Rapid Generation of Parametric Aircraft Structural Models

John Joe*, Viraj Gandhi†

Advanced Composite Structures Engineering Laboratory,
Purdue School of Engineering and Technology, IUPUI, Indianapolis, Indiana, 46202

John F. Dannenhoffer, III‡

Aerospace Computational Methods Laboratory, Syracuse University, Syracuse, New York, 13244

Hamid Dalir§

Advanced Composite Structures Engineering Laboratory,
Purdue School of Engineering and Technology, IUPUI, Indianapolis, Indiana, 46202

Within the aerospace design, analysis and optimization community, there is an increasing demand for automatic generation of parametric feature tree (build recipe) attributed multidisciplinary models. Currently, this is mainly done by creating separate models for different disciplines such as mid-surface model for aeroelasticity, outer-mold line for aerodynamics and CFD, and built-up element model for structural analysis. Since all of these models are built independently, any changes in design parameters require updates on all the models which is inefficient, time-consuming and prone to deficiencies. Here a browser-based system, called the Engineering Sketch Pad (ESP), is used. It provides the user with the ability to interact with a configuration by building and/or modifying the design parameters and feature tree that define the configuration. ESP is based an open-source constructive solid modeler, named OpenCSM, which is built upon the OpenCASCADE geometry kernel and the EGADS geometry generation system. The use of OpenCSM as part of the AFRL's CAPS project on Computational Aircraft Prototype Syntheses for automatic commercial and fighter jet models is demonstrated. The rapid generation of parametric aircraft structural models proposed and developed in this work will benefit the aerospace industry with coming up with efficient, fast and robust multidisciplinary design standardization of aircraft structures.

*Graduate Student, Department of Mechanical and Energy Engineering, AIAA Student Member.
†Graduate Student, Department of Mechanical and Energy Engineering, AIAA Student Member.
‡Associate Professor, Department of Mechanical and Aerospace Engineering, AIAA Associate Fellow.
§Associate Professor, Department of Mechanical and Energy Engineering, AIAA Member.

Nomenclature

BEM	Built Up Element Model
BRep	Boundary Representation
CAD	Computer Aided Drafting, Drawing, Design, Development
CAPS	Computational Aircraft Prototype Syntheses
EGADS	Engineering Geometry Aircraft Design System
ESP	Engineering Sketch Pad
MDAO	Multi-Disciplinary Analysis and Optimization
MSA	Mid-Surface Aero
OML	Outer Mold Line
IML	Inner Mold Line
OpenCSM	Open-source Constructive Solid Modeler
UDP	User-Defined Primitive

I.   Background

In the design, analysis and optimization of aerospace vehicles and structures, it is absolutely crucial to generate the geometry fast and in a robust way. For a given geometry, the number of structural solutions to support the design are unlimited. However, there is only one solution which could lead to the minimum weight for the structure. To realize this, a single common consistent parametric description of the design against different disciplines is necessary.

In Multi-Disciplinary Analysis and Optimization (MDAO) environments, it is a common practice to import the models from manufacturing design tools with usually IGES and STEP extensions. Although these structural parts and components are intended to be ultimately manufactured, the use of these extensions will create static (non-parametric) geometry models which are not intended for design optimization. Also to create a Boundary Representation (BRep), the models should be closed watertight which is extremely difficult due to the lack of a complete solid modeling geometry kernel to deal with the topology data if any.

A web browser based integrated software referred to as the Engineering Sketch Pad (ESP),[1] is used here which completely resolves the issues mentioned above. ESP is built upon the WebViewer[1] and OpenCSM[2] and is fully-parametric, attributed and is based on a feature-based solid-modeling system. OpenCSM in turn is built upon EGADS[3] and OpenCASCADE. All of this software is open-source, freely available without licensing restrictions, and is in general use.[4]

The main objective here is to demonstrate through examples on how ESP could help the aerospace community by generation of parametric, feature-based analysis models to perform efficient MDAO. This would hopefully fill the existing gap between fully realizable 3D representations and conceptual design and thus can be used to an advantage throughout the preliminary and detailed design stage.

II. Commercial and Military Aircraft Prototype Syntheses

Engineering Sketch Pad (ESP) is used here as the design tool to generate the structure of a commercial and a military aircraft models parametrically and create the built-up-element (BEM) ready for structural analysis. The input of ESP is written in a CSM file which is human readable and parsed by ESP. It is an ASCII file that contains all the information needed to create a model or set of sub-models.

To create an aircraft parametric model, 'despmtr' is used to create user input parameters and 'set' is used to create variables based on the inputs. These variables are mainly used to generate internal structures. In ESP if the user changes a parameter, the software will efficiently regenerate only those parts which are associated with that parameter.

ESP Master Model usually contains one or more user input design parameters. These parameters could be 1-D single value or n×n Matrices. These parameters can be 'set' using 'set' command to interconnect or can directly be given by user in ESP's Graphical User Interface. They are used to input values in command arguments. Another way of using parameters is using them in if/else loop or set them as Flag.

To be able to create computational grid to be used in Computational Fluid Dynamics (CFD) or other 3D field analysis tools, the generated body has to be watertight. To ensure this, ESP uses constructive solid modelling process which guarantees the model to be realizable solids. But, for global and local structural analysis, ESP can generate non-manifold sheet bodies as thin structural plates or wire bodies. These sheet structures are necessary to generate BEM models enabling the designer to perform structural analysis using quad shell elements.

The ESP model of a military fighter aircraft with different number of ribs, spars and wing tip angles along with the associated design parameters are shown in Figure 1 and Table 1, respectively.
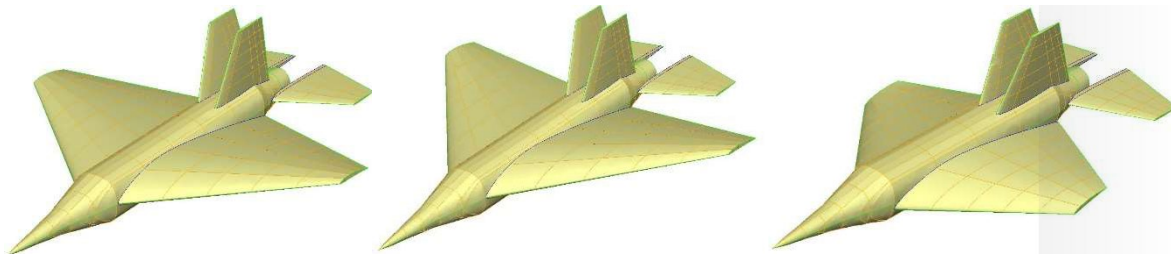

Figure 1. An ESP example of a military fighter aircraft with different number of ribs, spars and wing tip angles.

Table 1. Design parameters used to create the geometry of the military fighter aircraft.

Parameter name	Value	Description	Parameter name	Value	Description
cone_radius	0.25	Radius of nose cone	series_w	4409	NACA profile
cone_length	1.2	Length of nose cone	AOA1	2.0	Angle of attack at root
cockpit_length	5.5	Length of cockpit	AOA2	5.0	Angle of attack at tip
cockpit_num	3	Frame number in cockpit	series_h	406	NACA profile
cockpit_width	2.0	Width of cockpit	hwing_start_length	8.0	Length of horizontal wing at root
engine_length	4.5	Length of engine	hwing_end_length	3.0	Length of horizontal wing at tip
engine_num	2	Width of engine	hwing_spars_num	3	Number of spars in horizontal wing
engine_width	4.0	Frame number in engine	hwing_tip	36.0	Horizontal wing tip leading edge distance from nose
spars_num	6	Number of spars	hwing_span	15.0	Span of horizontal wing
spars_initial_length	20.0	Length of wing at root	vwing_height	6.0	Vertical wing tip height from nose
spars_final_length	4.0	Length of wing at tip	vwing_end_length	3.5	Length of vertical wing at tip
wing_tip	22.5	Wing tip leading edge distance from nose	vwing_tip_dist	33.0	vertical wing tip leading edge distance from nose
wing_span	30.0	Span of wing	mid_ribs	7	Number of ribs in fuselage
nozzle_width	2.8	Initial width of nozzle	wing_ribs	5	Number of ribs in wing
nozzle_length	3.0	Length of nozzle	hwing_ribs	2	Number of ribs in horizontal wing
nozzle_out_radius	1.15	Radius of nozzle at exit	vwing_ribs	4	Number of ribs in Vertical wing
nozzle_num	3	Number of frames in nozzle section			

The master models in ESP are defined in terms of a feature tree and a set of design parameters. This tree depicts the sequence of the operations used to create the final design which can be extracted from the CSM file and is shown in Figure 2.
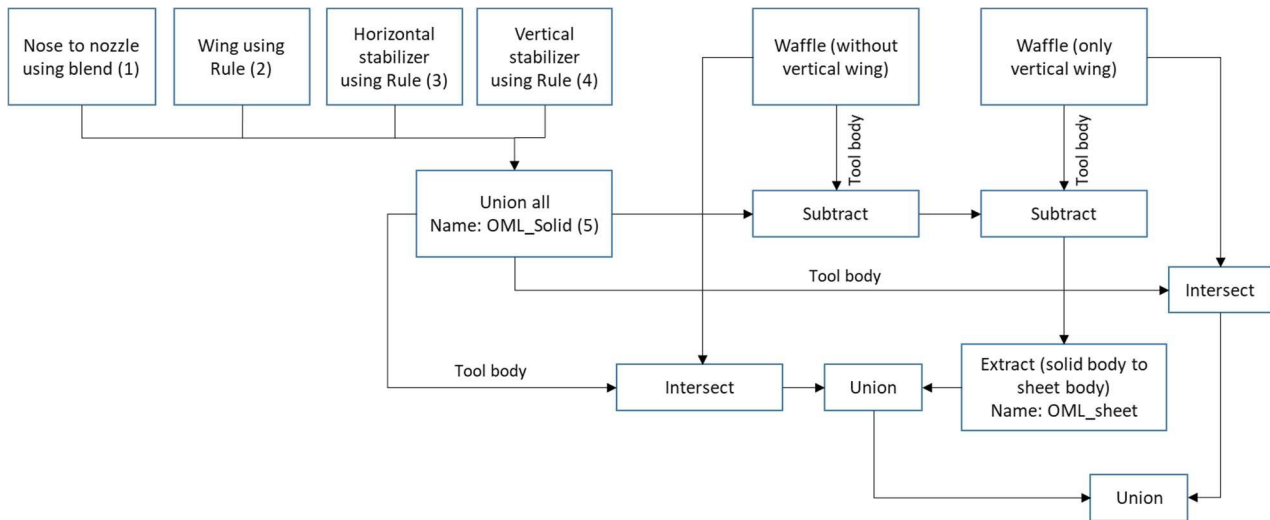

Figure 2. The ESP tree structure to generate a military fighter aircraft.

In this tree structure, each part contains of several steps. These steps are called 'Branches'. Each part starts with generation of standard primitives which includes Box, sphere, cone, cylinder, or torus. Some primitives are used to join sketches such as extrude, rule, blend, revolve, sweep, or loft. And some are User Defined Primitives (UDP) such as 'Naca' and 'supell' (super ellipse). ESP arranges bodies in a stack order approach. This means that a given command is being operated on the last generated body or the last two bodies in case of the Boolean operations.

Figure 3 shows some key steps in generation of the fighter aircraft model. Figure 3a demonstrates the OML which is made from geometric user input parameters. Figure 3b shows a parametric waffle structure which upon its intersection with the OML will generate the internal structure of the aircraft (see Figure 3c). This structure is fully parametric and one can easily and efficiently change the number, thickness and the shape of the internal structures.
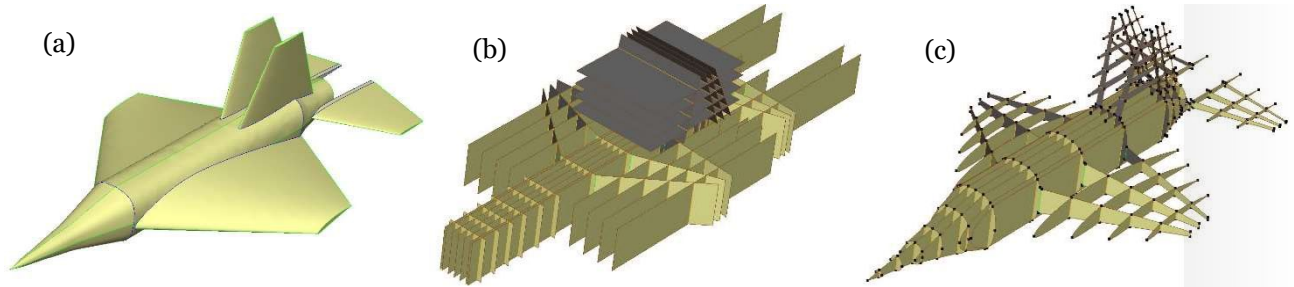

Figure 3. Parametric generation of the OML and the internal structure of a fighter plane in ESP.

The internal structure is created using Waffle UDP which takes a group of crossing lines in X-Y plane and extrudes them up in Z direction to create a non-manifold group of Faces. The waffle is then subtracted from the OML, which enforces the outer sheet Body to be scribed by the faces of the waffle.

5

Table 2 shows the design parameters used in building the parametric model of the commercial aircraft. The three models shown in Figure 4 are different in terms of the configuration of their internal structures. The design parameters of each model have been depicted in Table 3. To create a new model with a new set of design parameters, one needs to vary the relevant design parameters. The new ESP model takes about 10 - 15 minutes to regenerate which will result in a fast and accurate multidisciplinary design optimization platform.

Table 2. Design parameters used to create the geometry of the commercial aircraft

| Parameter name	Value	Description	Parameter name	Value	Description
Fuse	[23x4] matrix	Dimensions of the fuselage(x,y,z1,z2)	xroot_v	13.2	Distance of root of horizontal stabilizer from nose
noseList	[2x4] matrix	Curvature of nose cone in three directions	zroot_v	0.4	Distance of root of horizontal stabilizer from central plane of plane
series_w	4409	NACA profile, location and orientation data for the wing	area_v	9.6	Area of the vertical tail
wing	[3x5] matrix	x,y,z, chord length & angle of attack of 3 profiles in wing	taper_v	0.3	Taper ratio of the horizontal tail
series_h	406	NACA profile for the horizontal stabilizer	aspect_v	3	Aspect ratio of the vertical tail
xroot_h	14.5	Distance of root of horizontal stabilizer from nose	sweep_v	45	Swept angle of the vertical tail
zroot_h	0.2	Distance of root of horizontal stabilizer from the central plane	stringers_no	4	Number of stringers in one half plane (this ensures even number of stringers)
aroot_h	0	Angle of attack of the horizontal tail at the tip	fore_frames_no	6	Number of frames between nose and wing
area_h	0.78	Area of the horizontal tail	aft_frames_no	7	Number of frames between wing and vertical stabilizer
taper_h	0.55	Taper ratio	ribs_no	8	Number of ribs
aspect_h	3.7	Aspect ratio of the horizontal tail	iribs_no	3	Number of ribs in the region joining the wing and fuselage
sweep_h	25	Swept angle of the horizontal tail	hribs_no	6	Number of ribs in the horizontal stabilizer
dihed_h	3	Dihedral angle of the horizontal tail	vribs_no	6	Number of ribs in the vertical stabilizer
twist_h	2	Twist angle of horizontal tail	spars_no	2	Number of spars
series_v	404	NACA profile for the vertical stabilizer			
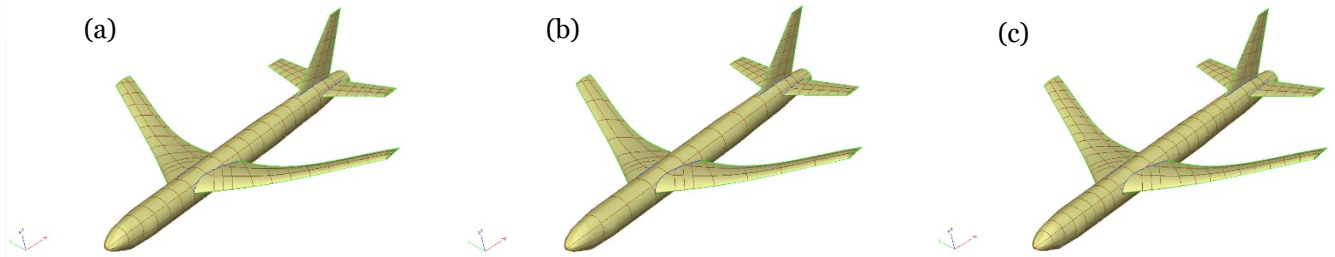
Figure 4. Parametric generation of the OML and the internal structure of a commercial plane in ESP.

Table 3. Design parameters used to generate different internal structures

	Number of ribs in the wing	Number of fore frames	Number of aft frames
Figure 4a	8	6	7
Figure 4b	5	3	4
Figure 4c	10	8	8

Figure 5 shows different stages of the model generation process. Figure 5a depicts the Outer Mold Line (OML) of the aircraft which is the union of all the skins of the plane. Figure 5b is an extruded waffle to generate some of the internal aircraft structure which upon its intersection with the skin OML will result in the internal structure of the plane. The waffle for the vertical tail is intersected separately with the vertical tail and then is unioned with the main waffle. Figure 5c shows the union of the two horizontal and vertical waffles with only the two central stringers. The remaining stringers are intersected with the fuselage, rotated and then unioned with the waffle, thus forming the final internal structure of the aircraft (see Figure 5d). The waffle structure is then subtracted from the OML to scribe it. This divides the OML into different skin panels intersected by the waffle. The scribed OML is then unioned with the internal structure and the Inner Mold Line (IML) is subtracted from the model. The resulting final model is shown in Figure 5e.
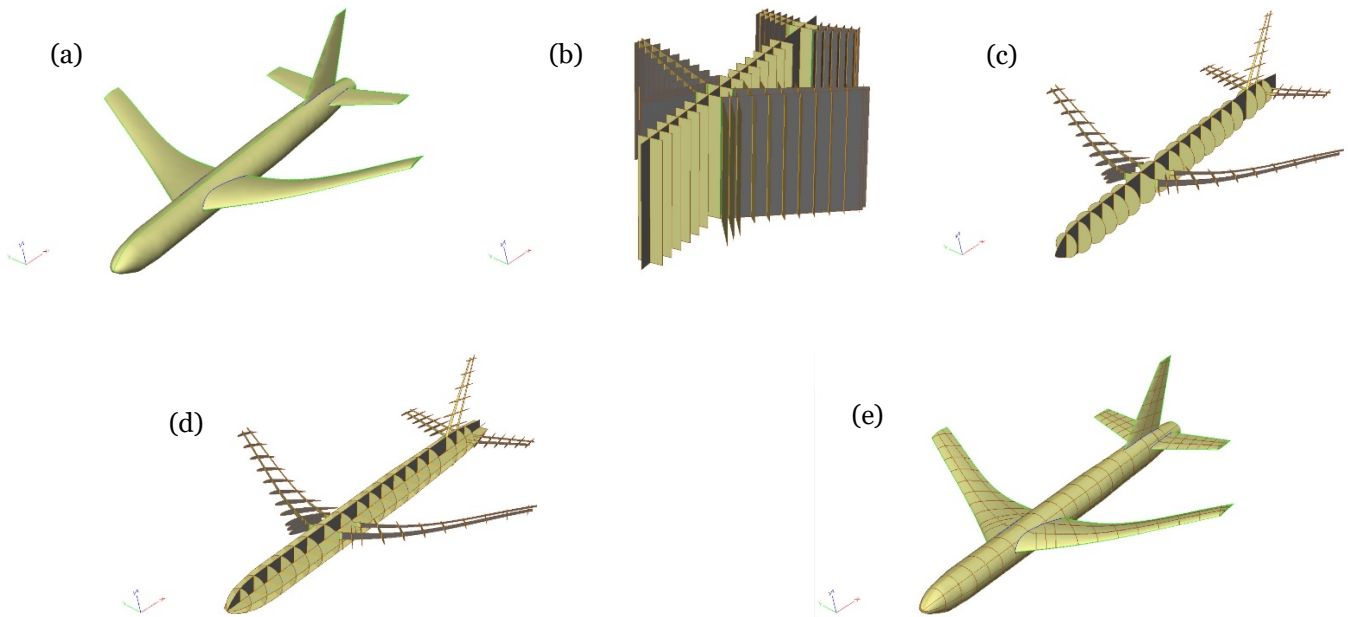

Figure 5. Parametric generation of the OML and the internal structure of a commercial plane in ESP.
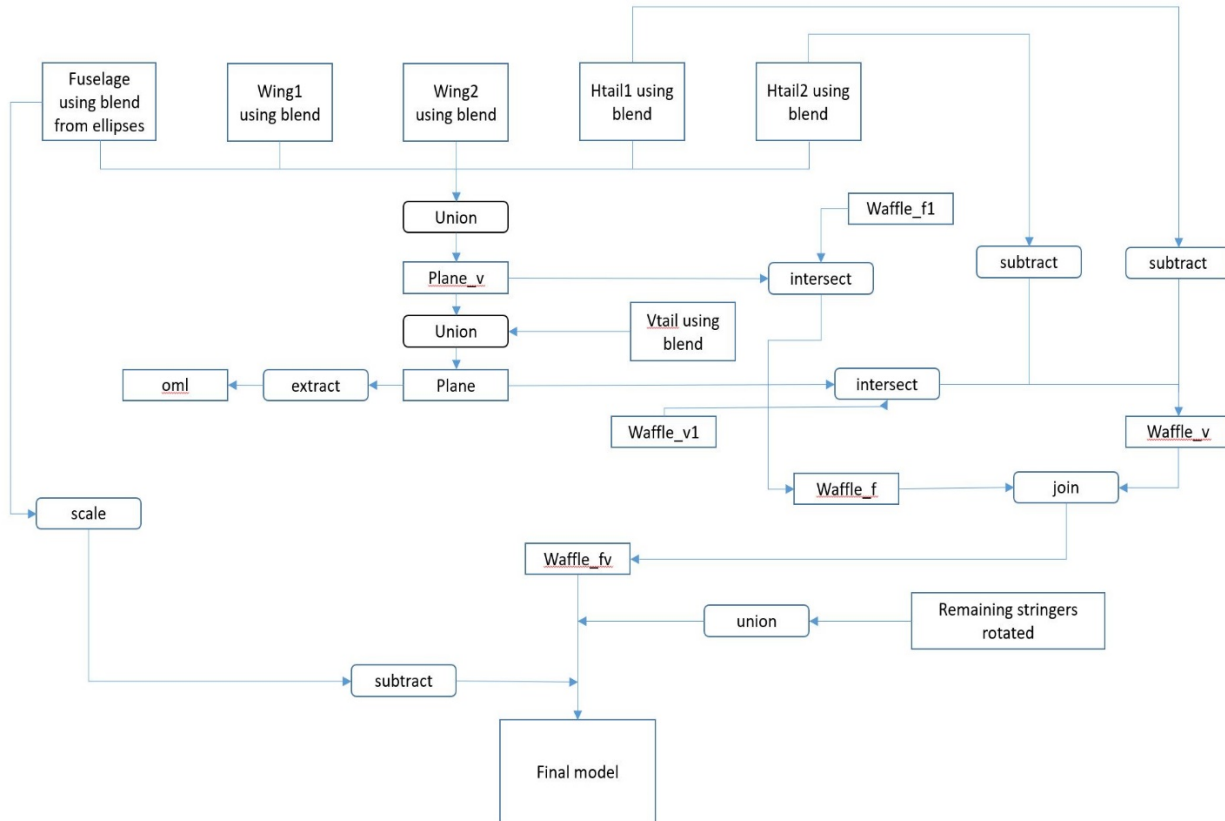
Figure 6. The ESP tree structure to generate a commercial aircraft.

The tree structure shown in Figure 6 explains the process involved in the generation of the commercial aircraft. The OML is generated by the union of the fuselage, the wing, the engine and the horizontal and vertical stabilizers, each of which are in turn generated using either the UDP blend for quadratic surface splines or UDP rule for linear surface splines from different profiles of the target solids. A parametric waffle is generated which contains the two central stringers as well as all the frames in the fuselage, the ribs and spars in the wing and the horizontal stabilizers. This waffle is intersected with the entire aircraft excluding the vertical stabilizer. A second waffle is generated that corresponds to the internal structure of just the vertical stabilizer and the frames inside the vertical tail supporting it. The result model is intersected with the vertical stabilizer. The remaining protruding parts are removed by subtracting the horizontal stabilizers from this waffle. The two waffles are unioned together to form a single body. Sheet bodies are then created and rotated, forming the remaining stringers, and are then unioned to the join of the two waffles. The OML, which is a solid body is then extracted to generate a sheet body. The waffles are subtracted from the OML to scribe the OML with the internal structure. The internal structure is then unioned with the OML to generate the final model.

In this section a more detailed design of the wing including the panel stiffeners using the parameters in Table 4 is discussed. The wing as shown in Figure 7a is modeled by creating two NACA profiles and connecting them. The internals as shown in Figure 7b are created using the UDP 'waffle'. The UDP waffle allows the creation of a 2D sketch in the X-Y plane, which is then extruded in the Z direction. ESP allows the waffle to be created from a detailed text file which provides control over the geometry of the waffle. Figure 7c shows the waffle intersected with the OML of the wing generating the internal support structure.

Table 4. Design parameters used to create the geometry of the detailed parametric wing

Parameter name	Value	Description
series_w	4409	NACA profile of the wing
area	10	area of the wing
aspect	6	aspect ratio of the wing
taper	0.7	taper ratio of the wing
sweep	20	sweep angle of the wing
nrib	5	number of ribs in the wing
xfirst	0.2	percentage distance in the chordwise length of the first spar
xlast	0.75	percentage distance in the chordwise length of the last spar
nspar	3	number of spars in the wing
nstiff	3	number of stiffeners on the wing panel
depth	-0.01	depth of the stiffener
angle	45	angle of the runoffs at the ends of the stiffener

More intricate details about the wing such as the stiffeners can be modelled using the UDP stiffeners. Stiffeners are critical in the conceptual design as they are responsible for the stability of the model under buckling. UDP stiffener enables generating runoffs at both ends of the stiffeners. Figure 7e demonstrates the entire wing with all individual panels stiffened.
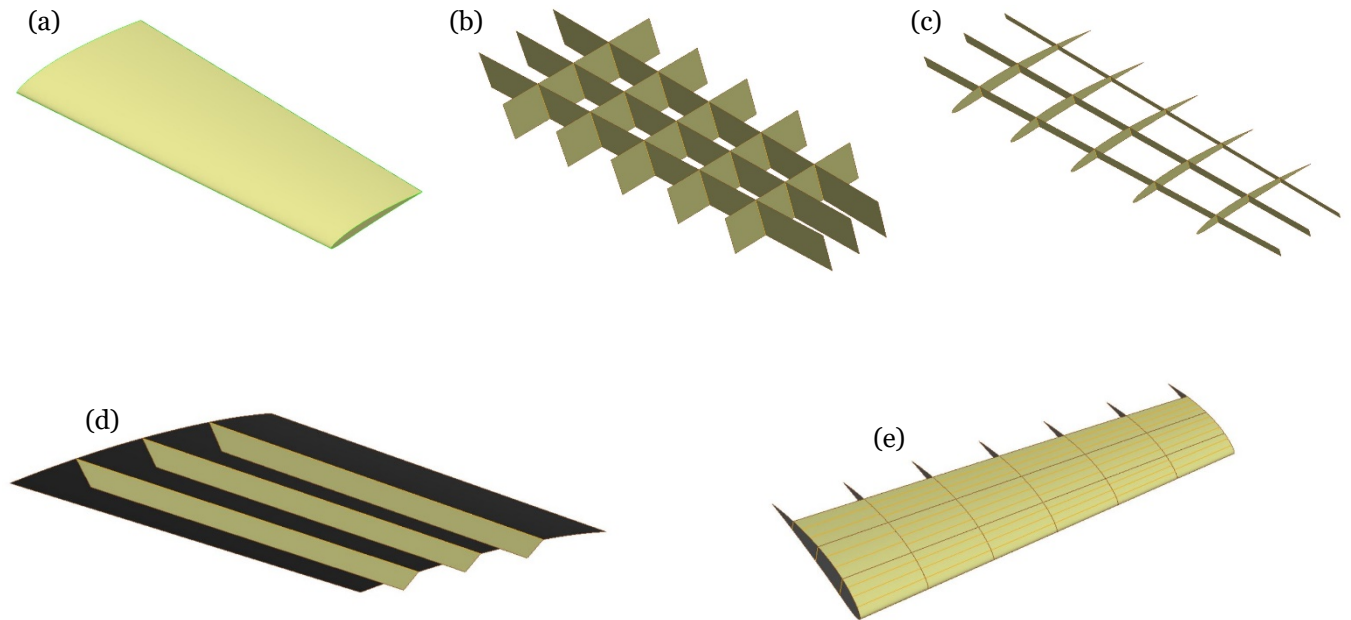
(a)

(b)

(c)

(d)

(e)

Figure 7. Parametric generation of the OML and the internal structure of a detailed wing in ESP.

III. Integration with the Analysis Tools

One of the main advantages of ESP is its capability to generate BEMs which could be robustly imported by structural analysis tools such as NASTRAN. To demonstrate this, the parametric generated model of the wing of the fighter was discretized into structured quadrilateral mesh using 'createBEM' UDP in ESP (see Figure 8). This mesh structure will provide a platform for performing structural analysis.
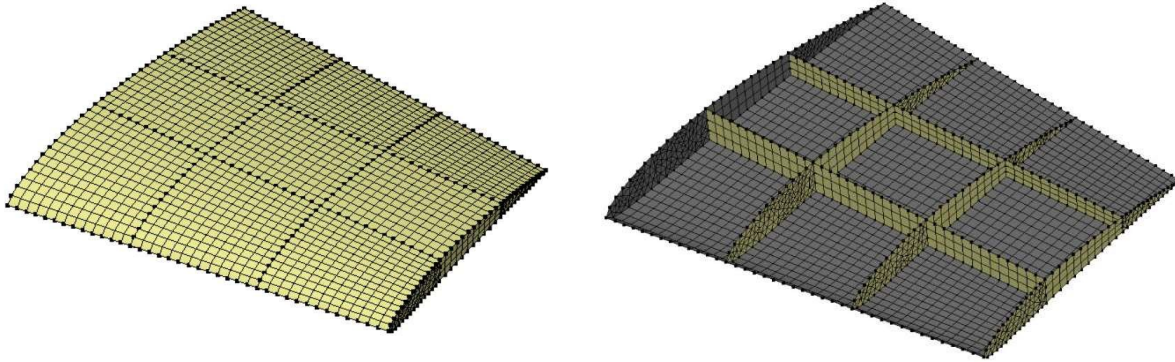

Figure 8. the parametric meshed model of the wing of the fighter in ESP.

IV. Conclusions

The CAPS program set out with the goal of having a single source geometry capability that could provide inputs to multi-fidelity, multi-physics solvers in a quick and efficient way. We are currently working on elaborating this capability by rapid generation of commercial and military aircraft prototypes to be used in conceptual design, multi-disciplinary design optimization, and high fidelity physics simulations (notably absent is CAD assemblies and three view drawings). The main advantage is that the models are parametric, attributable and have geometric sensitivities associated with the parameters. Finally, this paper will include the steps involved in creating rapid models of two commercial and military aircrafts as well as a detailed wing where the user-intensive generation of the BEM and interface connections are automated via the CAPS infrastructure.

V. Acknowledgement

References

[1]Haimes, R. and Dannenhoffer, J., "The Engineering Sketch Pad: A Solid-Modeling, Feature-Based, Web-Enabled System for Building Parametric Geometry," 21st AIAA Computational Fluid Dynamics Conference, No. 2013-3073, American Institute of Aeronautics and Astronautics, Jun. 2013.

[2]Dannenhoffer, J., "OpenCSM: An Open-Source Constructive Solid Modeler for MDAO," 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, No. 2013-0701, American Institute of Aeronautics and Astronautics, Jan. 2013.

[3]Haimes, R. and Drela, M., "On The Construction of Aircraft Conceptual Geometry for High-Fidelity Analysis and Design," 50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, No. 2012-0683, American Institute of Aeronautics and Astronautics, Jan. 2012.

[4]Bhagat, N. D. and Alyanak, E. J., "Computational Geometry for Multi-fidelity and Multi-disciplinary Analysis and Optimization," 52nd Aerospace Sciences Meeting , No. 2014-0188, American Institute of Aeronautics and Astronautics, Jan. 2014.