Physics-based Surrogate Models for UAM Weight Prediction

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Physics-based Surrogate Models for Urban Air Mobility Vehicle Weight Prediction

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Successful conceptual aircraft design requires accurate structural layout and weight prediction. Empirical formulations exist for many archetypal aircraft, but are not available for novel aircraft concepts. We propose a methodology for creating physics-based weight equations that can be used in lieu of empirical weight equations. The methodology relies on M4 Structures Studio, a toolset that can rapidly estimate the structural weight of conceptual designs for unconventional aerospace vehicles. Hundreds of design variants are used in conjunction with the M4 Structures Studio parametric structural mode to create hundreds of shell-based finite element models. Structural weight is calculated for each model and an n-dimensional, 2nd-order polynomial is fitted to each weight dataset. The polynomials can be used to predict the weight of urban air mobility variants, and they can be used within a larger multi-disciplinary design optimization as weight-prediction surrogate models. The methodology was demonstrated with NASA's Lift+Cruise Configuration.

I. Introduction

Urban air mobility (UAM) is poised to improve the life of many commuters by serving as a point-to-point air taxi service. Air taxis can serve as a cargo delivery vehicle and emergency medical transport. As of yet, no UAM vehicle has seen widespread usage. Furthermore, no UAM configuration has become the standard akin to how the tube and wing configuration has for commercial transport. There are many concepts being considered and the design space includes many novel features, such as electric propulsion. Rapid and accurate design evaluation tools are invaluable when exploring this large design space.

At the early stages of design, engineers typically rely on empirical weight equations to help evaluate a design. However, there is little empirical data for UAM configurations since they are part of a new class of vehicles. Since little data exists, we propose creating simulated weight equations as a stand-in until empirical data is available. These simulated weight equations will be limited to UAM structural components. Kowalski et al. presented a similar approach for a fuselage with additional structure to support a boundary layer ingestion device [1]. The paper looked at three different variants of a single aircraft configuration. We plan to greatly expand on this concept and look at hundreds of variants for the Lift+Cruise, Tiltwing, and Quadrotor UAM configurations. The larger dataset facilitates generalized, multi-variable weight equations. An automated process was developed to populate the database.

The work presented in this paper is the work of one of nine teams developing a larger UAM design toolset. The toolset is being developed under the NASA University Leadership Initiative (ULI) for rapid development of urban air mobility vehicle concepts through full-configuration multidisciplinary design, analysis, & optimization (MDAO). The weight

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models developed are being be used for the lowest-fidelity system-level MDAO. It will be coupled with a range of disciplines in order to accurately evaluate a wide range of designs.

II. Methodology

A. Overview

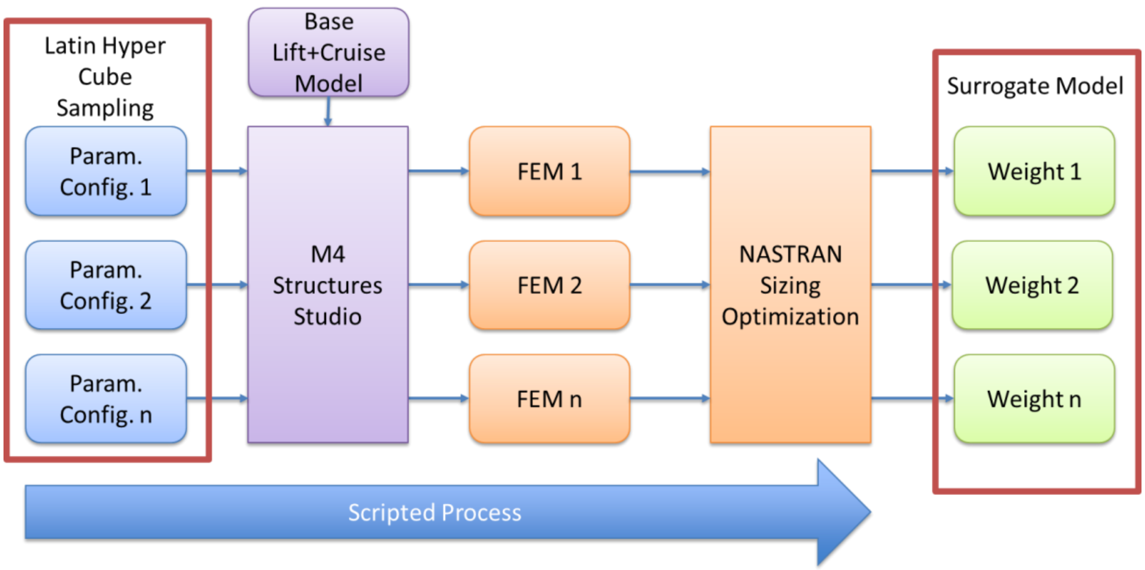

Figure 1: Overview of the automated process for obtaining weights for a large number of design variants.

An automated process was developed to generate a wide range of data necessary for accurate surrogate modeling. The process will automatically generate hundreds of unique design parameters sets for a given UAM configuration. The automated process also generates a FEM for each variant using the tool M4 Structures Studio (M4SS). In order to do this, M4 Structures Studio utilizes a parameterized base model. The base model sketches important features relevant for determining structural weight, such as structural layout, critical load cases, material properties, and nonstructural masses. The base model for the Lift+Cruise configuration is outlined in Section III. The FEMs are then sized using Nastran optimization and the sized structural weight is obtained. An overview of the approach is shown in Figure 1. In the end, the process produces a unique structural sizing FEM for each set of design parameters and a corresponding structural weight. The weights are then used to create weight equations.

B. Automated Sampling Process

Parameter variants for the weight model were generated using a Latin hypercube sampling method [2], and additional single-parameter sweeps were done for model validation purposes. Latin hypercube sampling is a method for generating nearly-random multidimensional parameter input values. Rather than a purely random set of parameters, it randomly associates indices from linear ranges of all inputs. This ensures the full design space is represented irrespective of the sample quantity and removes the potential for artificial input coupling effects.

C. M4 Structures Studio—Physics-based Weight Prediction

M4 Structures Studio is a parameterized structural modeling tool that creates optimization-ready structural sizing finite element models for NASTRAN. It does this by enabling the user to rapidly develop a structural finite element model (including internal structure) from an outer model line (OML) geometry definition in OpenVSP [3]. M4 Structures Studio has been used to build structural weight prediction models for a variety of UAM configurations [4] [5] [6]. M4 Structures Studio has been validated against historical airplanes, rotorcraft, and a wide variety of unconventional configurations. A subset of these configurations is shown in Figure 3. The application GUI is shown in Figure 2. The GUI is used to layout structure and specify sizing load cases, among other sizing relevant components.

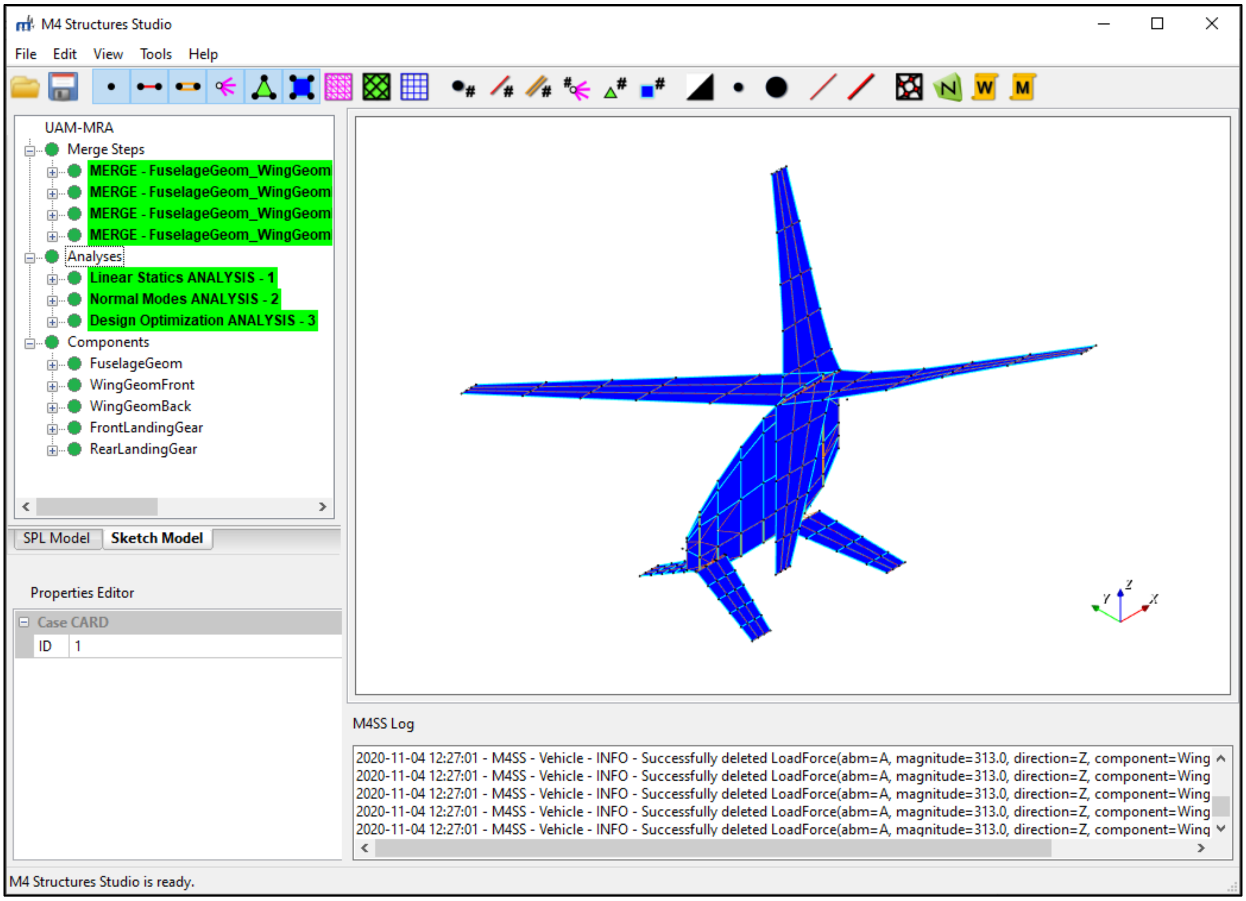

Figure 2: The M4 Structures Studio GUI with the metadata for a quadrotor UAM concept loaded.

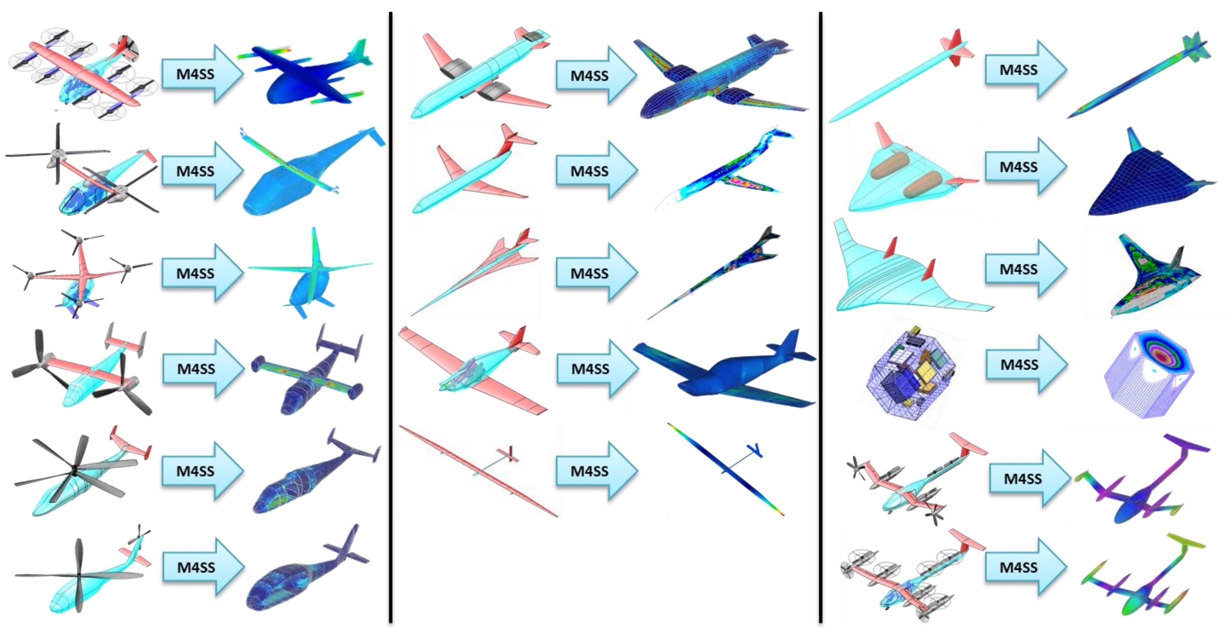

Figure 3: Example Selection of Vehicles Modeled and Sized using M4 Structures Studio.

Defining and assembling the internal structure is traditionally a time-consuming process that must be repeated for every change in the structural planform. M4 Structures Studio significantly improves this process by allowing the user to define the structural layout in parametric terms. The structural FEM is shell-based and can be sized using a combination of static, aeroelastic, flutter, and gust load cases. Additional features important to structural weight prediction include nonstructural mass representation, trim maneuvers, and aerodynamic control surfaces. Therefore, it is possible to build a complete FEM, including the analysis definition and optimization parameters, for a wide variety of design configurations. It is this functionality that enables the automatic generation of structural models for UAM configuration variants. The model created in M4 Structures Studio is detailed in Section III.

D. Surrogate modeling

As the weight prediction can be assumed to be coupled and nonlinear with regards to parameter inputs, an n-dimensional, 2nd order polynomial curve was fitted to the weight dataset. A 2nd order polynomial was used to capture the primary coupling effects between major design variables (e.g., wing aspect ratio with wing planform area). The constants for this polynomial curve fit are found with a least-squares regression and the predictions are shown to have high correlation with our test data. The present shortcomings of this approach lie with the optimizer and structural modeling fidelity. The optimizer used for minimizing weights has a chance of converging to a local minimum away from the expected optimized weight. Although these local minima are feasible, they always overestimate the design weight. It can be difficult to identify the outliers because each optimization result is compared to the initial dataset's corresponding weight prediction result. Each outlier's impact is quantified by the relative overall accuracy of the predictor over the dataset before and after outlier removal (with a re-fitting of the curve each time). The optimization for each outlier is re-run with a different starting point in order to nudge it away from the undesired local minimum. If both optimizations for the same design converge to different feasible designs, the lowest optimized weight is used.

III. Lift+Cruise Base Structural Model

The methodology was applied to NASA's Lift+Cruise concept, specifically the all-electric version. The vehicle is designed to take off and land vertically using eight distributed motors attached to the wing with four booms. During forward flight, the eight vertical rotors become stowed and a single pusher prop at the rear of the vehicle provides the forward thrust. The base geometry and non-structural masses are sourced from the publicly available reports and their corresponding OpenVSP models and NDARC models [7]. The OpenVSP model is shown in Figure 4.

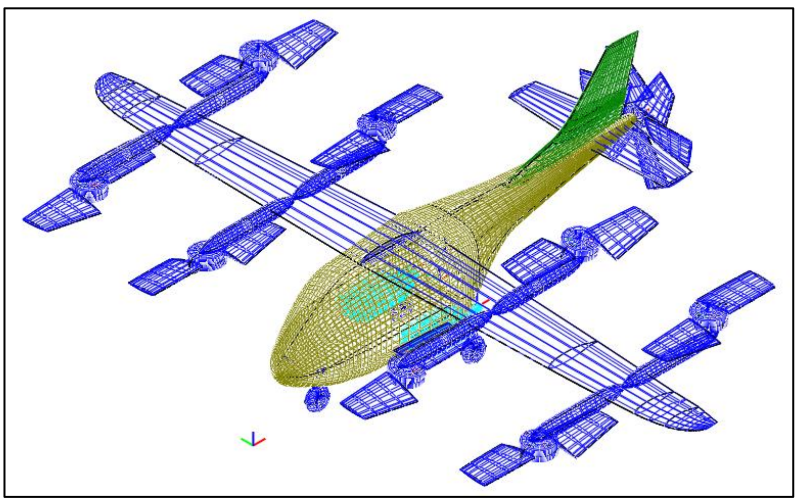

Figure 4: OpenVSP model for the Lift+Cruise concept.

The structural model of the Lift+Cruise vehicle was built up from the OpenVSP model using M4 Structures Studio. A visualization of the process is shown in Figure 5. M4 Structures Studio is capable of defining materials, property regions, skin structure, internal structure, component connections, and nonstructural masses from NASA's published reports and data [8]. Engineering judgement was used to specify certain qualities of the vehicle were not well defined. These judgement decisions certainly effect the baseline vehicle weight, but become less important when looking at the sensitivity of the weight to design variables. The structural model was created only for predicting vehicle weights. None of the modeling aspects laid out in this section should be taken as fabrication-ready or as a definitive answer to the structural layout of the Lift+Cruise configuration.

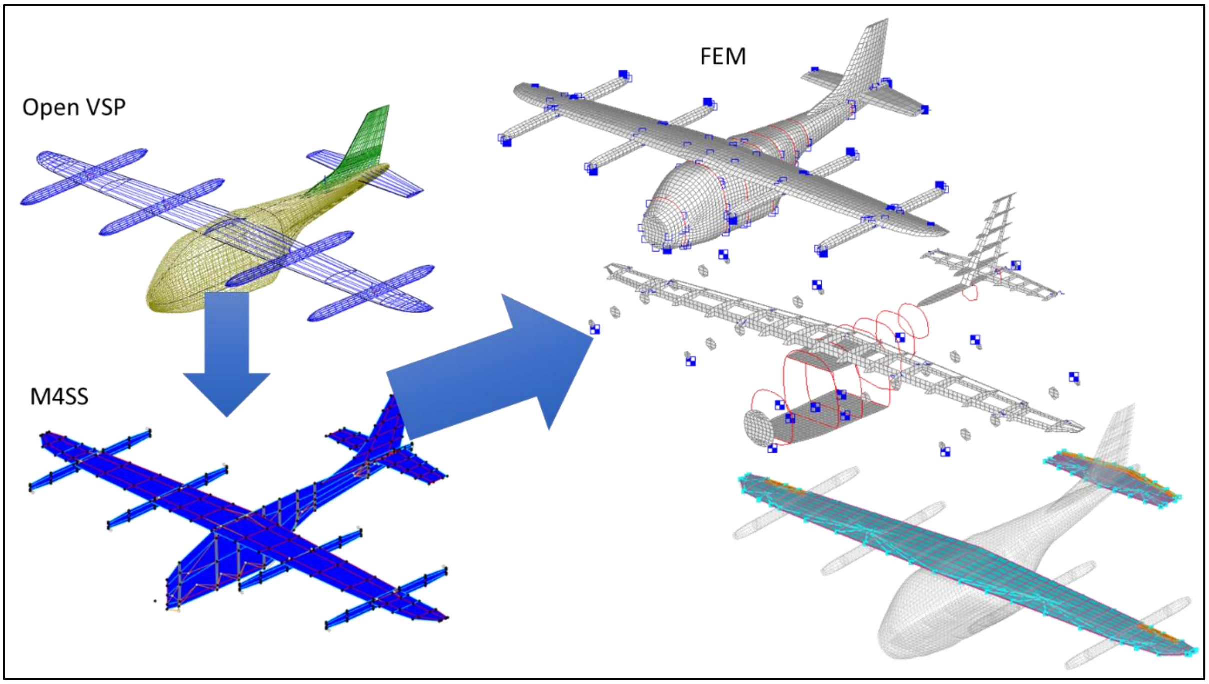

Figure 5: The M4SS model with the input geometry and output FEM (skin, internal, and aero) shown.

Materials & Element Properties

The model utilizes three different materials: a unidirectional (UD) carbon, a plain weave (PW) carbon, and aluminum 2024 T6. The Unidirectional (UD) carbon is Cytec MTM45-1/ 12K HTS5632 UD Carbon and the PW Fabric is Cytec MTM45-1 PW C2 3K PW G30-500.

All elements in the model share common element properties. They consist of composite shell element ply thicknesses and aluminum bar element cross-sections. The cross-section dimensions and ply thickness are used as the design variables of the sizing optimization. The distribution of aluminum and composite is shown in Figure 6.

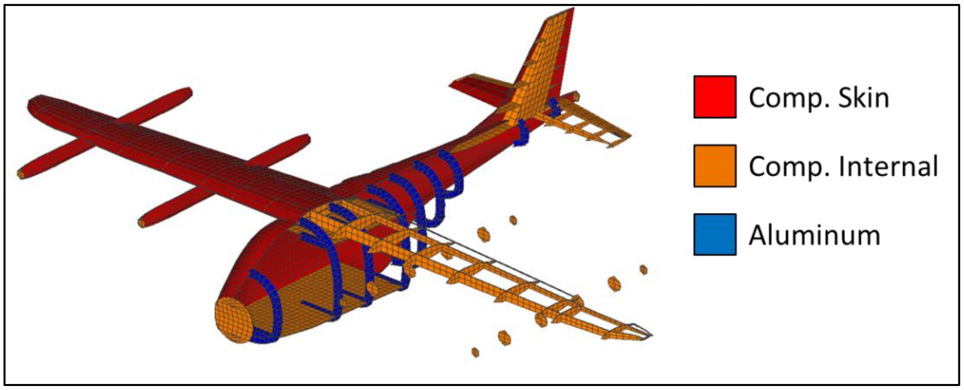

Figure 6: The distribution of composite and aluminum elements in the Lift+Cruise FEM.

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

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

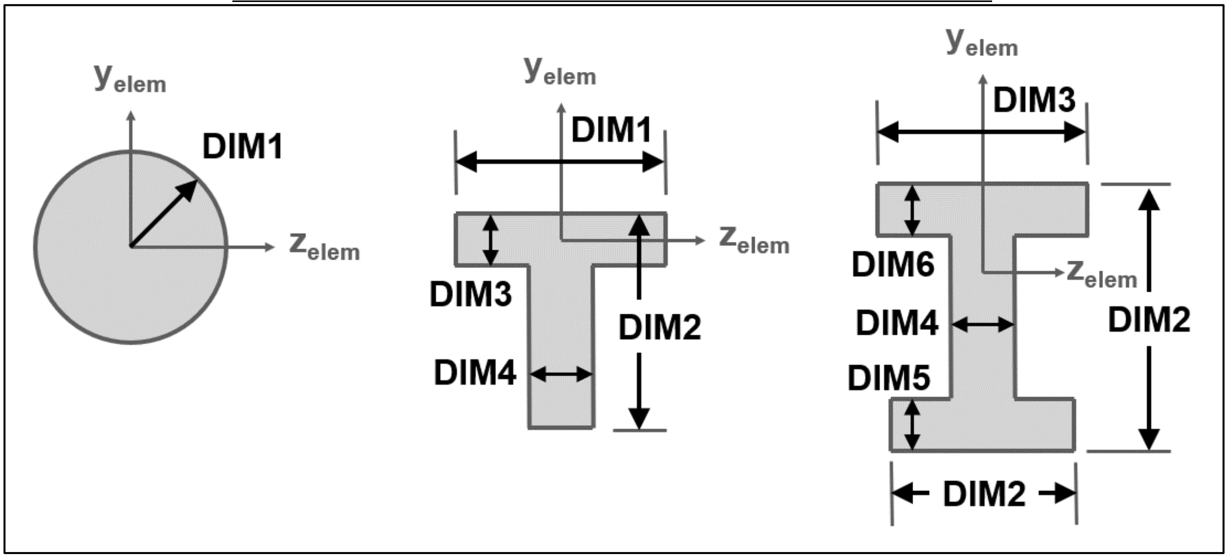

Figure 7: Rod, T-cross, & I-beam section dimension visualization.

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 in the UAM models use the ply layup outlined in Table 1 and are sized independently the model's 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 7 and the starting thickness and optimization bounds are shown in Table 3, Table 4, and Table 5.

Property Regions
The Lift+Cruise UAM model divides its property regions as follows in Table 6. The material thickness of each property region is sized independently by the optimizer.

Table 6: Lift-plus-Cruise property regions.

Component	Property Region Distribution	Number of Shell Property Regions	Number of Bar Property Regions
Fuselage	Lengthwise Sections	14	18
Wing	Spanwise Sections	20	0
Hstab	Chordwise Sections	5	0
Vstab	Chordwise Sections	5	0
Boom	Homogeneous	1	1

Aero Model

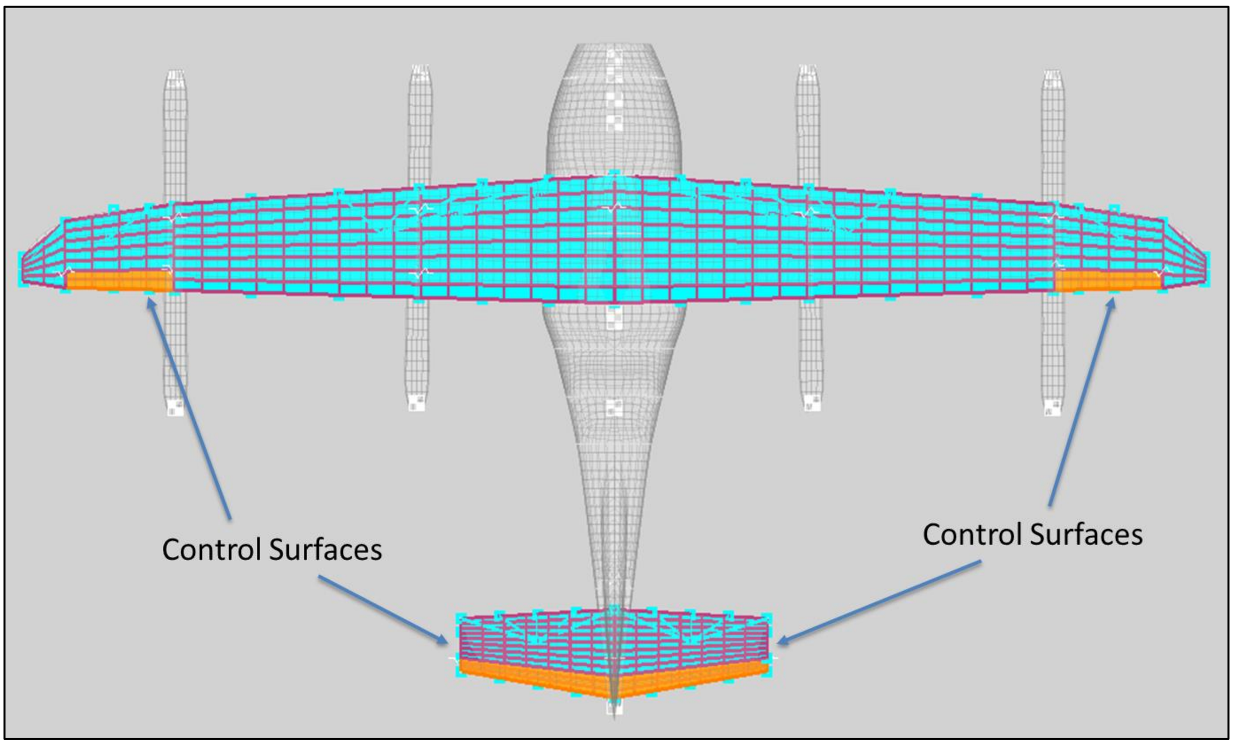

Figure 8: Aero panels and control surfaces used for static aeroelastic trim solutions and flutter analysis.

M4 Structures Studio also allows the definition of an aeroelastic model. The aeroelastic model relies on the Doublet-Lattice method for subsonic flow. The aero panels are showing in Figure 8. Additionally, each panel is tied to the structure with splines that create a coupled aeroelastic analysis. The aero model also includes four control surfaces that are used for static aeroelastic trim load cases. Only pitching load cases were considered, and the deflections of the port and starboard control surfaces are linked together as a single trim variable.

Load Cases
The load cases applied to the Lift-plus-cruise UAM model for structural sizing are described in Table 7 and are shown in Figure 9.

Table 7: An overview of the eight load cases used to size the vehicle.

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

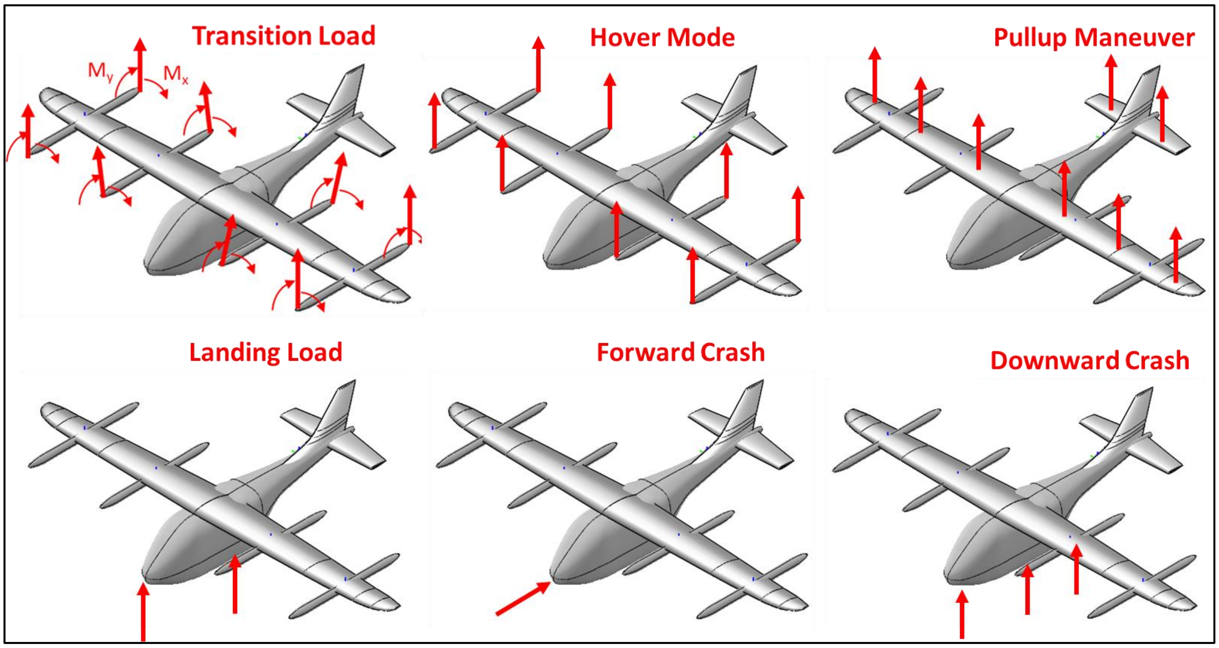

Figure 9: A visualization of six sizing load cases.

Baseline Sizing

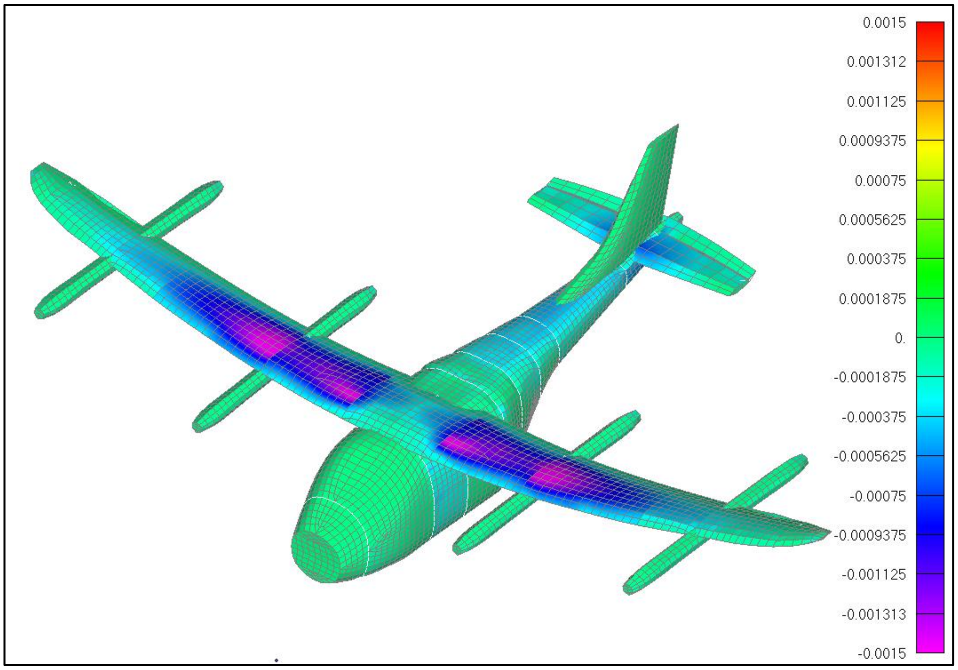

Figure 10: A visualization of minor principal strain in the outer composite ply for the pullup maneuver. Deflection is magnified by a factor of six.

All property regions were sized using the eight load cases. Figure 10 shows an example strain output for the pullup maneuver. The baseline configuration's optimization results have been compared with the existing NDARC-sized component weights in Table 8. The gross weight of the M4 Structures Studio model is about 2.5% lighter than the NDARC model.

Table 8: Weight comparison of the sized shell FEM to the NDARC Lift-Cruise E6 model.

Load Case Description	NDARC Lift-Cruise E6 (lb)	M4SS Shell FEM (lb)
Modeled Structure		
Wing	818	757
Fuselage	771	778
Empennage	208	118
Rotor Booms	319	252
Total Model Structure	2,116	1,905
NSM		
Landing Gear	423	423
Push Rotor	409	409
Lift Rotor	1,317	1,317
Battery	2,675	2,675
Systems	549	549
Misc.	783	783
Total NSM	6,156	6,156
Empty Weight	8,272	8,061
Payload	1,200	1,200
MTOGW	9,472	9,261

Parameterization

The model is parameterized with seven independent variables and are listed in Table 9.

Table 9: The Lift+Cruise design parameters.

	Parameter
#1	Wing Area
#2	Wing AR
#3	Tail Area
#4	Fin Area
#5	Fuselage Length
#6	Battery Weight
#7	Cruise Speed

The first five parameters control aspects of the vehicles geometry and alter the shell mesh. The sixth parameter, battery weight, controls the value of a nonstructural mass within the model. The seventh parameter, cruise speed, controls the flight conditions for the static aeroelastic trim load cases. The design parameters controlling the empennage had virtually no effect on the sizing of other components and the other design parameters had virtually no effect on the sizing of the empennage.

IV. Results

The methodology was used with the base Lift+Cruise model to obtain 112 different weights. The Latin hypercube sampling method was used to generate 96 design parameter combinations by varying the 5 non-empennage design parameters and 16 deign parameter combinations by varying the two empennage design parameters. The design parameters were varied within a ±10% range. Each design parameter combination was fed into M4SS and 112 unique FEMs were generated. Each FEM was sized and the structural weights for each design parameter combination were obtained. These weights were then used to build a weight surrogate model that takes the seven Lift+Cruise design parameters as inputs.

The correlation between the surrogate model and the FEM results are shown in Figure 11 and Figure 12. The first figure shows the non-empennage design parameters and structural weights, while the second figure shows the empennage design parameters and structural weights. The surrogate model for the empennage matches the FEM weights almost exactly. This is because the horizontal and vertical tail weights scale linearly with tail area and are unaffected by other design parameters. The surrogate model for the other component weights matches the FEM weights with an r^2 value of .942.

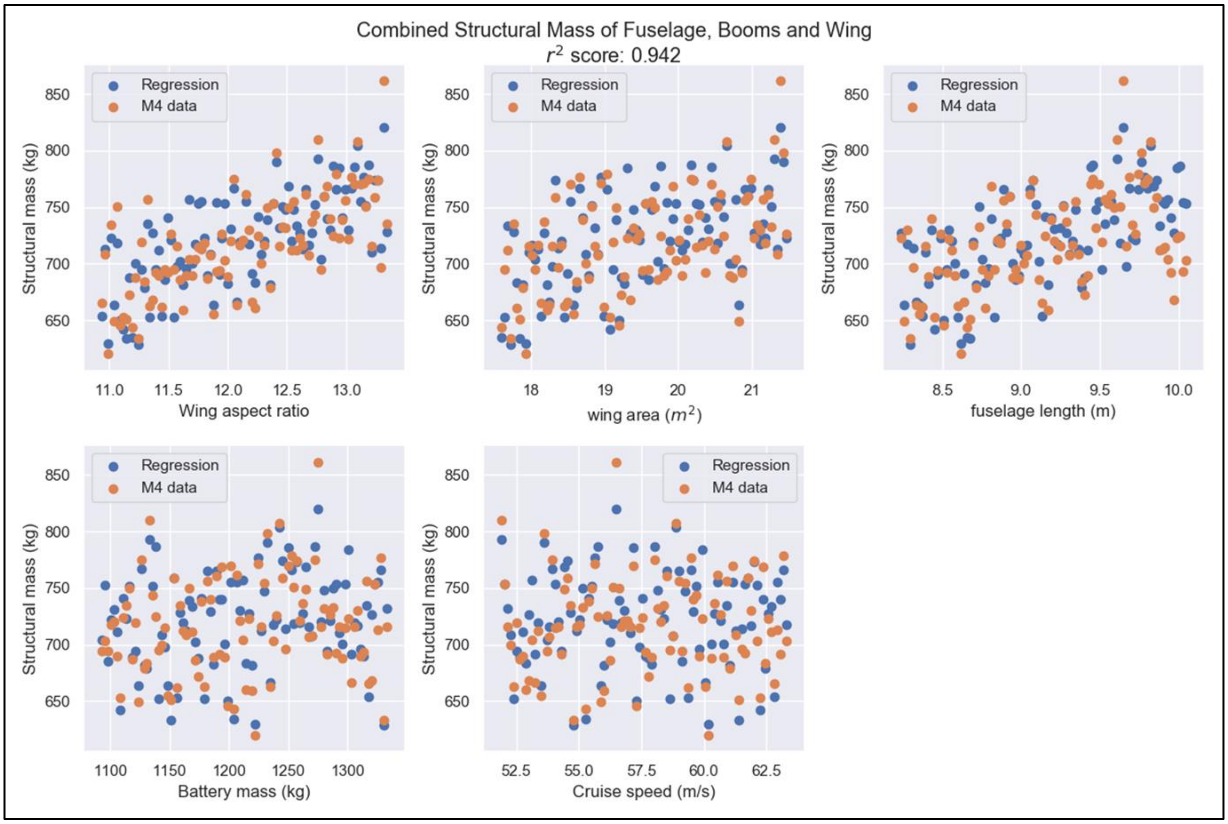

Figure 11: Plots showing the FEM and surrogate model non-empennage structural weights for the 96 non-empennage design parameter combinations. Each plot contains all 96 combinations.

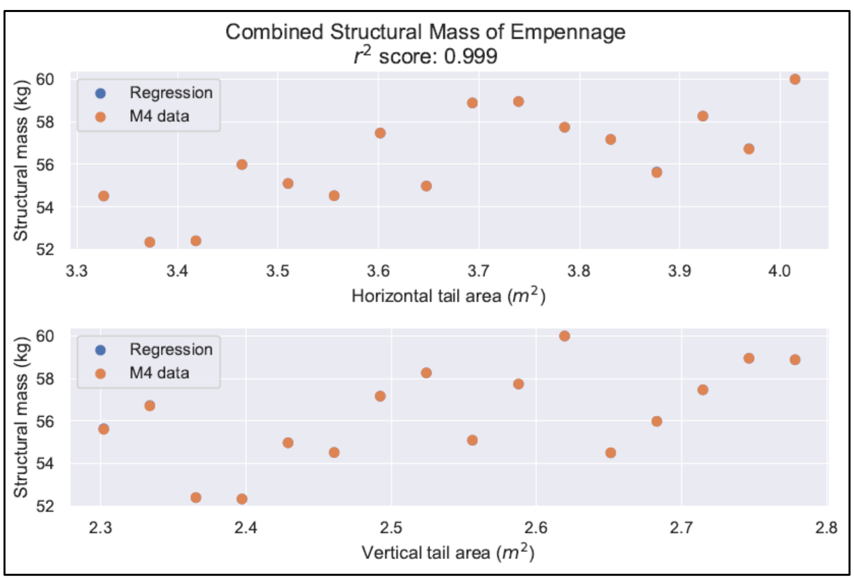

Figure 12: Plots showing the FEM and surrogate model empennage structural weights for the 16 empennage design parameter combinations. Each plot contains all 16 combinations.

Additional studies were done to verify look at the effect of single parameter variations on weight. Figure 13 shows the vehicle weight versus wing area.

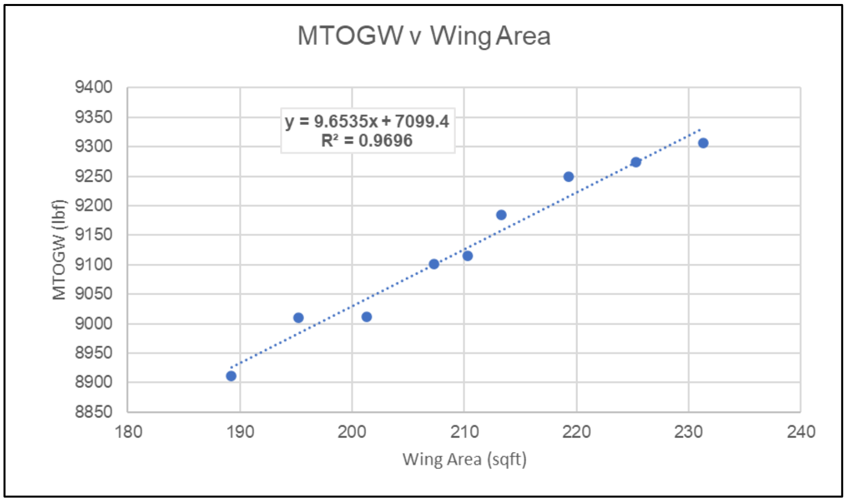

Figure 13: Plot showing FEM generated weights versus the wing area design parameter.

V. Conclusion

This paper offers a novel M4SS-based methodology for creating surrogate weight models for conceptual vehicles for which little or no empirical weight data exists. The methodology was demonstrated on the Lift+Cruise configuration and the resulting weight surrogate model is already being used in the ULI effort for low-fidelity, large-scale design optimization. Surrogate weight models could be a valuable tool for conceptual design engineers that work on unconventional vehicles across industry and academia.

Future work will focus on expanding the range of configurations and generalizing the parameterization. The surrogate model made for the Lift+Cruise concept is narrow cannot be utilized when developing other UAM concepts. The first next steps will focus on expanding within the Lift+Cruise category and then to move on to other UAM eVTOL categories.

Acknowledgments

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References

[1] 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.

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

[3] A. Hahn, "Vehicle Sketch Pad: Parametric Geometry for Conceptual Aircraft Design," in *48th AIAA Aerospace Sciences Meeting*, Orlando, FL, January 4-7 2010.

[4] T. F. Winter, J. H. Robinson, A. Gamez and T. Nascenzi, "Crashworthiness Loads for Conceptual Design Structural Sizing of an UAM Quad Rotor Aircraft," *AIAA AVIATION 2021 FORUM*, p. 2437, 2021.

[5] T. F. Winter, J. H. Robinson, M. Sutton, J. Chua, A. Gamez and T. Nascenzi, "Structural Weight Prediction for an Urban Air Mobility Concept," *AIAA AVIATION 2020 FORUM*, p. 2653, 2020.

[6] T. F. Winter, J. Robinson, A. Gamez and T. Nascenzi, "Conceptual Design Structural Sizing for Urban Air Mobility," *AIAA Scitech 2021 Forum*, p. 1722, 2021.

[7] NASA Langley Research Center, Systems Analysis and Concepts Directorate, "NASA UAM Reference Vehicles," [Online]. Available: https://sacd.larc.nasa.gov/uam-refs/. [Accessed May 2022].

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

[9] S. K. S. Whiteside, B. P. Pollard, K. R. Antcliff, N. S. Zawodny, X. Fei, C. Silva and G. L. Medina, "Design of a Tiltwing Concept Vehicle for Urban Air Mobility," 2021.