

Continuing the Development of a Physics-Based Weight (PBWeight) Prediction Tool for Conceptual Design: Build 2

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I. Introduction

Many critical challenges currently exist for designing, developing, and analyzing physics-based conceptual aircraft design tools. One challenge of particular relevance to the current effort is the desire to accurately and efficiently predict weights and loadings for unconventional designs. Unconventional designs are required to break through the common or 'expected' limitations associated with conventional designs. Furthermore, the ability to assess, in a rapid manner, the feasibility of these unconventional designs is crucial to NASA's Environmentally Responsible Aviation (ERA) project as well as many other efforts seeking to develop enabling technologies required to solve a variety of important design problems (high lift-to-drag ratios, community noise, reduced drag, etc.). The Blended Wing Body (BWB) or Hybrid Wing Body (HWB) aircraft, for example, has been researched and analyzed for many years as an unconventional efficient transport configuration.

Approaches for weight prediction in the conceptual design phase typically consist of parametric relations or empirical databases [1] [2]. Historical databases work reasonably well when applied to existing or conventional designs, however, they fail to predict accurately the weights and loads associated with unconventional designs (like the BWB). There exists a need to augment existing historical databases with a physics-based methodology/capability for predicting the weights and loads of unconventional designs.

In the current effort, M4 Engineering has further developed the PBWeight software to enhance the current capabilities of the software as well as add new enhancements in an effort to build a complete weight statement for unconventional (and conventional) conceptual designs. The main goal for this effort was primarily to streamline the internal structural layout process for conventional and unconventional designs. The core of the PBWeight software is built upon three key software components. First is OpenVSP, which is an open source parametric aircraft geometry tool capable of rapidly creating geometry OMLs. Second is RapidFEM, a previously developed tool capable of automatically generating geometry and Finite Element Models (FEMs) of complex built-up structures for rapid concept evaluation and structural optimization. The last software component is the RapidFEM Sketch File Editor, an efficient and user-friendly interface for streamlining the internal structural layout process, assigning material properties, attachments, loads, and optimization analysis information.

The main objective of this paper is to describe the new additions to the PBWeight software tools aimed at increasing the efficiency and usability of the interface for streamlining the internal structural layout process, assigning material properties, attachments, loads, and optimization analysis information.

In the following section, a brief overview of the PBWeight process work flow is given. In Section III, an overview of the Automated Wing and Fuselage Layout Tools that were integrated within OpenVSP is given. In Section IV, explanations of the added capabilities to the RapidFEM Sketch File Editor, including the RapidFEM BEAM Paver Tool and RapidFEM SKIN4 Paver Tool will be provided. In Section V, an examination of the Parametrically Driven Trade Study Engine will be given. Finally, in Section VI, conclusions and future work are discussed.

II. PBWeight Process Work Flow Overview

There are four main steps involved for producing an optimized weight statement using the PBWeight software suite. The PBWeight software work flow can be seen in Figure 1. An overview of the PBWeight process is shown below followed by a detailed description of each step:

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PBWeight Process Work Flow Summary

1. Place RapidFEM Sketch Points (these are the points that will connect internal structural entities as well as boundaries) on each geometry component.
2. Specify RapidFEM Explicit Sketch Cards in order to “build up” the internal structure, assign property regions, non-structural mass attachments, mesh properties, and analysis deck information.
3. Merge and trim component FEMs.
4. Perform weight optimization analysis (including static aeroelastic analyses, flutter, etc.) to size aircraft and generate weight statement.

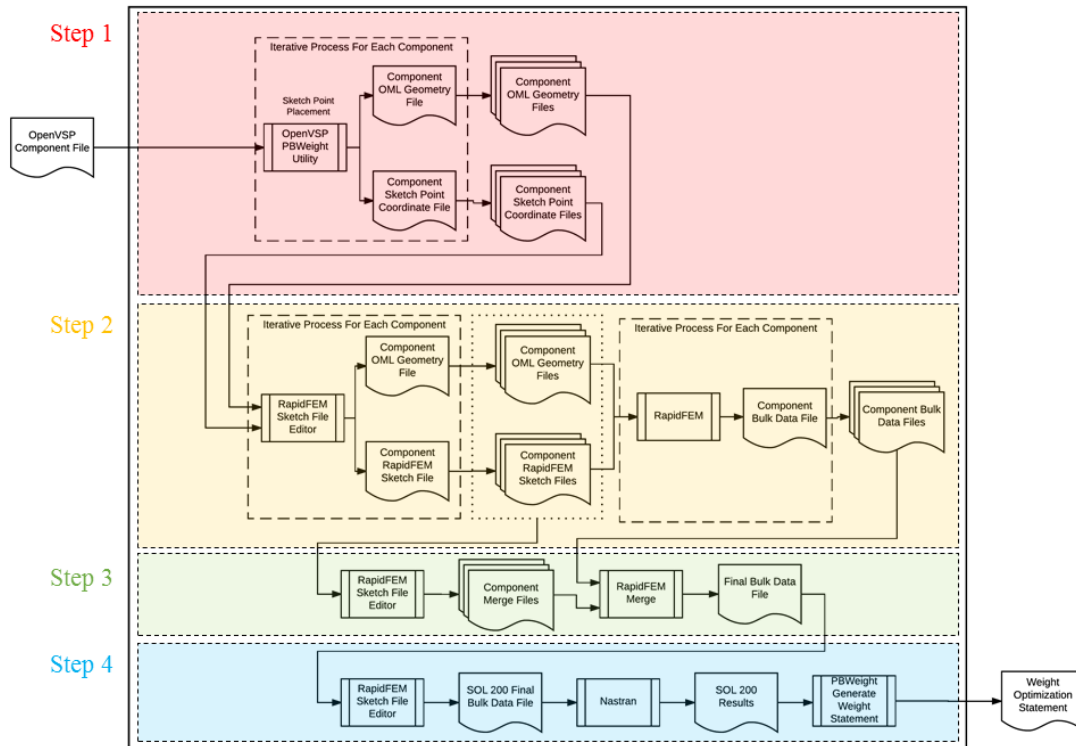


Figure 1: PBWeight Data File Work Flow.

The first step in the process is to create a Sketch Point Layout for each component containing internal structure using the PBWeight Utilities developed within OpenVSP. For example, the Sketch Point Layout Creator Tool allows a user to attach Sketch Points to the surface of an OpenVSP component, such as a wing or a fuselage. These Sketch Points share a parent/child relationship that keeps them attached to the parent component, which is particularly important when design parameters change after Sketch Points have been placed. By leveraging this parent/child component relationship, the previously placed points move accordingly when the parent component geometry is altered. Further on in this paper, the Automated Wing Layout Tool and Automated Fuselage Layout Tool will be discussed to show how M4 Engineering was able to further streamline this process by utilizing these newly added tools. Once the Sketch Points are properly placed, the user must build up the internal structure (i.e. define ribs/spars, skins, attachments, etc.) within the RapidFEM Sketch File Editor. This utility is accessed by selecting “Setup RapidFEM Sketch File” under the PBWeight menu within OpenVSP. Once selected, both a RapidFEM Sketch File (.rfs), as well as an STL representing the OML of the component are exported to the RapidFEM Sketch File Editor. After these files have been exported for each component, the RapidFEM Sketch File Editor is automatically opened and loaded with the newly created RapidFEM Sketch Files.

The second step in the PBWeight process is to create RapidFEM explicit sketch cards used to define internal structure, such as BEAMs and SKINs, using the RapidFEM Sketch File Editor. In section IV, the BEAM Paver and SKIN4 Paver tools, which make this internal structural definition process even more efficient, will be discussed. After the meta-geometry definitions have been created, the RapidFEM Sketch File and STL for each component are used as inputs for RapidFEM, which will produce component FEMs.

After a complete set of component FEMs has been produced by RapidFEM, the third step in the PBWeight process is to Merge/Trim the individual components into a final FEM representing the entire vehicle. The desired Merge/Trim locations are designated by specifying a set of precise property regions. Once the Merge/Trim regions are created, RapidFEM will process these regions through an iterative procedure and produce a final completely merged and trimmed FEM.

After analyzing a variety of important load cases (static aeroelastic, flutter, etc.) to properly size the aircraft components and validate the design, the last step in the PBWeight process is to run Nastran Solution 200 to produce the optimized weight statement. From the PBWeight dropdown menu, the user selects “Generate Weight Statement” and a weight statement detailing individual component weights is displayed.

III. PBWeight Integration Enhancements within OpenVSP

The goal for the PBWeight GUI software is to provide a natural extension to OpenVSP for allowing users to create meta-geometry definitions of internal structure rapidly. The PBWeight GUI software has been developed to support version 3.11.0 of OpenVSP and was successfully built from source code obtained from OpenVSP’s GitHub repository. OpenVSP is constantly being improved to increase functionality and robustness, thus this causes PBWeight’s GUI to be developed in such a way that promotes ease of version upgrading. This will not only ensure the PBWeight GUI will have access to the new functionality within OpenVSP as its software progresses, but it will also ensure that the PBWeight GUI will be compatible with an up-to-date version of OpenVSP.

A. PBWeight GUI Integration within OpenVSP

Development of the source code for the meta-geometry definition process (e.g. PBWeight GUI) is consistent with the current OpenVSP source code, while the core PBWeight analysis software is separate and callable from the PBWeight dropdown menu and from the RapidFEM Sketch File Editor. Integration began with the creation of a PBWeight dropdown menu on OpenVSP’s main window as shown in. This dropdown menu gives the user access to the PBWeight specific toolset, which includes a Sketch Point Layout Creator, the RapidFEM Sketch File Editor, the Automated Wing Layout Tool, the Automated Fuselage Layout Tool, as well as a Weight Statement Utility tool.

B. Automated Wing Layout Tool

To further increase efficiency and throughput of the PBWeight software during the Sketch Point Layout process for wing-like components within OpenVSP, M4 Engineering has developed an Automated Wing Layout Tool. The Sketch Point Layout process is a very important step because it is the foundation upon which the internal structure is defined. By using the Automated Wing Layout Tool, the required tasks for the user are reduced to simply defining the number of ribs/spars and spar locations as a function of percent chord.

The Automated Wing Layout Tool takes advantage of the low-level capabilities that were added to OpenVSP including sketch point layout creation, sketch point placement, sketch point location adjustment, and RapidFEM attribute assignment. The purpose of the Automated Wing Layout Tool is to have the PBWeight toolset generate a sketch point layout and construct a RapidFEM Sketch File, including RapidFEM attributes such as ribs and spars (BEAM cards), skins (SKIN3 and SKIN4 cards), control surfaces, etc., with minimal user interaction.

To access the Automated Wing Layout Tool, the users selects the tool from the PBWeight menu in OpenVSP as shown below in Figure 2.

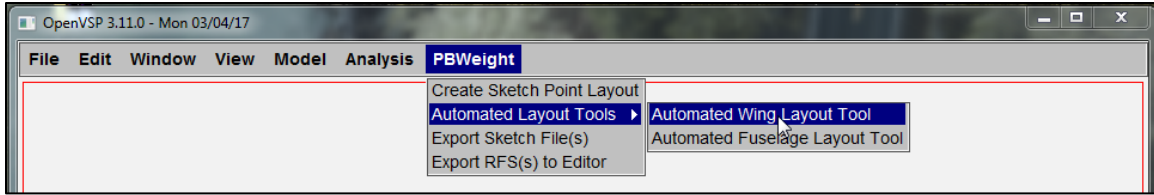


Figure 2: Automated Wing Layout Tool Menu Option.

When this is selected, a window appears asking the user to specify the sketch plane orientation upon which the Sketch Point Layout will be created, as seen in Figure 3 below.

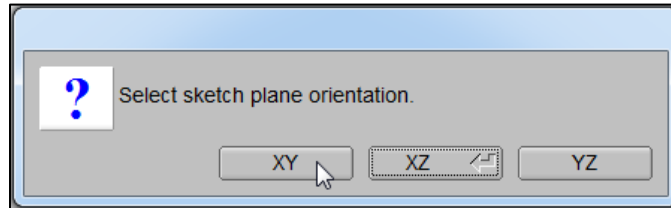


Figure 3: Automated Wing Layout Tool - Sketch Plane Orientation.

Once the sketch plane has been chosen, the Automated Wing Layout Tool wizard opens allowing a user to specify wing specific parameters of which will be used to automatically create a complete Sketch File. As seen below in Figure 4, the user first specifies the number of ribs that will be created.

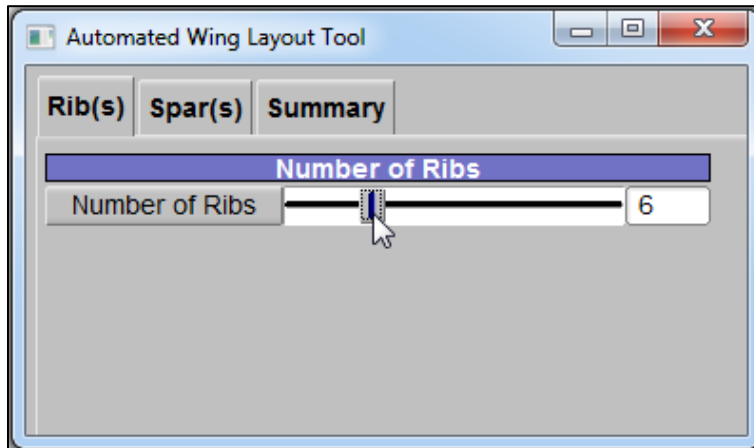


Figure 4: Automated Wing Layout Tool – Rib Definition.

The Automated Wing Layout routine places ribs equidistant across the entire span of the wing component. If the rib spacing needs to be altered, the multipoint traverse, or multipoint adjustment tools can be used. After rib definition, the user moves onto defining the spars. The parameters offered to the user are number of spars and the location of the leading edge and trailing edge spars (if applicable), specified by a % chord position from the leading edge, as seen in Figure 5 below. If more than two spars are specified, the intermediate spars are placed equidistant between the leading edge, and trailing edge spars. Like the ribs, if the intermediate spar locations need to be adjusted, the multipoint traverse or multipoint adjustment tools will have to be used.

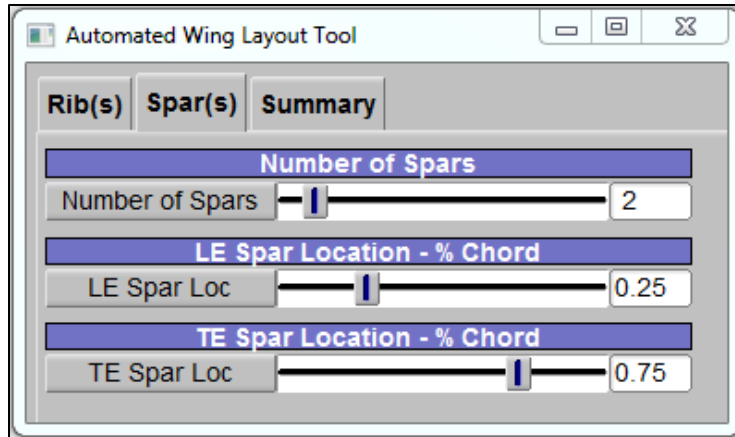


Figure 5: Automated Wing Layout Tool – Spar Definition.

After the ribs and spars have been specified, the user continues to the “Summary” tab on the Automated Wing Layout Tool screen and press the “Build Wing Layout” button. Once pressed, the routine calculates the correct spacing of both the ribs and the spars. After the requisite points have been placed, addition logic is used to place additional points if needed to ensure a proper RFS will be created. Below in Figure 6 an example of a completed point layout can be seen, with 6 ribs and 2 spars, created with the Automated Wing Layout Tool.

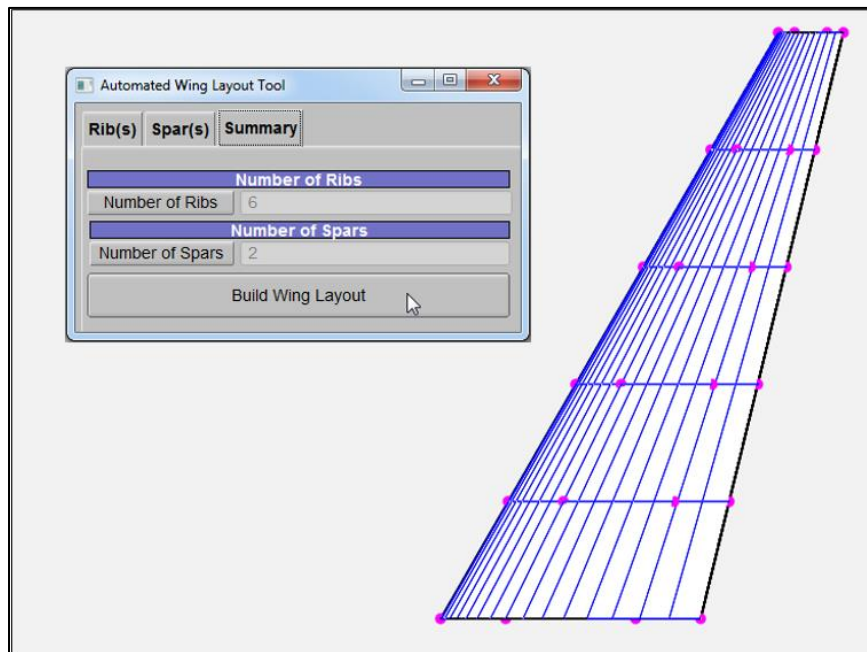


Figure 6: Automated Wing Layout Tool – Completed Point Layout.

When all the points have been placed, the automated tool builds up an RFS data structure containing RapidFEM BEAM cards, SKIN3/SKIN4 cards. To ensure the RFS generated by the tool can be used by RapidFEM to produce a satisfactory BDF, a minimum set of RapidFEM cards (PROP, MTRL, NODE0, etc.) are created as well. This can be seen in Figure 7 below.

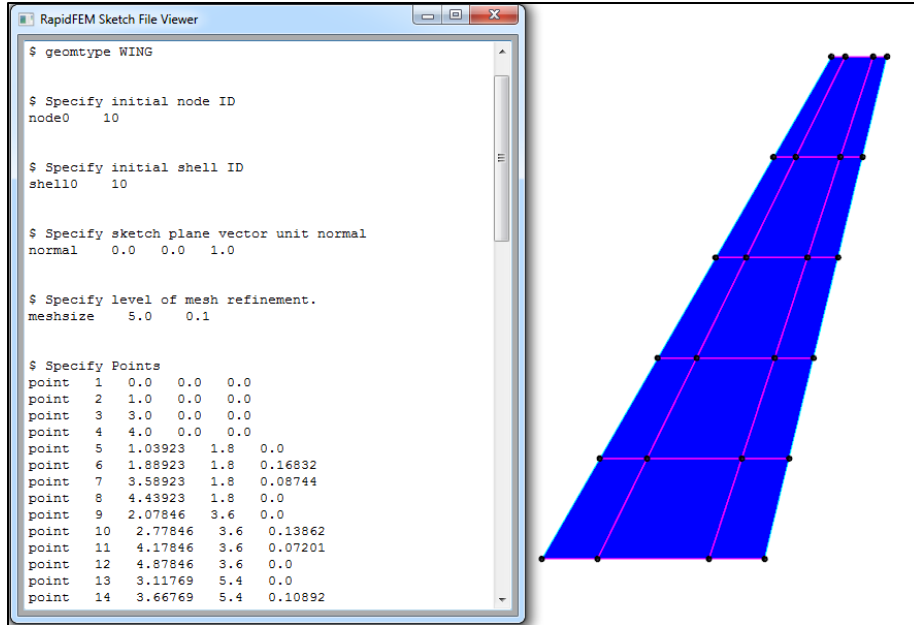


Figure 7: Automated Wing Layout Tool - Completed Layout.

Below in Figure 8 is the FEM produced by RapidFEM using the RFS automatically generated by the Automated Wing Layout Tool. The FEM is water tight and contains the internal structure (6 ribs and 2 spars) specified in the tool.

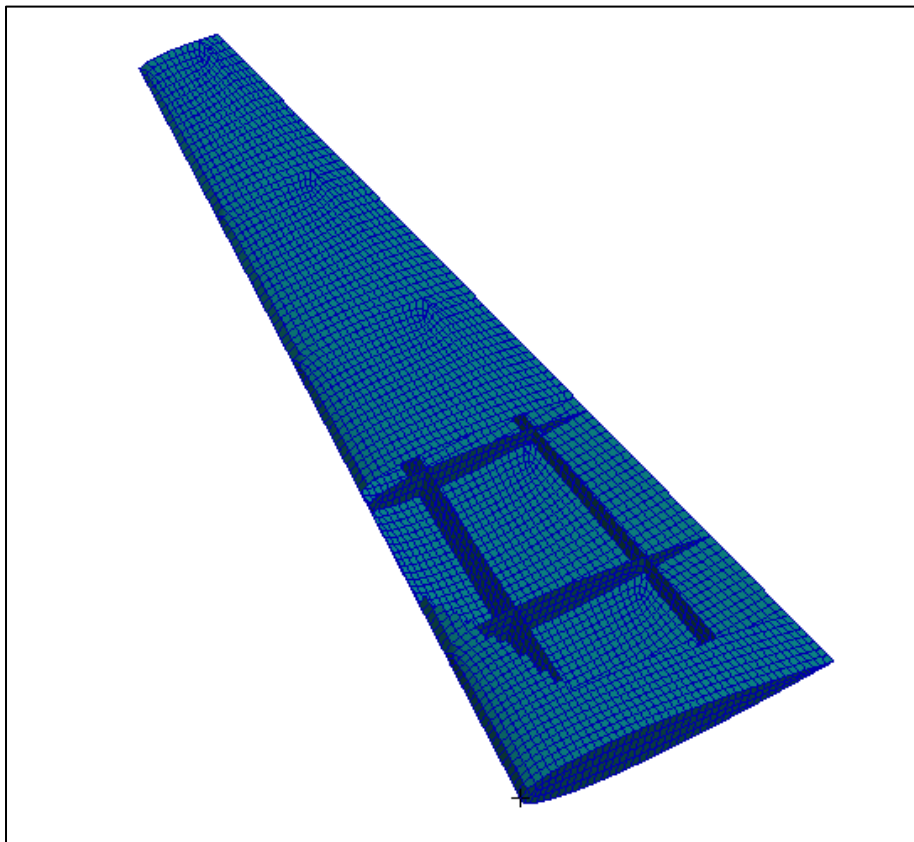


Figure 8: FEM Produced Using the Automated Wing Layout Tool.

C. Automated Fuselage Layout Tool

In addition to the Automated Wing Layout Tool, M4 Engineering has developed an Automated Fuselage Layout Tool. Similar to the Automated Wing Layout Tool, the Automated Fuselage Tool is capable of producing a complete .rfs file containing Sketch Points, BEAMs, SKINs, and other RapidFEM cards to prescribe the internal structure of a fuselage-like component. The tool is capable of modeling bulkheads and a single floor. Shown in Figure 9 below, a “Automated Fuselage Layout Tool” menu option has been added to the existing PBWeight menu on the OpenVSP menu bar.

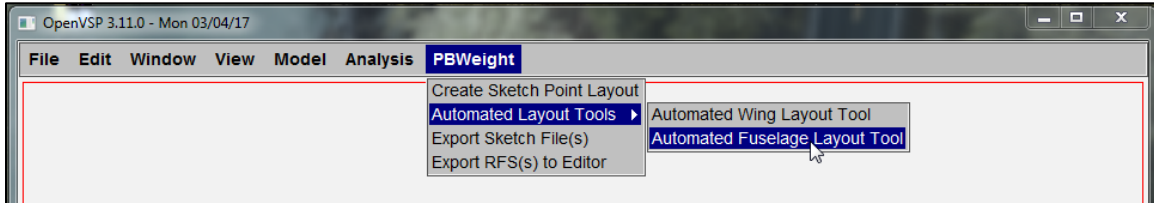


Figure 9: Automated Fuselage Layout Tool Menu Option.

Once selected, the Automated Fuselage Layout Tool wizard opens allowing a user to specify fuselage specific parameters, of which will be used to create a complete Sketch File automatically. As seen below in Figure 10, the user first specifies the number of bulkheads and their locations.

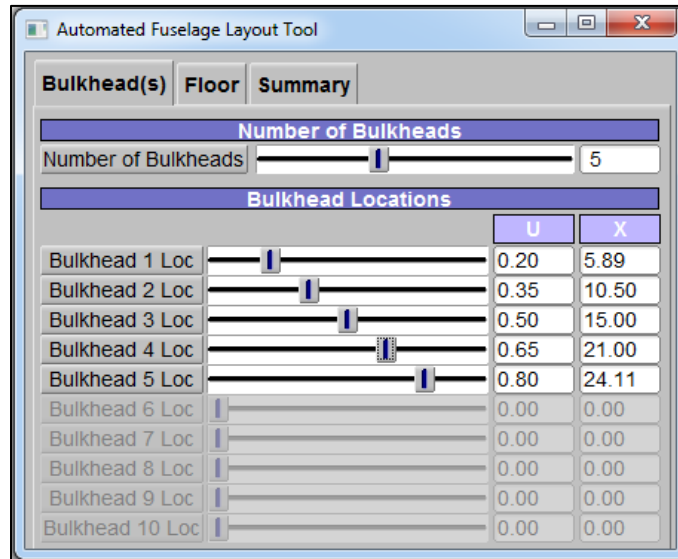


Figure 10: Automated Fuselage Layout Tool – Bulkhead Definition.

The user has the option of using the bulkhead location sliders, manually selecting a U location, or manually specifying an X location. When the user manually inputs an X value, the sketch point location solver computes a U value that satisfies the given X value.

After the bulkheads have been defined, the user moves onto defining the floor. To fully define a floor, the user must specify a bulkhead where the floor starts at, a bulkhead where the floor ends at, and the vertical location of the floor. These parameters can be seen in Figure 11 below.

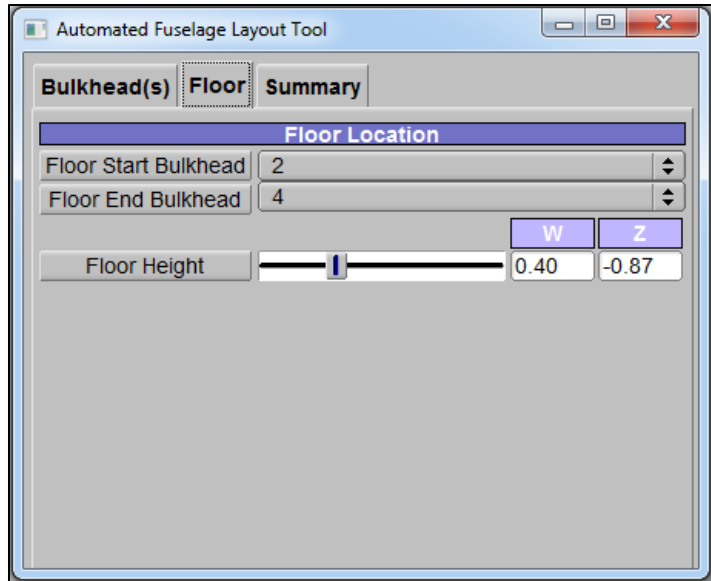


Figure 11: Automated Fuselage Layout Tool – Floor Definition.

After the bulkheads and floor have been specified, the user continues to the “Summary” tab on the Automated Fuselage Layout Tool screen, and press the “Build Fuselage Layout” button. Once pressed, the routine calculates the correct spacing of both the bulkheads and the floor. Once the requisite points have been placed, addition logic is used to place additional points if needed to ensure a proper RFS will be created. Below in Figure 12 is an example of a completed point layout, with 5 bulkheads and a floor, created with the Automated Fuselage Layout Tool.

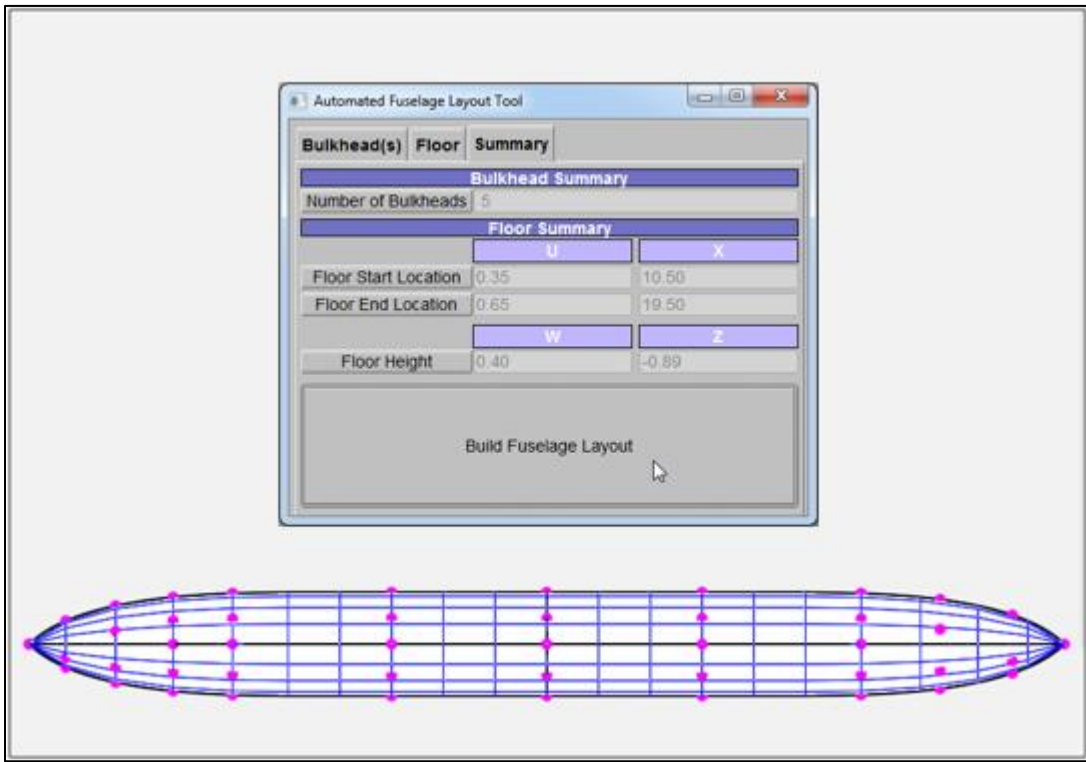


Figure 12: Automated Fuselage Layout Tool – Completed Point Layout.

Once the points have been placed, the automated tool builds up an RFS data structure containing RapidFEM BEAM cards, SKIN3/SKIN4 cards, and a required minimum set of RapidFEM cards (PROP, MTRL, NODE0, etc.) to create an RFS file that can be executed in RapidFEM, as seen in Figure 13.

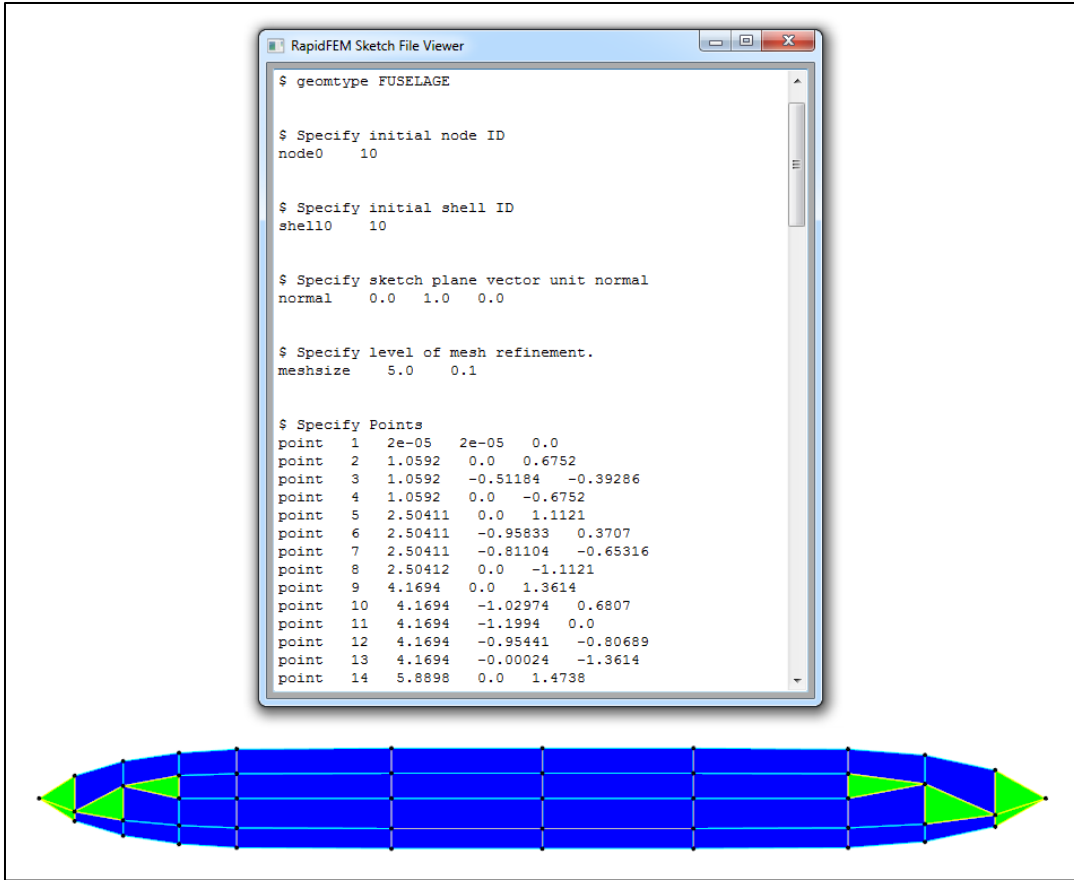


Figure 13: Automated Fuselage Layout Tool - Completed Layout.

Figure 14 shows a basic example FEM produced by RapidFEM using the RFS automatically generated by the Automated Fuselage Layout Tool. The FEM is water tight and contains the internal structure (5 bulkheads and a floor) specified in the tool.

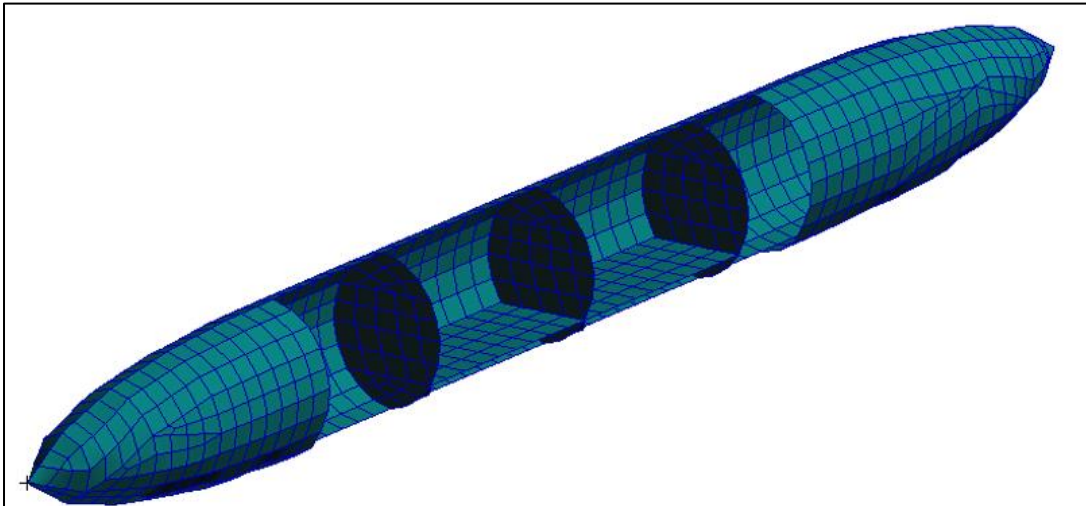


Figure 14: FEM Produced Using the Automated Fuselage Layout Tool.

IV. RapidFEM Sketch File Editor Enhancements

A. RapidFEM BEAM Paver Tool

When internal structure such as ribs and spars in a wing become complex (or numerous), it can be tedious for the user to place individual RapidFEM BEAMs one at a time to represent these internal structural components. It can be very inefficient as well. To solve this problem and make the act of placing BEAMs much more efficient, M4 Engineering has created an Automated BEAM Paver Tool within the RapidFEM Sketch File Editor. With the addition of this BEAM Paver Tool, the user is able to place BEAM components using two different methods.

The first method is the original method of placing individual BEAMs. The second is to use the new BEAM Paver Tool, which allows the user to place multiple RapidFEM BEAMs with the same material property at once. This method is especially useful for creating BEAMs to represent ribs and spars when there is a large number of BEAMs. As seen in Figure 15 below, to use the Beam Paver Tool, the user selects two Sketch Points. Once the second point is defined, the Beam Paver Tool automatically creates individual BEAMs between points that lie between the two user defined points.

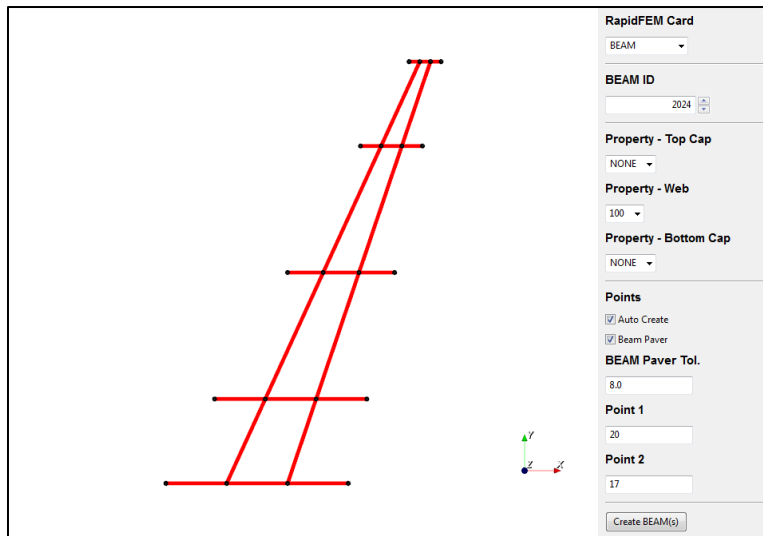


Figure 15: Automated BEAM Paver Tool.

B. RapidFEM SKIN4 Paver Tool

When sub-system components such as fuselages and wings become large, they require higher number of skins to be defined. Similar to the inefficiency caused by placing individual BEAMs, placing large amounts of RapidFEM SKIN4 attributes can be time consuming. To shorten the time required to place a regular grid of SKIN4s, M4 Engineering has added an Automated SKIN4 Paver capability to the RapidFEM Sketch File Editor. Users are still able to create one SKIN4 at a time, but now they have the ability to place multiple SKIN4s at once. This drastically lowers the time required to skin a component.

To use the SKIN4 Paver Tool, the user selects four bounding points that define a regular grid of Sketch Points that the tool uses to construct multiple SKIN4 panels. After the last point has been selected, the tool creates the SKIN4 panels as seen below in Figure 16.

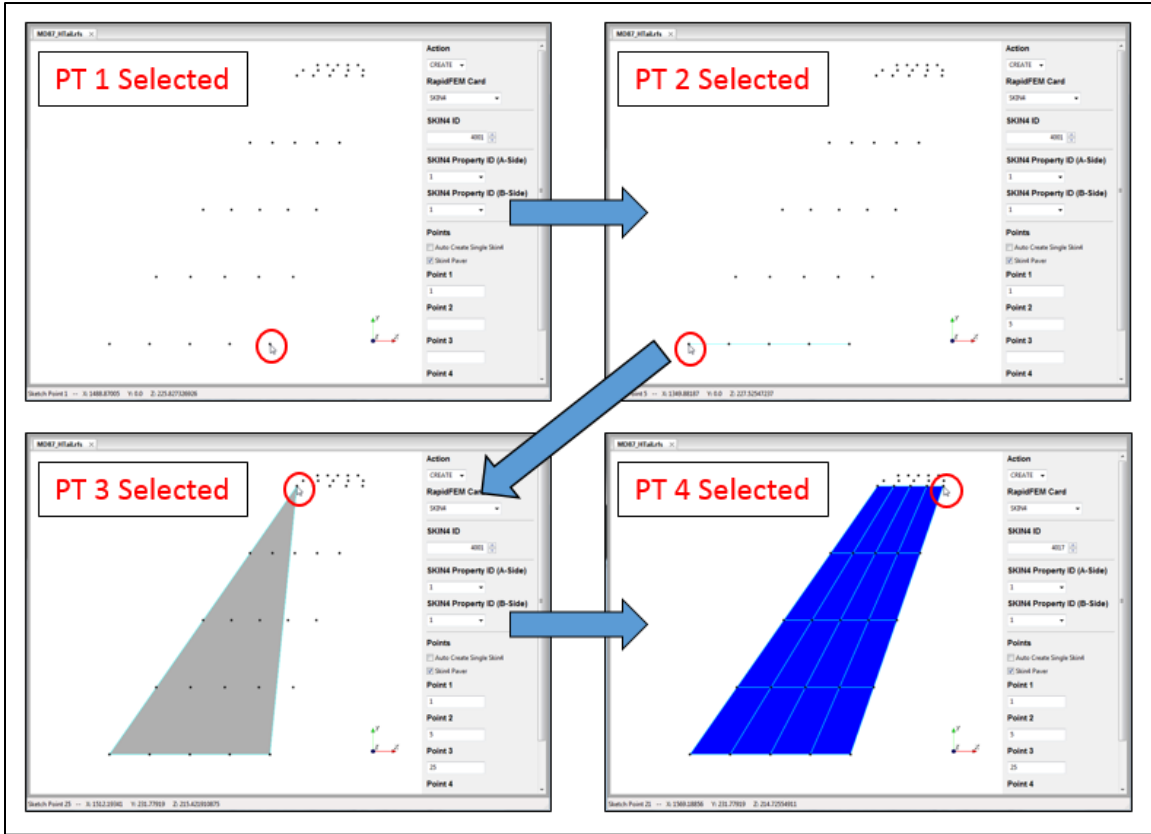


Figure 16: Automated SKIN4 Paver Tool.

In order for the SKIN4 Paver to work properly, the grid of Sketch Points that is defined within the four bounding points must be a regular grid, or a set of Sketch Points from which a tessellation of Euclidean space into 2-parallelotopes can be created.

V. Parametric Trade Study Engine

All the previously discussed tools within the PBWeight software can be viewed as modular software blocks which will be driven by the Parametric Trade Study Engine. The purpose of this engine is to allow a user to quickly and easily setup a parametrically driven trade study job. This trade study engine will be able to control virtually all aspects of the PBWeight software autonomously to produce a set of models that have one or several parameters varied. In Figure 17 below, a diagram of the process is shown.

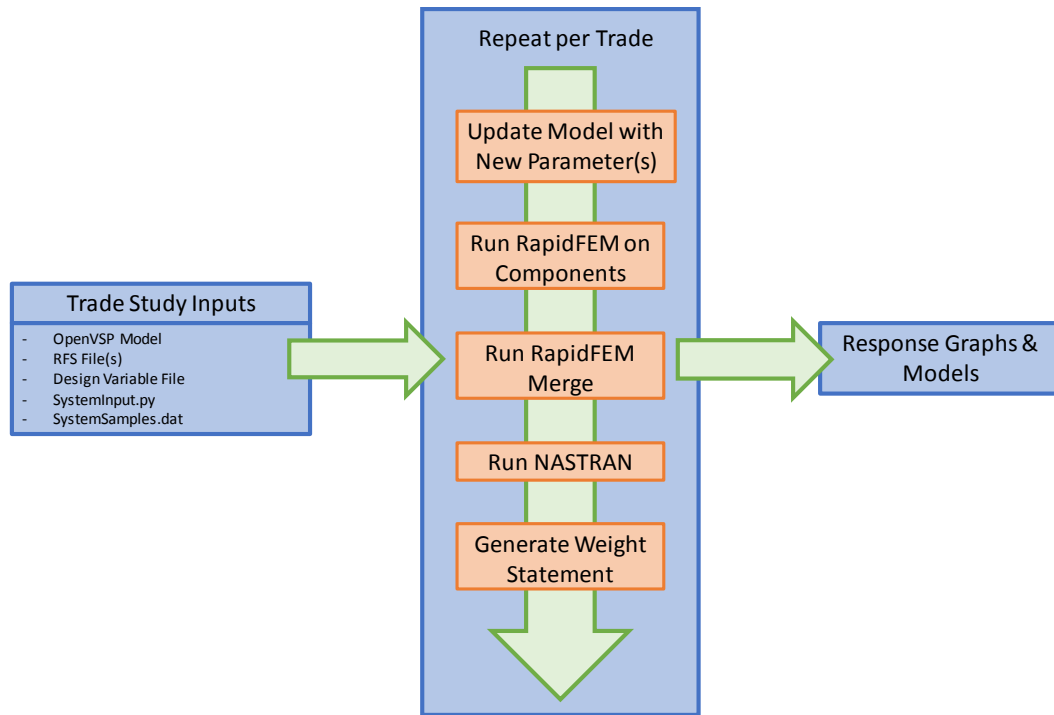


Figure 17: Parametrically Driven Trade Study Engine Process Overview.

To perform a PBWeight trade study, a baseline model has to be created which includes the following:

Baseline Model Files

1. OpenVSP Model File(s)
2. Component RFS File(s)
3. Design Variable File [.des]
4. RapidFEM Merge File(s) [.txt] (If applicable)

The PBWeight Trade Study Tool is capable of running trade studies on many different parameters found within OpenVSP. A few examples include wing sweep, wing span, fuselage length, fuselage height, or a combination of multiple parameters at once. To control how the PBWeight trade study tool performs the study, an input file (.py) is required. This file specifies the baseline model files, the parameters to adjust, the components to merge, and other crucial trade study parameters. To specify the trade parameter values, a sample file (.dat) is required.

For every trade run, the model is updated within OpenVSP using an updated DesVar (.des) file. This DesVar file contains the parameters that are being modified as well as their updated values. A new DesVar file is created for each trade study run. The OpenVSP model is then used to create an updated STL, DegenGeom, and RFS (sketch points only) using the PBWeight export function within the OpenVSP Python API. The RFS file is updated with the baseline RapidFEM cards using the RapidFEM Sketch File Editor update capability. Once all files have been updated based on the trade parameter(s), RapidFEM produces component BDFs, followed by merged component BDFs. Lastly, the weight statement is generated. This process is repeated for each design sample. After all trade runs have been completed, trade study parameter vs weight graphs are created. These graphs include trade study parameter vs: vehicle total weight, vehicle total structure weight, vehicle total NSM, component structure weight, component NSM, etc.

To improve the user’s experience, a Trade Study GUI was developed that walks a user through the required steps to setting up and running a parametric trade study job. The GUI constructs the correct folder architecture required by the trade study tool, and creates both the system input file and the system sample file.

One example use case for the Parametrically Driven Trade Study Engine is a study to examine the effects on fuselage structure weight by varying fuselage length as seen in Figure 18 below for the MD-87. Details on model development and problem setup are given in [3].

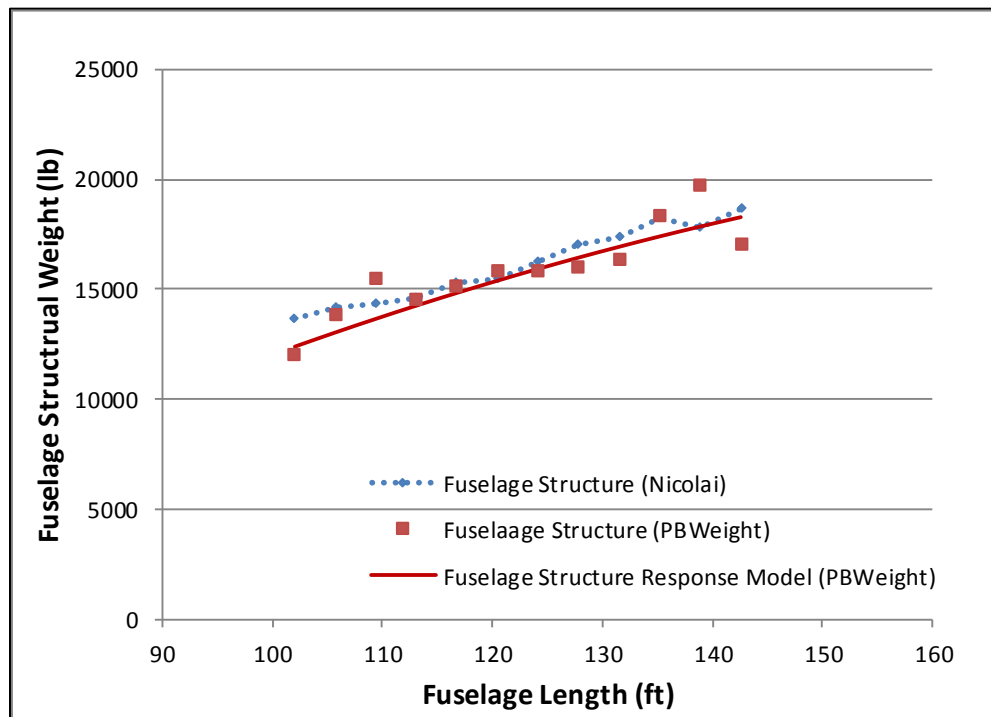


Figure 18: MD-87 Fuselage Length Variation Study.

In this study, the fuselage length of the MD-87 was varied between 100 feet to 150 feet, while the fuselage height was fixed at a height of 11.59 feet. Overall, PBWeight predictions using Nastran Solution 200 for fuselage structural weight shows good agreement with the results tabulated from Nicolai’s empirical equations.

Compared to traditional methods, the PBWeight software drastically shortens the time required to conduct a complete parametrically driven trade study with the help of the Parametric Trade Study Engine. With short turn-around times, users are able to perform many more variation studies in the same time it historically would take using traditional methods.

VI. Conclusions

The purpose of this effort was to further enhance the existing capabilities of the PBWeight software, as well as add new features to increase the efficiency and usability of the software. Additional tools such as the Automated Wing Layout Tool and Automated Fuselage Layout Tool were added to OpenVSP to drastically speed up the time required to prescribe an internal structural layout. To accomplish this, both layout tools automatically create Sketch Point Layouts upon vehicle subcomponents (Wing, Fuselage, etc.) upon which material property regions, attachments, loads, and optimization analysis information is applied. Additionally, an Automated RapidFEM BEAM Paver and an Automated SKIN4 Paver were added to the RapidFEM Sketch File Editor to increase the efficiency of creating RapidFEM BEAMs, used to represent rib and spar like structural components in wings, as well as creating RapidFEM SKIN4s to represent component skins. Both paving tools allow users to create multiple RapidFEM BEAM or SKIN4 entities at once. Lastly, the Parametrically Driven Trade Study Engine was discussed. This allows for quick and simple setup and model creation for parametrically driven trade study analyses. Using traditional techniques to produce the same MD-87 results presented in this paper would take months. By leveraging the PBWeight toolset, M4 Engineering was capable of reducing this time to as little as a week.

Acknowledgments

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