

		Parameter
1	$W_{battery}$	Battery Weight
2	$W_{payload}$	Payload
3	v	Cruise Speed
4	S	Wing Area
5	S_H	Lifting Surface 2 Area
6	S_V	Vertical Stabilizer Area
7	$L_{fuselage}$	Fuselage Length
8	AR	Wing Aspect Ratio

Table 8 shows the 8 parameters that are sampled using the Latin hypercube sampling method. The first two parameters, battery weight and payload, change nonstructural mass components in the models. Based on the typical mission requirements, for each category of UAM we have that the payload varies from 290 lbs which is the amount of payload in the long range and small payload mission to 1200 lbs which is the assumed payload in the short range and large payload mission [11]. The upper and lower bounds of the battery weight depend on the aircraft and how much volume we had found was available in each. Cruise speed affects the flight conditions for the static aeroelastic trim load cases. The rest of the parameters affect the aircraft geometry sizing. Lifting Surface 2 refers to the secondary horizontal lifting surface to the main wing, so depending on what configuration it refers to either the canard, the tandem wing, or the horizontal tail. For some of the configurations, like in cases where there is a rear wing and a canard, the vertical stabilizer will refer to winglets.

IV.Urban Air Mobility—Classifications

As noted, there are several different categories of UAM and there are new designs being added regularly. This study will be focused on the aircraft in the Lift+Cruise category of eVTOL. In the Lift+Cruise category on evtol.news there are currently a total of 129 aircraft listed. Within this category, there were a few that did not have sufficient information available for our purpose, so those aircraft were excluded from this study. A total of 105 Lift + Cruise eVTOLs were left to categorize. Many of the aircraft listed were difficult to group since they have unique designs. We were able to categorize 58 of the 105 Lift + Cruise aircraft into the following 4 categories:

1. Inside Booms Connected only to Wing and Has No Outer Booms
2. Inside Booms Connected only to Wing and Has Outer Booms
3. Inside Booms Connected to Wing and Another Lifting Surface and Has No Outer Booms
4. Inside Booms Connected to Wing and Another Lifting Surface and Has Outer Booms

Some of the common characteristics of these 4 categories include that they all have a main wing with attached booms and propellers attached to the booms that are not ducted. The base models for each of these categories were derived from NASA Urban Air Mobility Lift Plus Cruise (UAM-LPC) configuration [8].

1. Inside Booms Connected Only to Wing and Has No Outer Booms

Overview

Out of 58 eVTOL aircraft that were categorized, 10 of them fall into this category. Figure 5 shows the aircraft that was referenced for this subcategory of Lift+Cruise and what the OML design is based on.

Figure 5: Aircraft with inner booms connected to wing and no outer booms from the eVTOL directory [5].

OpenVSP Model

The overall OpenVSP model is very similar to NASA's Urban Air Mobility Lift Plus Cruise (UAM-LPC) configuration [8]. The only difference is the arrangement of the propellers and that this model has only one pair of booms rather than two. This model has a pair of propellers at each end of the boom whereas the UAM-LPC has one at each boom end.

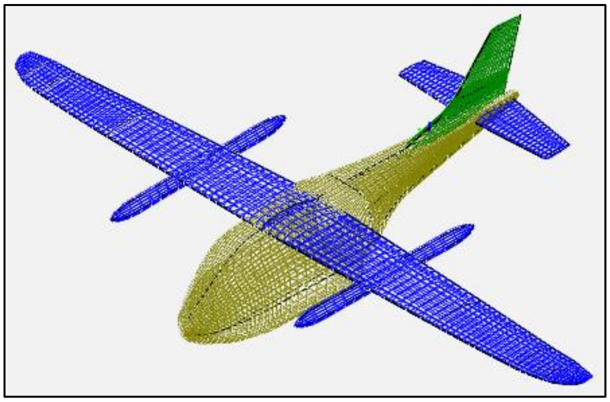

Figure 6: Base OpenVSP model for category 1.

Structural Model

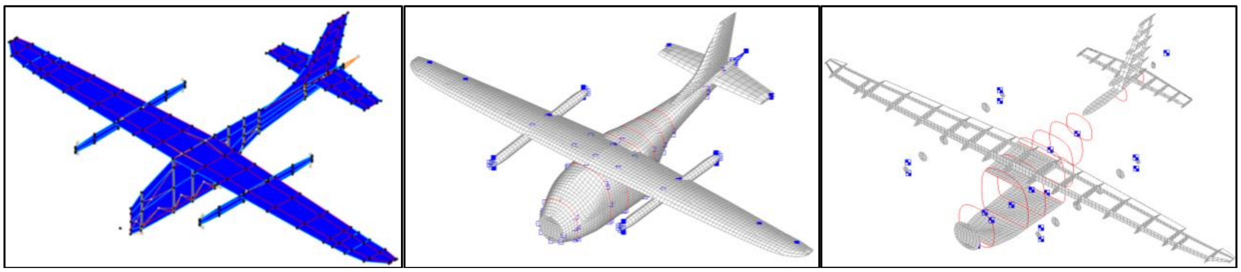

Figure 7: Structural model build-up of category 1 from OpenVSP using M4 Structures Studio.

Parameterization

Table 8 summarizes the upper and lower bounds of each of the input parameters that was sampled using the Latin Hypercube sampling method for the Category 1 of Lift+Cruise vehicles.

Table 8: Parameter bounds for category 1.

Input	Lower Bound	Upper Bound
Battery Weight	1625 lbs	2225 lbs
Payload	290 lbs	1200 lbs
Cruise Speed	100.8 knots	123.2 knots
Wing Area	189.25 ft^2	231.31 ft^2
Lifting Surface 2 Area	35.56 ft^2	43.46 ft^2
Vertical Stabilizer Area	24.61 ft^2	30.07 ft^2
Fuselage Length	27 ft	33 ft
Wing Aspect Ratio	10.93	13.36

2. Inside Booms Connected Only to Wing and Has Outer Booms

Overview

From the aircraft researched, we found that there are 13 aircraft from the Lift+Cruise category that fit within this subcategorization, and they are shown in Figure 8.

Figure 8: Inner booms connected only to wing and has outer booms from the eVTOL directory [5].

OpenVSP Model

The baseline OpenVSP model for this category was developed from the publicly available NASA Urban Air Mobility Lift Plus Cruise (UAM-LPC) configuration as seen in Figure 9. It fits the description of this category and represents the typical configuration within this category well. It has a pair of inner booms and a pair of outer booms that are only connected to the wing and they are all the same length, which seemed to be the usual case for the aircraft in this category. There are a total of 8 lifting propellers and 1 pusher propeller. The 8 lifting propellers are configured with one on each end of the booms.

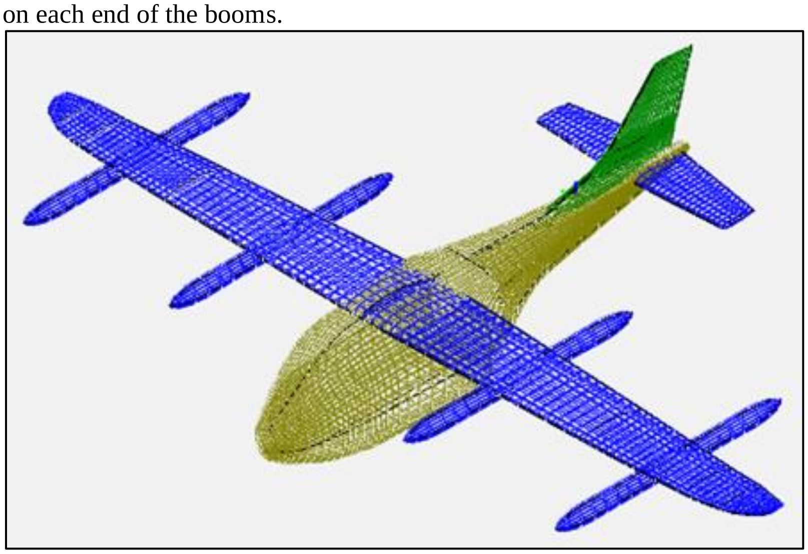

Figure 9: Base OpenVSP model for category 2.

Structural Model

The structural model for this category will be the same as that of NASA's Lift-plus-cruise UAM vehicle which was built up from the OpenVSP model using M4 Structures Studio (Figure 9). M4 Structures Studio defines materials, property regions, skin structure, internal structure, component connections, and nonstructural masses from NASA's published reports and data [8].

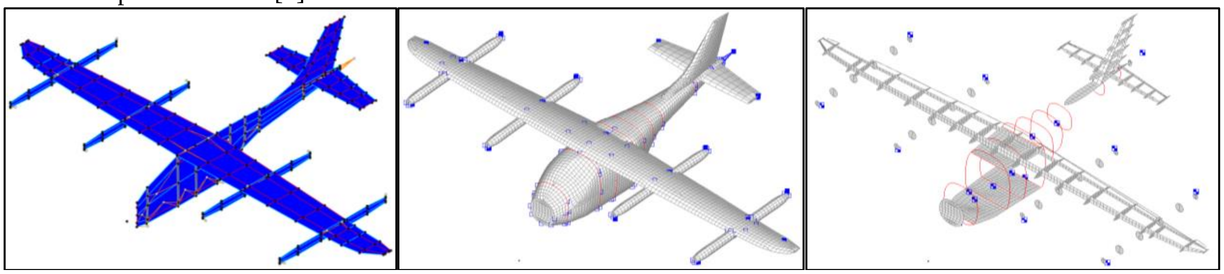

Figure 10: Structural model build-up of category 2 from OpenVSP using M4 Structures Studio.

Parameterization

Table 9 summarizes the upper and lower bounds of each of the input parameters that was sampled using the Latin Hypercube sampling method for the Category 2 of Lift+Cruise vehicles.

Table 9: Parameter bounds for category 2.

Input	Lower Bound	Upper Bound
Battery Weight	1715 lbs	2415 lbs
Payload	290 lbs	1200 lbs
Cruise Speed	100.8 knots	123.2 knots
Wing Area	189.25 ft^2	231.31 ft^2
Lifting Surface 2 Area	35.56 ft^2	43.46 ft^2
Vertical Stabilizer Area	24.61 ft^2	30.07 ft^2
Fuselage Length	27 ft	33 ft
Wing Aspect Ratio	10.93	13.36

3. Inside Booms Connected to Wing and Another Lifting Surface and Has No Outer Booms

Overview

There are 105 eVTOLs that we are considering in our study and 22 of them fall into this category. A majority of the aircraft in this category have a rear main wing with a canard instead of a horizontal tail. Almost all of the vehicles in seem below has two vertical stabilizer of sorts, some are connected to the ends of the booms while others have them attached to the ends of the rear wing, like winglets as seen in Figure 11.

Figure 11: Aircraft with inside booms connected to wing and another lifting surface and has no outer booms from the eVTOL directory [5].

OpenVSP Model

Based on these observations of the aircraft within this category, the baseline OpenVSP model was created as shown in Figure 12. The fuselage is very similar to that of NASA's Lift + Cruise but the afterbody circumference was increased to better support the rear wing that this configuration has. The wing shape and size were not changed, only the position relative to the fuselage was moved to the rear. Instead of a horizontal tail, there is a canard that is connected to the booms at its tips. Lastly, winglets were added since most of the configurations in this category have either two vertical fins or winglets.

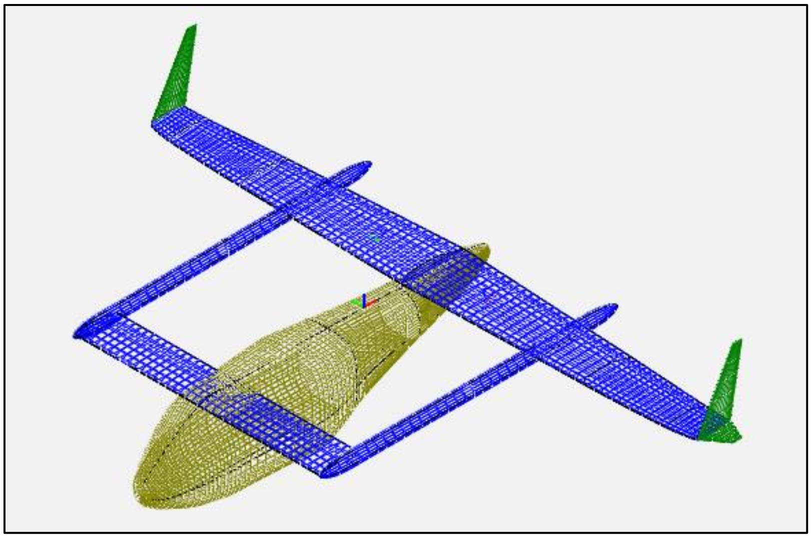

Figure 12: OpenVSP model for category 3.

Structural Model

The structural layout was build up to be similar to NASA's Lift+Cruise UAM vehicle. Booms are longer in this model than in NASA's model, so more structure is added within to account for that. Figure 13 shows the structural layout build up in M4SS and also shows the FEM OML and FEM internal structure.

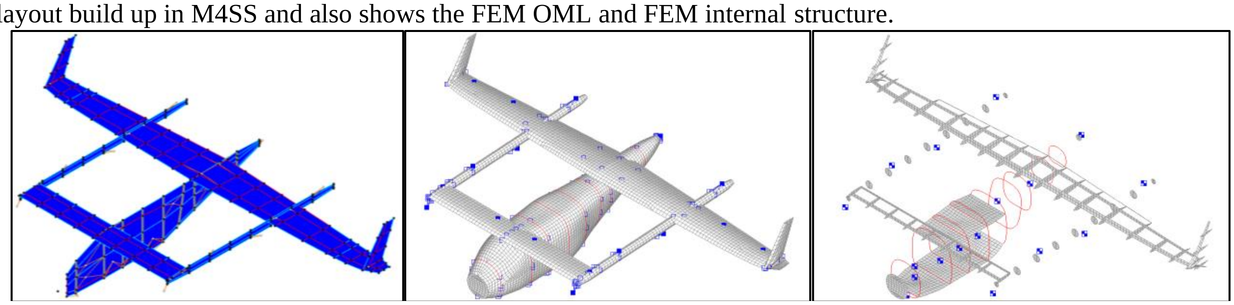

Figure 13: Structural model build-up of Category 3 from OpenVSP using M4 Structures Studio.

Parameterization

Table 10 summarizes the upper and lower bounds of each of the input parameters that was sampled using the Latin Hypercube sampling method for the Category 3 of Lift+Cruise vehicles.

Table 10: Parameter bounds for category 3.

Input	Lower Bound	Upper Bound
Battery Weight	1900 lbs	2600 lbs
Payload	290 lbs	1200 lbs
Cruise Speed	108 knots	132 knots
Wing Area	182.92 ft^2	223.57 ft^2
Lifting Surface 2 Area	62.23 ft^2	76.06 ft^2
Vertical Stabilizer Area	23.63 ft^2	28.89 ft^2
Fuselage Length	27 ft	33 ft
Wing Aspect Ratio	9.73	11.90

4. Inside Booms Connected to Wing and Another Lifting Surface and Has Outer Booms

Overview

Out of 13 total eVTOL aircraft that fall into this category, only 1 has a canard while the rest have a horizontal stabilizer that is connected to the inner booms. Because of this, the wing was left as is and the span of the horizontal tail was increased to connect to the booms. There are only 3 that have only 1 vertical tail fin, so the vertical fin was duplicated and then placed at each end of the inner booms. 9 of the 13 aircraft have a fuselage that is not connected to the horizontal tail so the afterbody that was normally attached to the fuselage was shortened greatly. The aircraft in this category are shown in Figure 14.

Figure 14: Aircraft with inside booms connected to wing and another lifting surface and has outer booms from the eVTOL directory [5].

OpenVSP Model
Based on these observations of the aircraft within this category, the baseline OpenVSP model was created as shown in Figure 15.

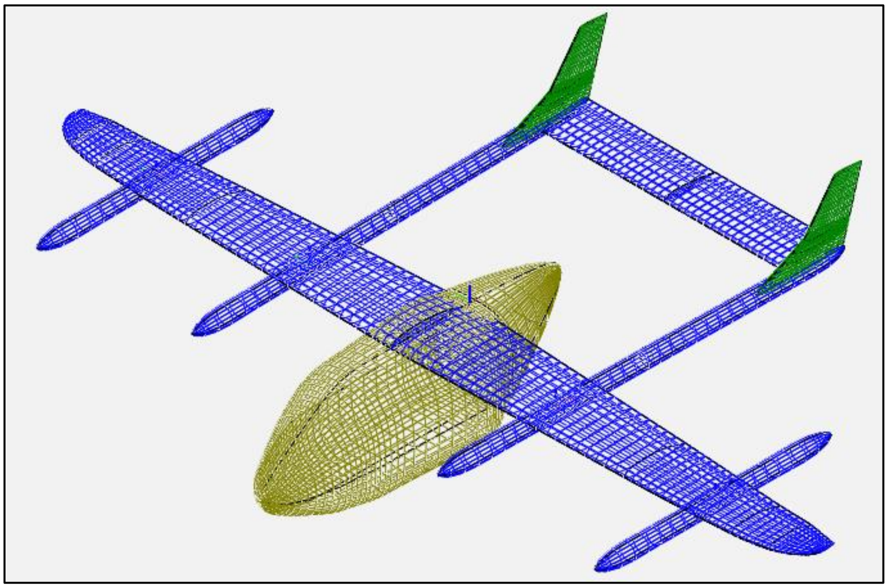

Figure 15: OpenVSP model for category 4.

Structural Model

The structural layout was built up from the OpenVSP model shown in Figure 15.

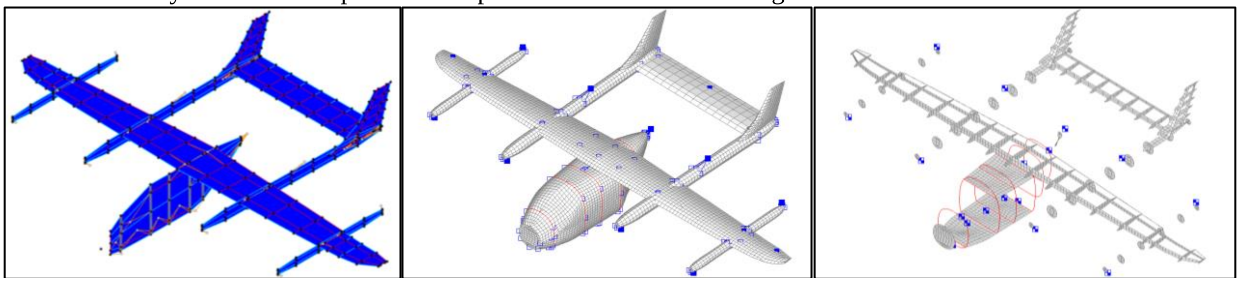

Figure 16: Structural model build-up of category 4 from OpenVSP using M4 Structures Studio.

Parameterization

Table 11 summarizes the upper and lower bounds of each of the input parameters that was sampled using the Latin Hypercube sampling method for the Category 4 of Lift+Cruise vehicles.

Table 11: Parameter bounds for category 4.

Input	Lower Bound	Upper Bound
Battery Weight	1900 lbs	2600 lbs
Payload	290 lbs	1200 lbs
Cruise Speed	108 knots	132 knots
Wing Area	189.25 ft^2	231.31 ft^2
Lifting Surface 2 Area	65.60 ft^2	80.18 ft^2
Vertical Stabilizer Area	35.47 ft^2	43.36 ft^2
Fuselage Length	18 ft	22 ft
Wing Aspect Ratio	10.93	13.36

V. Results

Using the Latin Hypercube sampling method, we generated 100 parameter sets for the second category of Lift+Cruise UAM which is based off NASA's Lift+Cruise UAM model. Using the automated process, we have thus far generated 100 surrogate weights from those 100 parameter sets. All the models that were generated were verified by checking that they converged to a feasible solution, and all were checked for a reasonable static margin. Using a second-order polynomial regression, we found correlations between the inputs and the structural weight of the aircraft components. The plots of the FEM compared to the data generated from the surrogate models are shown in Figure 17 and Figure 18.

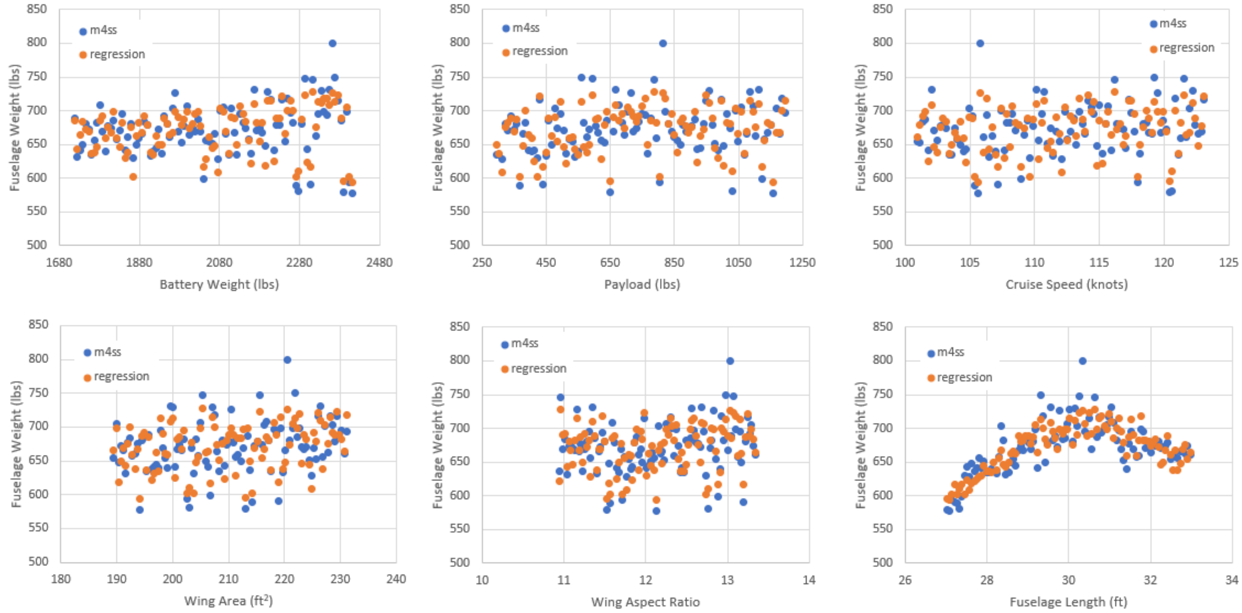

Figure 17: Plots showing the FEM and surrogate model fuselage structural weight for all 100 design parameter combinations created from category 2.

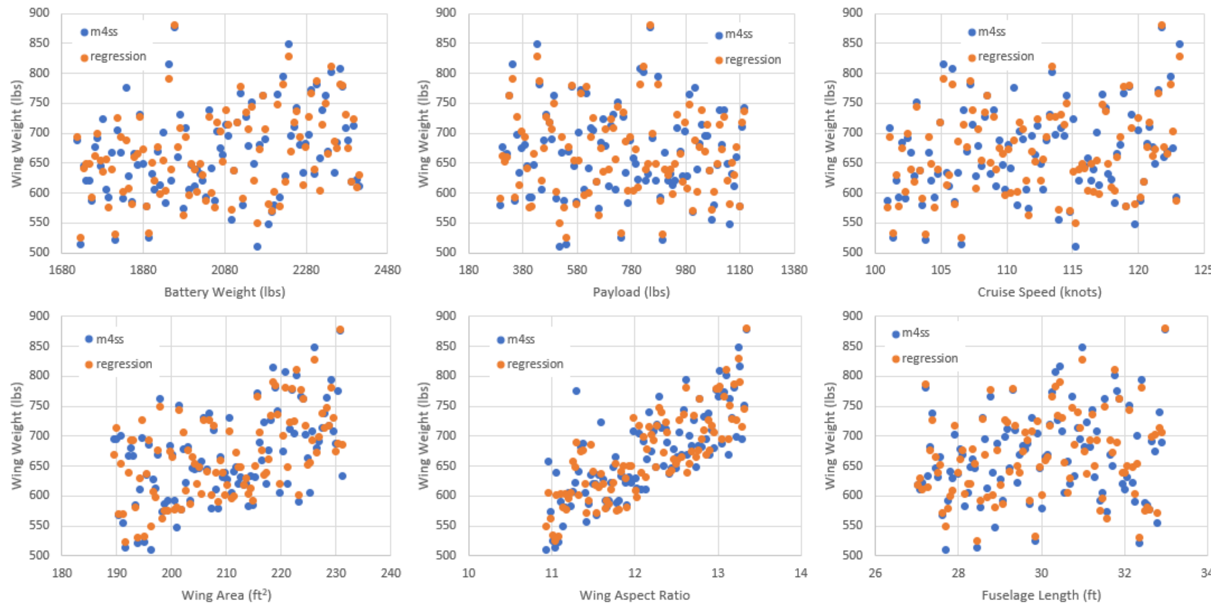

Figure 18: Plots showing the FEM and surrogate model wing structural weight for all 100 design parameter combinations created from category 2.

VI.Conclusions

This study provides the methodology used to generate surrogate weight models for several UAM configurations. The surrogate model for one of these configurations has been built up but there are still many more configurations to continue work on to develop this simulated weight database. There are the other three categories listed in this study which we have yet to generate the surrogate models for, and there are also other categories of eVTOLs that we have yet to explore. Before we release the surrogate models generated we plan to do more testing for verification and validation of the models generated. We want to ensure that the models can accurately predict weight not only for models within the parameter ranges in which we obtained our samples, but also for those that are outside of this range. We anticipate the full results to be completed by AIAA Scitech Forum in 2024.

In continuations of this study, we hope to find relations between structural weight and inputs like range, wing loading, hover rotor loading etc., which will require even more collaboration with other teams in NASA's University Leadership Initiative (ULI) with whom we have been working with on this project. Additionally, by working more closely with other teams in their development of optimization tools, we will be able to incorporate even more accurate rotor weights, battery weights, and drag calculations into this effort.

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References

[1] D. P. Raymer, Aircraft Design: A Conceptual Approach, Washington, D.C.: AIAA, 1992.

[2] D. P. Wells, B. L. Horvath and L. A. McCullers, "The Flight Optimization System Weights Estimation Method," 2017.

[3] E. Torenbeek, Advanced Aircraft Design: Conceptual Design, Analysis, and Optimization of Subsonic Civil Airplanes, John Wiley & Sons, United Kingdom, 2013, pp. 229-239.

[4] M. Kowalski, Z. J. Goraj and B. Goliszek, "The use of FEA and semi-empirical equations for weight estimation of a passenger aircraft," *Aircraft Engineering and Aerospace Technology,* 2021.

[5] "Electric VTOL News," Vertical Flight Society, [Online]. Available: https://evtol.news/aircraft.

[6] M. Stein, "Large sample properties of simulations using Latin hypercube sampling," *Technometrics,* vol. 29, no. 2, pp. 143-151, 1987.

[7] T. Nascenzi, T. Cuatt, S. Kiani and T. Winter, "Physics-based Surrogate Models for Urban Air Mobility Vehicle Weight Prediction," *AIAA Scitech 2023 Forum,* 2023.

[8] C. Silva, W. Johnson, K. R. Antcliff and M. D. Paterson, "VTOL Urban Air Mobility Concept Vehicles for Technology Development," 2018.

[9] S. Black, "Lightning strike protection strategies for composite aircraft," CompositesWorld, 2013. [Online]. Available: https://www.compositesworld.com/articles/lightning-strike-protection-strategies-for-composite-aircraft.

[10] "Lightning to composite: Niles expanded metals," Niles International LLC, 2022. [Online]. Available: https://nilesexpandedmetals.com/lightning-strike-protection/.

[11] M. D. Patterson, K. R. Antcliff and L. W. Kohlman, "A Proposed Approach to Studying Urban Air Mobility Missions Including an Initial Exploration of Mission Requirements," *AHS International 74th Annual Forum and Technology Display,* 2018.

[12] D. Meade, "NASA Crash Tests eVTOL Concept," National Aeronautics and Space Administration, 2022. [Online]. Available: https://www.nasa.gov/feature/nasa-crash-tests-evtol-concept.

[13] "The All-New Amprius 500 Wh/kg Battery Platform is Here," Amprius Technologies, 23 March 2023. [Online]. Available: https://amprius.com/the-all-new-amprius-500-wh-kg-battery-platform-is-here/.

[14] I. Stefan, "High Energy Density Lithium-Ion Cells with Silicon Nanowire Anode Technology," in *NASA Battery Industry Day,* 2020.

[15] R. A. McDonald, "Perspectives on Batteries for Electric Aircraft Design," in *AIAA Aviation, Design of Electric and Hybrid-Electric Aircraft,* Atlanta, 2018.