



Project 012 Aircraft Design and Performance Tool Connectivity with AEDT

Stanford University

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- P.I.: Prof. Juan J. Alonso
- FAA Award Number: 13-C-AJFE-SU-003
- Period of Performance: August 1, 2014 – August 31, 2015

Project Funding Level

The project is funded at a total of \$90,000 for the duration of the grant. Stanford University has contributed matching funds for a total of \$90,000 using a combination of elements. Firstly, Stanford University is cost sharing, through tuition reductions for the students working on this project, approximately \$20,000 for the current period of performance. In addition, our partners at the International Council for Clean Transportation are providing in-kind cost-sharing for the remainder through internal and external efforts funded to better understand the impact of cruise speed reduction. Finally, our collaborators at Embraer are also contributing cost-sharing funds, through personnel expenses to collaborate in the development of the SUAVE environment, for a total of \$80,000. The total amount of cost sharing for this project significantly exceeds the necessary total of \$90,000. Excess cost-sharing will be applied to other ASCENT COE projects at Stanford University

Investigation Team

Principal Investigator: Prof. Juan J. Alonso

Aircraft Modeling Technical Lead: Anil Variyar

AEDT Modeling Technical Lead: Timothy MacDonald

The team also includes other researchers that have been assisting with the technical work and the development of our aircraft optimization framework, SUAVE, and its interface with AEDT. The list of additional personnel follows:

- Dr. Michael Colonno, SUAVE lead developer, propulsion systems.
- Mr. Emilio Botero, SUAVE optimization lead.
- Mr. Ved Chirayath, SUAVE-AEDT (XML) integration.

Project Overview

The FAA Office of Environment and Energy has devoted considerable effort and resources to the development of the Aviation Environmental Design Tool (AEDT) to perform full four-dimensional analyses, using arbitrary levels of detail and complexity, of the NAS and its environmental and economic impacts. AEDT relies on models of aircraft performance supplied to it by external aircraft modeling capabilities for the quantification of fuel burn, emissions, and noise at the source (the aircraft being considered), as well as the trajectories to be flown by said aircraft. As stated in the ASCENT COE Project Notice, there is an interest on the side of the FAA to enhance the variety of external tools that may be used to supply aircraft performance / environmental impact information to AEDT. This work describes the efforts that were pursued over the course of the past 13 months to create a module for SUave (the Stanford University Aerospace Vehicle Environment) that enables full connectivity with AEDT and is used to create a database of AEDT aircraft that is representative of aircraft flying today (in all five aircraft classes and with specific models as needed). In addition, we also showcased some of the unique capabilities of SUave, by demonstrating the introduction of an advanced technology that would require higher-fidelity tools to be used within SUave into a particular aircraft class. Such an advanced technology aircraft was made available to AEDT for further analysis. The addition of this new module (from SUave to AEDT) has the benefit of ensuring that a more diverse set of aircraft analysis / design tools can be interfaced with AEDT and that, as future aircraft configurations (and aircraft technologies and/or mission specification changes) need to be modeled, they are incorporated into aircraft design processes with a sufficiently-high level of fidelity so that the input information provided to AEDT can credibly be used to assess system-level impacts.

Background and Previous Accomplishments

SUave (the Stanford University Aerospace Vehicle Environment) is being developed as a flexible, easily extensible, and open-source software framework for the analysis and design of aerospace vehicles at the Aerospace Design Laboratory at Stanford University. SUave is capable of modeling conventional aircraft configurations in a manner similar (but significantly enhanced in its mission description and propulsion models) to our predecessor tool, PASS (Program for Aircraft Synthesis Studies). In order to enable advanced technologies and advanced aircraft configurations (such as higher-span strut-braced wing aircraft, blended-wing body configurations, or even more electric aircraft that might materialize in the future) a method of conceptual design was required that could accept arbitrary aircraft configurations. Many current software tools for aircraft conceptual design rely upon empirical correlations and other low-fidelity approximations for the propulsion and power system as well as the architecture of the airframe (fuselage and wing or, in some cases, certain types of blended wing-body.) On the other hand, designing unconventional aircraft configurations featuring integrated, game-changing technologies, including but not limited to hybrid concepts, requires the ability to perform conceptual design using both physics-based predictions (higher-fidelity) as well as relevant correlations (lower-fidelity) based on available historical trends. In short, a design tool was required that allows for an arbitrary aerospace vehicle to be designed with an arbitrary level of fidelity in its supporting data.

SUave, Stanford University Aerospace Vehicle Environment (see suave.stanford.edu), is being developed in the Aerospace Design Laboratory (ADL) to fulfill this need. SUave is a Python module, a language chosen for its widespread support in the science and engineering communities as well as its exceptional ability to interface between various languages. It is designed as an easy-to-use application programming interface (API) with clearly-understandable syntax accessible to those with minimal Python experience. By design, SUave is intended to be driven by or interfaced with other tools, including numerical optimization frameworks such as NASA's OpenMDAO (also a Python-based tool.)

SUave's core is a modular set of components that can be assembled and analyzed without having to write any additional software. **Vehicles**, the top-level data structure, are assembled from **Components** that include Wings, Fuselages, Propulsors, etc. These components themselves can be specified at a level chosen by the user to match the fidelity of the available analysis methods. For instance, a component can be described by only the minimal information necessary for completing a low-fidelity approximation of its performance or directly with high-fidelity data and geometry. Figure 1 shows an abbreviated class structure diagram used in the SUave framework. Though green aviation is our immediate research application, Vehicles are not limited to commercial aircraft: the class structure in SUave has been created with complete generality. For example, during the construction of the class structure, rotorcraft, personal air vehicles, and even launch vehicles were considered and can be analyzed within the framework.

During SUave's development, we have been fortunate to have Embraer personnel in direct collaborations, resulting in significant opportunities for enhancing the predictive capabilities of the tools and multiple validation efforts (particularly with regional jet aircraft). In addition, we are currently in discussions with NASA in order to include their personnel in our development efforts, as well as with Boeing's Advanced Concepts Development group. SUave is released under an open-source license for others to contribute to its improvement. All work done under this effort is available for others to use in

the future and to improve as appropriate when additional capabilities can be added to SUave, or when data requirements from AEDT change.

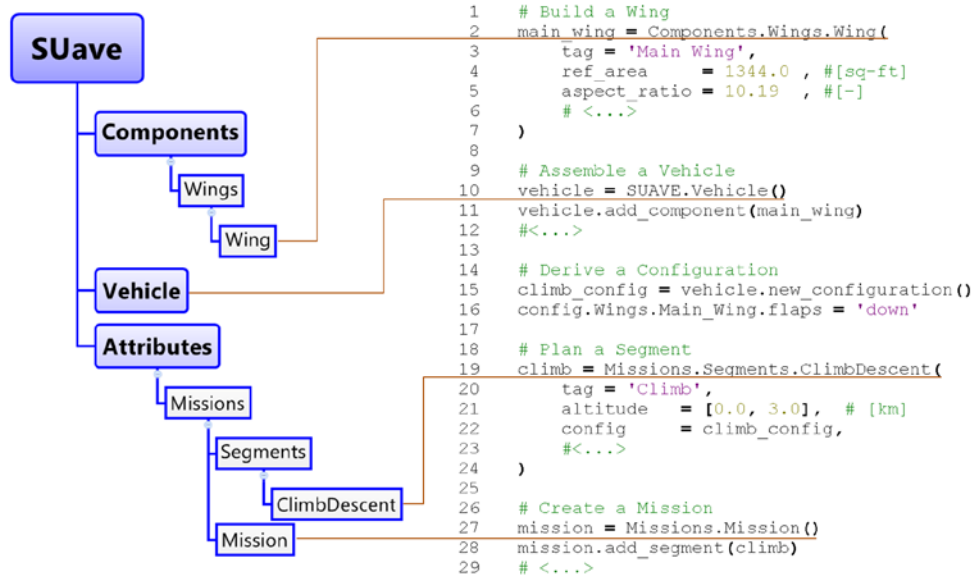


FIGURE 1. ABBREVIATED CLASS DIAGRAM AND SAMPLE SYNTAX DEMONSTRATING SUAVE’S MODULAR CONSTRUCTION AND FLEXIBILITY

Project Objectives

During the development of SUave, we have paid careful attention to a number of issues that can be particularly relevant to improving the accuracy of the models that are supplied to AEDT. In particular, SUave can handle with added accuracy (beyond standard conceptual analysis/design tools such as PASS) the following issues:

1. **Advanced engine model module:** the conventional propulsion module within SUave is based on a one-dimensional thermodynamic cycle including all component efficiencies and realistic inputs such as bleed flows and secondary flow system models. We have paid particular attention to the thrust and specific fuel consumption estimations in off-design conditions, which are particularly important for local noise and emission estimations. Ongoing efforts (joint with the NASA Glenn Research Center) have resulted in a further-enhanced propulsion modeling capability with arbitrary networks of components (similar to the NPSS approach) coupled together and the ability to model details of the thermodynamics and real gas effects in a variety of types of propulsion plants.
2. **Detailed Mission Integration Strategy:** In SUave, every portion of a particular flight (taxiing, take-off and landing, climb with multiple segments, descent & approach, etc.) is modeled based on first principles using the appropriate propulsion system model and the aerodynamic performance for that specific flight condition. The result is enhanced accuracy in the predictions that result. For example, advanced procedures such as Optimized Profile Descents (OPDs) can be modeled based on first principles, including the trajectory followed by the aircraft. Internal to AEDT, the aircraft mission profile is computed according to standard methodologies. A study to assess the differences between the flight profiles embedded in AEDT and those computed by SUave was completed as part of this effort.
3. **Ability to incorporate future technologies:** the multi-fidelity approach followed in SUave allows for the introduction of higher fidelity tools (we are currently working on better aerodynamics, see su2.stanford.edu, better weight estimation approaches for the primary structure based on FEM optimization, and more accurate stability and control assessments using a multi-fidelity database) when needed. This type of approach enables the system-level quantification of benefits of technologies that might have significant interactions within the aircraft system.
4. **Rapid execution of analyses:** to enable the possibility of examining the performance of the aircraft at a variety of range, weight, speed and altitudes that can then be passed on to AEDT for its analysis.
5. **Advanced optimization techniques:** the resulting SUave models are typically used as a starting point for entire vehicle and engine optimizations (single- and multi-objective) that can result in improved performance and environmental impact by suitable changes in the configuration and while ensuring that a large variety of

constraints are satisfied. As a result of this work (and work in ASCENT Project 10), we have completed a full optimization environment in SUave that will be published in the AIAA SciTech 2016 (January 2016) conference.

A sample of results for the detailed mission description for a B737-800 aircraft (using multiple climb and descent segments) is shown below in Figure 2.

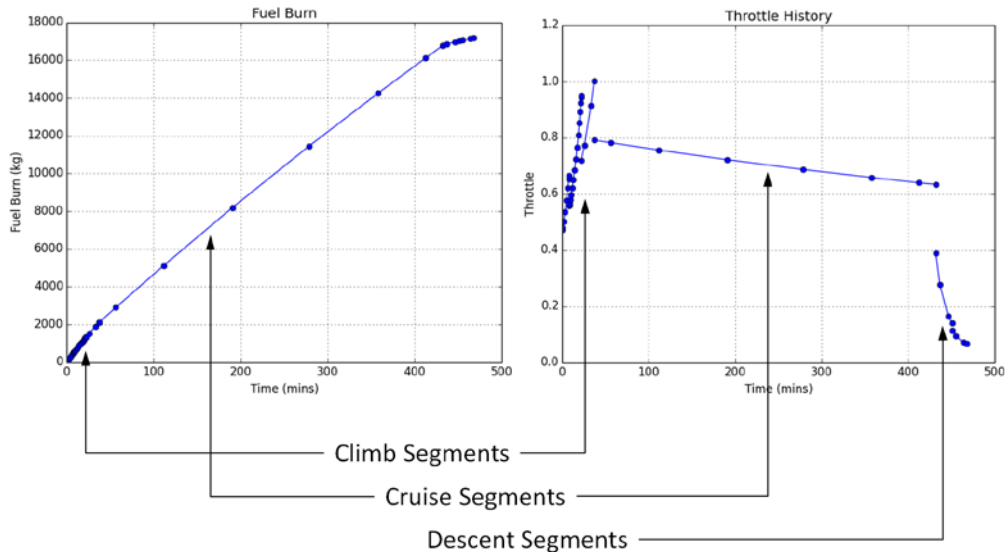


FIGURE 2. SAMPLE RESULTS FROM A SIX-SEGMENT BOEING 737-800 MISSION SIMULATED IN SUAVE, INCLUDING THREE CLIMB SEGMENTS, ONE TRIMMED CRUISE SEGMENT, AND TWO DESCENT SEGMENTS. TOTAL (INTEGRATED) FUEL CONSUMPTION AND THROTTLE HISTORY ARE PLOTTED.

Leveraging the existing SUave capabilities and multiple ongoing efforts at the Aerospace Design Laboratory, the main objective of this work is to automate all the necessary tasks to seamlessly integrate the output of any SUave analysis and / or design into AEDT. This integration involves all the necessary data transfer / formatting but, in addition, it also includes a validation & verification effort to ensure that, when the performance of a vehicle is transferred to AEDT using its XML interface definition, the calculations carried out by AEDT closely conform to the analyses performed by SUave.

The result, *pySUave-AEDT*, is a stand-alone program that can be used to automatically transfer any vehicle in SUave to the AEDT framework. Note that a library of SUave aircraft was also built, including an advanced technology airplane, and is available to the FAA for use in future AEDT studies. If at all possible, we would like to see the resulting *pySUave-AEDT* be added as either a contributed software module to the AEDT distribution or even as a plugin that might enable the reading of SUave aircraft directly from the AEDT GUI.

Statement of Work

During the proposal phase, we suggested to structure the work into the following three tasks.

Task 1: Create a SUave-AEDT module (*pySUave-AEDT*) to be able to provide all the necessary information for any aircraft that can be modeled in SUave to AEDT, including the ability to estimate fuel burn performance, associated emissions in each phase of the mission, and noise emitted in terminal area operations. The module automatically runs all of the simulations required and outputs the information from SUave in the XML format used within AEDT for seamless connectivity. Python, the language used in the core of SUave, already has excellent XML connectivity and the ability to convert the internal SUave database to any XML schema that is required. This effort will require the re-organization of the aircraft/engine information within SUave into an XML database that conforms to the requirements found in the AEDT Reference Manual. In addition, and

as mentioned earlier in this document, since AEDT represents aircraft by a series of parameters in an XML database and then proceeds to use its own internal models to translate those database parameters into actual aircraft trajectories and performance, there exists the possibility that the computed trajectories and performance in SUave might differ from what is assumed in AEDT. Given that the models in SUave are deemed to be of higher-fidelity than those in AEDT, we will ensure that the XML database can be specifically created so that performance differences can be minimized. The deliverable for this task is the entire source code for *pySUave-AEDT* including the necessary documentation and input files to be able to run it. During this effort, we focused our activities on ensuring that the current noise modeling capabilities in AEDT are leveraged to ensure a full accounting of the environmental impact of SUave aircraft. However, and although it was considered to be beyond the scope of this work, we managed to create, in collaboration with Embraer, a noise prediction module (including both airframe and engine noise models) that has been interfaced with SUave to further enhance the noise prediction capabilities. While these noise predictions are not yet fully interfaced with AEDT, we expect to complete this effort in the coming months.

Task 2: Create SUave-based AEDT models for representative aircraft in all five aircraft groups: leveraging our experience from previous efforts with FAA and NASA (Project 43, NASA LEARN program) we have created all the necessary models for at least one aircraft in each of the five major groups and make them available to AEDT. This effort has created an initial library of vehicles that can be used for AEDT-based studies. The various aircraft models that we modeled within each aircraft group are as follows: Regional Jet – CRJ900 and/or Embraer 175/190, Single Aisle – B737-800, Small Twin Aisle – B767-300, Large Twin Aisle – B777-200ER, Very Large Aircraft – A380 and B747-400. In addition to the XML databases required by AEDT, the deliverables for this task also include the detailed performance characteristics, in the form of detailed charts for all aspects of the aircraft mission, for all aircraft modeled.

Task 3: Demonstrate an advanced technology introduced into an aircraft: in order to showcase the future potential of SUave as a source of information for AEDT, we have introduced an advanced technology aircraft that requires the high-fidelity analysis capabilities in SUave. In this Task, we focused on the AEDT introduction of a large-span strut-braced wing aircraft of the size and mission capabilities of a B737-800.

All tasks described in this proposal were completed at the Aerospace Design Laboratory at Stanford University. Interactions with FAA and Volpe personnel were fundamental to the completion of the effort. The authors would like to acknowledge the guidance of Mr. Aniel Jardines and the AEDT-related input of Mr. David Senzig. Software for interaction between SUave and AEDT is now part of an open-source module that is maintained as part of the SUave standard distribution (see <http://github.com/suavecode>).

Task 1: Interface between SUAVE and AEDT

Stanford University

Objective(s)

AEDT is a tool recently developed by the FAA with the purpose of providing a program that could accurately predict emissions and noise patterns created by aircraft fleets around the world. A substantial amount of work has been done to collect data needed to model aircraft that are currently in use, but it is also desirable to have the ability to evaluate new aircraft within this framework. SUAVE is aircraft design tool with development headed at Stanford University. With the goal of allowing AEDT to use new aircraft designs, modules are added to SUAVE that will allow relevant data to be generated within SUAVE, and then exported for use in AEDT.

AEDT Aircraft Representation

To avoid the lengthy computations that would be required for a full simulation or the large amount of data required for interpolation in every mission type, AEDT breaks the aircraft into several simple modular components and uses two types of coefficient fitting in mission calculations.

AEDT Aircraft Structure

The AEDT aircraft structure is composed of several components that can be independently modified to suit the needs of a particular aircraft configuration. The overall structure uses an AEDT aircraft that is linked to five sub IDs. Each of these IDs contains information used in different aspects of the mission simulation. This structure and the associated data sets is displayed in Figure 3. The purpose of each component is described briefly in Table 1.

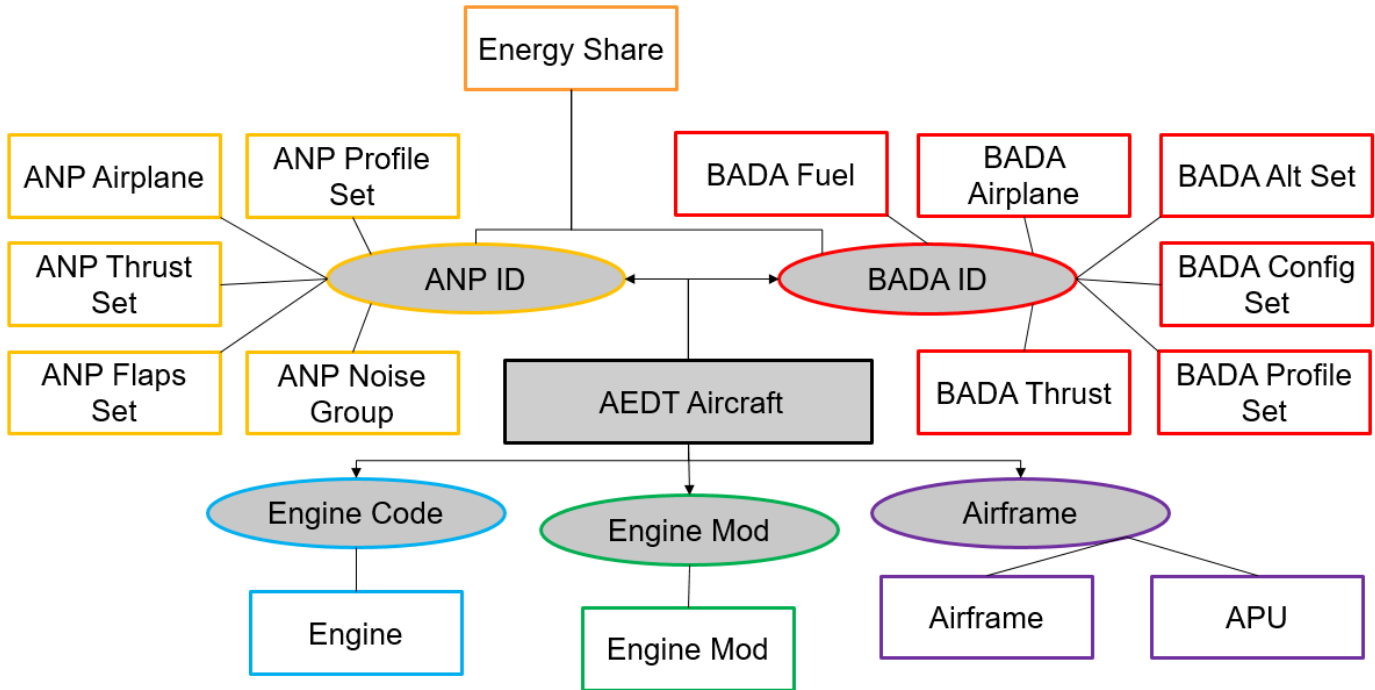


FIGURE 3. AEDT AIRCRAFT FILE STRUCTURE

AEDT Aircraft	This is the highest level in the structure. It provides the five IDs and codes shown in Figure 1, as well as a description of the aircraft.
ANP ID	This is the reference code for the aircraft ANP data sets
ANP Airplane	Contains basic values for the ANP model such as static thrust and maximum weights.
ANP Profile Set	Contains profile data for various segments that may be flown by the aircraft.
ANP Thrust Set	Contains thrust coefficients used in the ANP model.
ANP Flaps Set	Contains flap coefficients used in the ANP model.
ANP Noise Group	Contains noise data at various altitudes for given aircraft thrust levels and operation modes.
BADA ID	The reference code for the aircraft BADA data sets.
BADA Fuel	Contains coefficients for fuel flow in the BADA model.
BADA Airplane	Contains basic values for the BADA model such as aircraft weights and operating speeds.
BADA Altitude Distribution Set	Contains statistical information about aircraft altitudes. These are not used in the modeling process.
BADA Config Set	Contains data dependent on aircraft configuration – stall speed and drag coefficients.
BADA Profile Set	Contains information on climb, descent, and cruise profiles.
BADA Thrust	Contains coefficients for thrust levels in the BADA model.
Engine Code	Code identifying the engine that is used.
Engine	Contains key engine parameters such as emissions.
Engine Mod	Contains any engine modification data.

Airframe	Contains various aircraft designation codes used in the modeling process.
APU	Contains APU emission data.
Energy Share	Contains an energy share factor used in modeling climb and descent.

TABLE 1. DESCRIPTION OF AEDT AIRCRAFT ELEMENTS.

Aircraft-dependent data that must be calculated is primarily in the ANP and BADA data sets. These are what the SUAVE-AEDT interface is built to generate – specifically the BADA fuel, config, profile, and thrust sets, along with the ANP profile, thrust, and flaps set. The BADA altitude distribution set and ANP noise group must be manually entered in the SUAVE module if new values are needed. Otherwise default values from the AEDT 737 will be used to form a complete data file for the aircraft IDs.

Aircraft Trajectory Modeling

BADA and ANP are the two sets of modeling equations used in AEDT. The BADA (Base of Aircraft Data) model and the ANP (Aircraft Noise and Performance) model are both provided by EUROCONTROL. In AEDT, the BADA model is used to simulate trajectories above 10,000 feet greater than field elevation, while the ANP model is used below¹.

BADA Model

The BADA model consists of several coefficients principally set up to determine rate of climb and fuel burn. The primary equations, transformed for use in linear regression as per the EUROCONTROL modeling guide, are given below².

$$ROC_i = k_4(T_i - D_i) \frac{TAS_i}{m_i g} ESF_i$$

$$T_i = t_7 \left(t_0 - t_1 h_i + t_2 \frac{1}{TAS_i} - t_3 \frac{h_i}{TAS_i} + t_4 h_i^2 \right) (t_5 \Delta T_{ISA} + t_6)$$

$$D_i = \left(d_0 \rho_i TAS_i^2 + d_2 \frac{m_i^2}{\rho_i TAS_i^2 \cos^2 \gamma_i} \right) (1 + d_{16} M_i^{16})$$

Fuel Flow (kg/s):

$$F = f_5 [f_0 - f_1 h + (f_2 + f_3 V_{TAS} - f_4 V_{TAS}^2) T]$$

These equations are used for all types of aircraft, but the coefficients that may be set to zero vary between operation and engine types.

BADA Coefficient Calculation

EUROCONTROL has a specified process that can be used to determine BADA coefficients. This process manipulates the BADA equations to allow linear regression of a separate set of coefficients that can then be transformed into the coefficients that are used directly in the model.

The missions created are²:

- 9 climb trajectories combining 3 different aircraft masses (maximum, reference, and minimum) and 3 different speed profiles (high, reference, and low) performed under ISA conditions

k₄	Unit Conversion
TAS	True Airspeed (kts)
m	Aircraft mass (kg)
ESF	Energy share factor
h	Altitude (ft)
ΔT_{ISA}	Temperature change from ISA (K)
γ	Climb angle (rad)
M	Mach number
ROC	Rate of climb (fpm)
T	Thrust (N)
D	Drag (N)

- 3 descent trajectories for the reference mass and 3 different speed profiles performed under ISA conditions.
- 4 climb trajectories combining 3 different aircraft masses and 2 different non-ISA temperature conditions (ISA+10 and ISA+20) performed with the reference speed profile
- 1 cruise trajectory performed under ISA conditions, for the reference mass and speed profile.

The process outlined below is then followed²:

1. Initialization of the set of trajectories used to estimate $\{t_0, t_1, t_2, t_3, t_4, d_0, d_2, d_{16}\}$ with the ISA climb trajectories
2. Estimation of $\{t_0, t_1, t_2, t_3, t_4, d_0, d_2\}$ as described above from the set of ISA climbs, using as the aircraft mass at each point, m_i , the observed value until estimates of the fuel coefficients $\{f_0, f_1, f_2, f_3, f_4, f_5\}$ become available to allow the predicted value to be used instead.
3. Estimation of $\{t_5, t_6\}$ as described above using non ISA climbs.
4. Estimation of the hi and lo version of t_7 as described above using ISA descent trajectories. Provided that the estimates of $\{t_0, t_1, t_2, t_3, t_4, d_0, d_2\}$ are known from step 1, the observation matrix degenerates into a column vector. On the other hand, since h_{des} is unknown, it has to be determined as the one that makes the minimum corresponding RMS. (h_{des} is the altitude at which the t_7 coefficient switches from its hi to lo value)
5. Now, all the thrust and drag coefficients are estimated. Therefore, the thrust can be calculated for all the points in the various segments and thus, fuel consumption coefficients $\{f_0, f_1, f_2, f_3, f_4, f_5\}$ can be estimated as described above.
6. Repetition from step 1, considering all the trajectories used for modelling with the exception of cruise, and the BADA predicted values of the aircraft mass instead of the observed ones. Also, step 1 is to solve for the coefficients $\{t_0, t_1, t_2, t_3, t_4, d_0, d_2\}$ iterations can continue while effectively improving, until the improvements achieved in terms of RMS change fall below a given tolerance.

Note that the outlined process in the document also includes determining d_{16} . The SUAVE module is capable of doing this, but does not do so by default. This is because this coefficient is used for compressibility effects that are not included in the current BADA modeling in AEDT. SUAVE is also using 6 non-ISA climb trajectories to capture all the possible combinations.

ANP Model

The ANP model principally calculates fuel burn and net thrust. It is split into approach and descent models, with separate coefficient used above the engine breakpoint temperature. Net thrust is determined by¹

$$\frac{F_n}{\delta} = E + F \cdot v + G_A \cdot h + G_B \cdot h^2 + H \cdot T_C$$

Fuel flow rate in departure and approach is determined by

$$f_{n_{dep}} = (K_1 + K_2 M + K_3 h_{MSL} + K_4 F_n / \delta) \sqrt{\theta} F_n$$

$$f_{n_{arr}} = \left(\alpha + \beta_1 M + \beta_2 e^{-\left(\frac{\beta_3 F_n / \delta}{F_{n0}}\right)} \right) \sqrt{\theta} F_n$$

M	aircraft Mach number
θ	ratio of temperature at aircraft altitude to sea level ISA temperature
F_n / δ	aircraft corrected net thrust per engine (lbf)
F_n	aircraft net thrust per engine (kN)
F_{n0}	ISA sea-level static thrust (lbf)

ANP Coefficient Calculation

The ANP coefficients are calculated based on the procedure given in a reference document³. For the thrust equations, mission segment are simulated with an acceleration segment between typical climb speeds, along with a constant climb segment. This is done with all relevant configuration settings so that thrust and drag can be calculated for each.

F_n / δ	Corrected net thrust per engine (lbf)
v	Equivalent airspeed (kt)
h	Pressure altitude (ft)
T_C	Temperature (°C)

The descent segments are modeled similarly, but with deceleration and descent. In SUAVE, profiles are typically created to provide thrust and these can be used in AEDT in place of the thrust coefficients.

The fuel flow calculations are split only between approach and descent, with the same coefficients used for different configurations. These equations are fit using all the fuel rates in the simulation.

SUAVE Overview and AEDT Module

SUAVE General Structure

SUAVE is an aircraft design tool built to have the capability to work with unconventional configurations. It is written in Python to allow easy addition of modules. In order to allow unconventional designs, aircraft are modeled as a collection of components that are combined to form full aircraft. SUAVE aircraft are defined as Python classes, which for purposes relevant here can be considered as a large data structure. SUAVE simulates missions by taking this data and using a built-in mission solver. SUAVE is highly extensible, and allows aircraft data to be computed from many different sources. It is designed to be multi-fidelity tool so that the modeled aircraft can be built to an appropriate fidelity for the application. This may involve links to outside program, allowing data such as CFD results to be used.

SUAVE AEDT Module Structure

The SUAVE AEDT module is built as a set of modules that perform the basic operations needed to simulate aircraft and transfer the results into a file that can be imported by AEDT. The information flow in these module is shown in Figure 4.

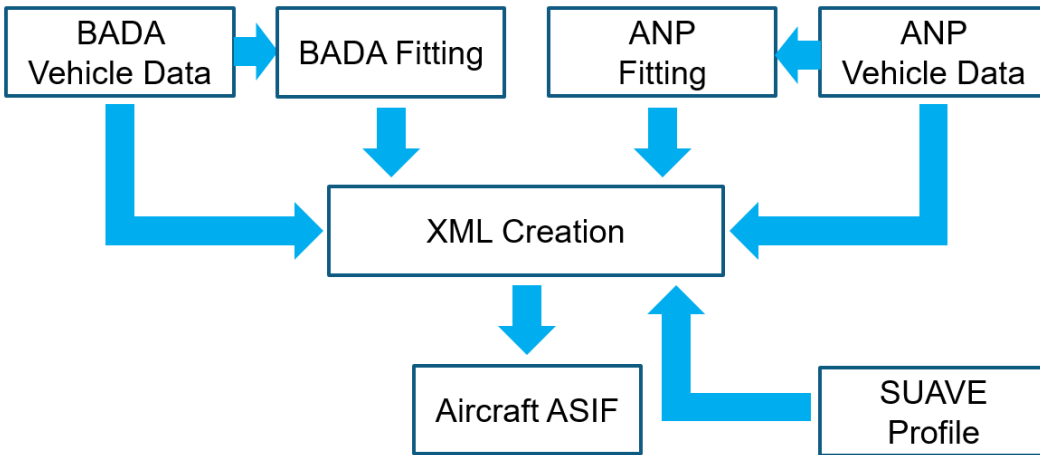


FIGURE 4. SUAVE INTERFACE WITH AEDT

Vehicle Data Input

The BADA Vehicle Data, ANP Vehicle Data, and SUAVE Profile modules all contains information on the vehicle setup. All three contain the data required by SUAVE to model the aircraft. This would typically be the same set of data, but could be modified if there is a reason for changes between different fitting algorithms. The BADA and ANP data sets also include data that is specifically needed for BADA and ANP models, along with specific missions for fitting purposes. The specialized data must be manually entered by the user in each case.

Fitting Algorithms

Both the BADA and ANP fitting algorithms rely on regression to generate coefficients that can be used in AEDT. Fitting is done by taking mission results data and using equations specified in the relevant documentation. The coefficients are then transformed as required to be used in the standard equations, and then output for use in export.

SUAVE Profile Creation

To create the SUAVE profile, the standard vehicle setup is used and mission data is created for all segments that are desired. This can include as many approach and descent segments as desired. Profiles must be indicated as approach or descent in this module. AEDT requires a particular set of values to be used when point-wise segments are used instead of trajectory steps. This are computed with SUAVE’s mission solver and output in a matrix for use.

XML Export

The export module brings together all of the data and sorts it into the XML trees needed for creating the ASIF (AEDT Standard Input File). General data for the aircraft should also be entered here.

SUAVE Output Testing

Verification was done using missions similar to what would be expected in a standard mission for a 737. This was designed to test that the coefficients being generated by SUAVE were indeed predicting the performance that was expected.

BADA Fitting Data

Since BADA fits based on climb rate and fuel flow rate, these numbers were calculated for the appropriate mission segments. Figure 5 and Figure 6 show the results for rate of climb in ISA conditions. Similar results were also found for other segments. This shows the BADA coefficients determined by SUAVE can accurately describe aircraft trajectories. Though in the future AEDT will use BADA 4 instead of 3, this demonstrates that the process for calculating coefficients is functioning properly. Since BADA 4 uses similar principals to determine coefficients, the methods in these modules should not be difficult to accurately apply with BADA 4.

ISA Climb Fitting – Rate of Climb and Fuel Flow

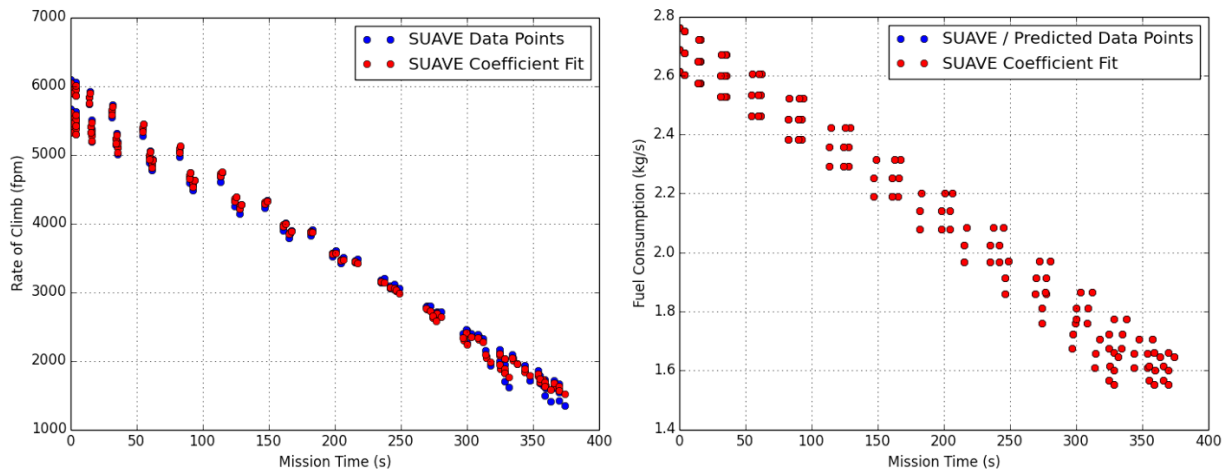


FIGURE 5. BADA CLIMB RATE

Climb Phase

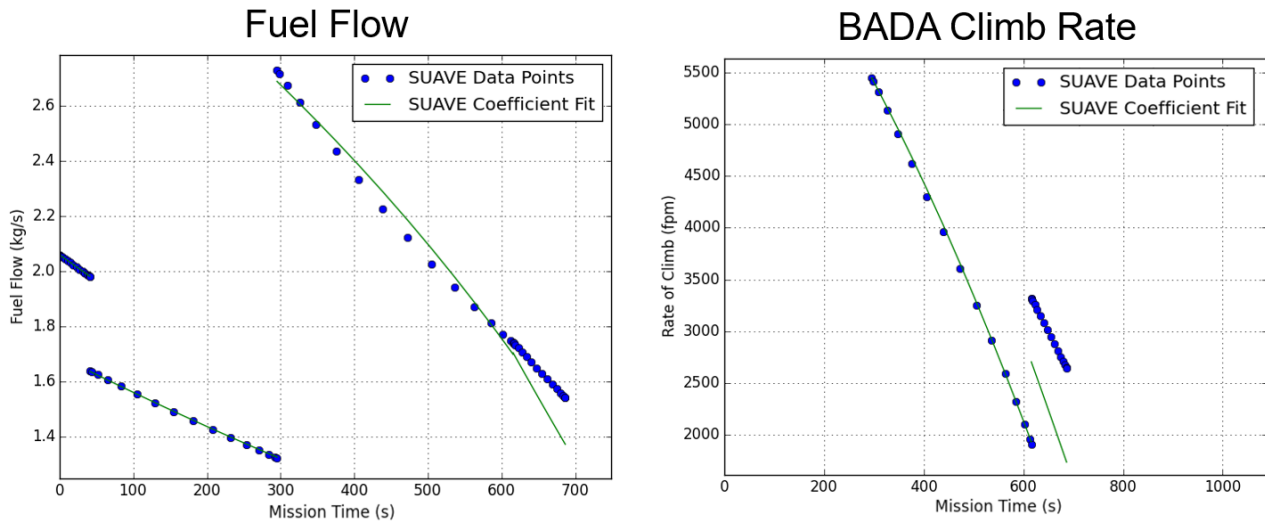


FIGURE 6. BADA FUEL FLOW

ANP Data

Using SUAVE data for point-wise mission segments, fuel flow modeling becomes the important aspect of the ANP data. These results (see **Error! Reference source not found.**Figure 7 below) demonstrate that the fuel flow coefficients generated in SUAVE match the performance expected.

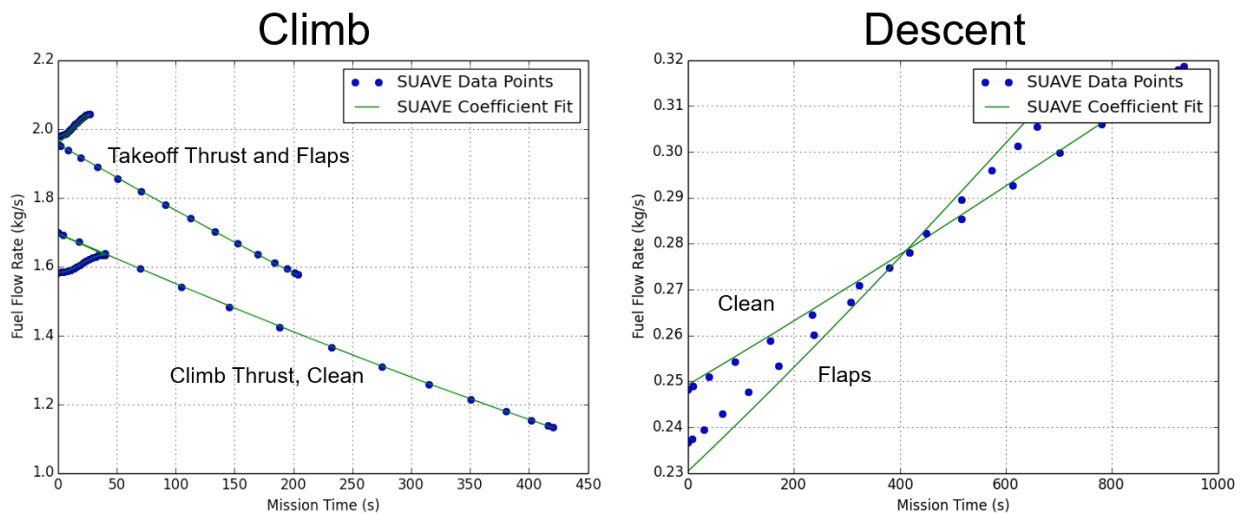


FIGURE 7. ANP FUEL FLOW

Running with New Aircraft

SUAVE Data Input

To create information for a new aircraft, data for the vehicle configuration and mission types must be input in the relevant SUAVE sections. The details of the process are essentially the same as those described in the tutorials on the SUAVE website⁴.

The difference is that BADA and ANP data must be included. These data sets can be found at the end of the vehicle definitions in their respective files.

Running the Full Module

Once vehicle and mission data is input as desired, the module can be run from the main XML export file. Inputs are required at the top of this file to select the vehicle and mission data, as well as file names for generated files. Airframe data (see Table 1) also must be entered here. It is important to select an engine and APU that are already define in AEDT, or one that you will create manually, as the data for these is not created in SUAVE. Once the inputs are entered, the module can be run and will produce an XML file that can be read directly into AEDT.

Summary

SUAVE has been extended with fitting algorithms and the capability to generate ASIFs ready for import into AEDT. These fitting algorithms contain BADA and ANP equations that are also used in AEDT, and are fit with mission data designed to provide coefficients that will be useful for the typical missions modeled in AEDT. These coefficients have been verified to produce rate of climb, fuel flow, and net corrected thrust values that match input values. With proper inputs, the module can be run and imported into AEDT with no additional file modification required.

Task 2: Creating a Library of Existing Aircraft

As part of the effort to create a SUAVE-AEDT interface, the need was felt to build a database/library of (conventional) aircraft in SUAVE which could then be used to perform fleet level analysis with aircraft having different payload-range characteristics. With this in mind representative aircraft from all the five ICAO classes were chosen and modeled in SUAVE. The five classes and the representative aircraft modeled are show in **Error! Reference source not found.**

ICAO Aircraft Class	Aircraft chosen
Regional Jet	CRJ900
Single Aisle	B737-800
Small Twin Aisle	B767-300ER
Large Twin Aisle	B777-200ER
Very Large Aircraft	B747-400

TABLE 2. LIST OF AIRCRAFT MODELED IN SUAVE FOR AEDT USE.

Aircraft Modeling in SUAVE

The aircraft are modeled in SUAVE as a collection of wing, fuselage and engine/propulsion components that are assembled together to obtain an aircraft model. A brief description of how these components are set up and assembled is given below. More detailed descriptions of these components and SUAVE in general are available in an AIAA Aviation 2015 paper (reference 5).

Wings

The main wing, horizontal and vertical tail of the aircraft are modeled using the Wing component in SUAVE. The geometric parameters of these components as well as their positions are specified. The inputs specified for the main wing of the B737-800 are shown in Figure 8. Once the parameters of the wing are defined, the wing is added to the aircraft model.



```
# -----
# Main Wing
# -----

wing = SUAVE.Components.Wings.Main_Wing()
wing.tag = 'main_wing'

wing.aspect_ratio           = 9.0
wing.sweep                  = 25.0 * Units.deg
wing.thickness_to_chord    = 0.1
wing.taper                  = 0.16
wing.span_efficiency       = 1.08
wing.spans.projected       = 35.66
wing.chords.root           = 6.81
wing.chords.tip            = 1.09
wing.chords.mean_aerodynamic = 4.235
wing.areas.reference       = 124
wing.twists.root           = 4.0 * Units.degrees
wing.twists.tip            = -4.0 * Units.degrees
wing.vertical               = False
wing.symmetric             = True
wing.high_lift             = True
wing.dynamic_pressure_ratio = 1.0

vehicle.append_component(wing)
```

FIGURE 8. SAMPLE WING DESCRIPTION FOR SUAVE B737-800 WING.

Fuselage

Setting up the fuselage is similar to the wing with the basic geometric parameters being specified as shown in Figure 9.

Engine/Propulsion System

Modeling the propulsion system is a little more complicated owing to the use of an energy network framework. The turbofan model is built using compressor, nozzle, fan, combustor and turbine components which are connected together as a network. The instantiation of an energy network and the addition of a component are shown in Figure 10. The model takes into account the pressure ratios and polytropic efficiencies of the components (specified as inputs) and solves the 1D propulsion equations at design and off-design conditions to obtain thrust, specific fuel consumption and the fuel flow rate at different instances of the mission.



```
# -----  
# Fuselage  
# -----  
  
fuselage = SUAVE.Components.Fuselages.Fuselage()  
fuselage.tag = 'fuselage'  
  
fuselage.seats_abreast      = 6  
fuselage.seat_pitch        = 1  
fuselage.fineness.nose     = 1.6  
fuselage.fineness.tail    = 2.  
fuselage.lengths.nose     = 6.4  
fuselage.lengths.tail     = 8.0  
fuselage.lengths.cabin    = 28.85  
fuselage.lengths.total    = 38.02  
fuselage.lengths.fore_space = 6.  
fuselage.lengths.aft_space = 5.  
fuselage.width            = 3.74  
  
fuselage.differential_pressure = 5.0e4 * Units.pascal  
  
vehicle.append_component(fuselage)
```

FIGURE 9. SAMPLE FUSELAGE DESCRIPTION FOR SUAVE B737-800.



```

# -----
# Turbofan Network
# -----

#instantiate the gas turbine network
turbofan = SUAVE.Components.Energy.Networks.Turbofan()
turbofan.tag = 'turbo_fan'

# setup
turbofan.number_of_engines = 2.0
turbofan.bypass_ratio     = vehicle_inputs.bypass_ratio #5.4
turbofan.engine_length    = 2.71
turbofan.nacelle_diameter = 2.05

# working fluid
turbofan.working_fluid = SUAVE.Attributes.Gases.Air()

# -----
# Component 2 - Inlet Nozzle
# instantiate
inlet_nozzle = SUAVE.Components.Energy.Converters.Compression_Nozzle()
inlet_nozzle.tag = 'inlet_nozzle'

# setup
inlet_nozzle.polytropic_efficiency = 1.0 #0.98
inlet_nozzle.pressure_ratio        = 0.999 #0.98

# add to network
turbofan.append(inlet_nozzle)

```

FIGURE 10. SAMPLE TURBOFAN NETWORK FOR B737-800 EXAMPLE

Mission

The mission the aircraft is designed for, is broken down into climb, cruise and descent segments which are modeled using segment objects (as shown in Figure 11) and these are then stitched together to form the mission for which the aircraft is flown. The mission solver solves the equations of motion for the aircraft at every point in the defined mission using the aerodynamic and propulsion data obtained from the analysis models.

```
# -----
# Climb Segment
# -----

segment = Segments.Climb.Linear_Mach_Constant_Rate(base_segment)
segment.tag = "climb_1"

segment.analyses.extend( analyses.takeoff )

segment.altitude_start = 0.0 * Units.km
segment.altitude_end   = 3.0 * Units.km
segment.climb_rate     = 6.0 * Units['m/s']

segment.mach_end       = 0.4
segment.mach_start    = 0.25

# add to mission
mission.append_segment(segment)
```

FIGURE 11. SAMPLE MISSION SEGMENT DEFINITION FOR B737-800 EXAMPLE.

Analysis Methods

For the simulation of conventional aircraft, correlation based methods are used to estimate the aircraft’s aerodynamics, propulsion performance, weight breakdown, stability characteristics, landing and takeoff performance and its overall mission performance. These methods have been described in detail in the SUAVE paper (reference 5).

Once the design is finalized, the aircraft can be flown in SUAVE for a variety of climb profiles, cruise altitudes, atmospheric models and cruise ranges as described in Section 6. This information is then used to generate the AEDT input files.

Performance Estimates of the Five Aircraft Classes

The aircraft for the five baseline classes are modeled in SUAVE and their performance for the design mission is obtained. The subplots in Figure 12 indicate the variation of the aircraft altitude during flight as well as the change in the weight of the aircraft (due to fuel burn) during the mission for the B737-800, including the reserve mission at the end of the typical flight profile. The change in the engine performance indicated by the specific fuel consumption is also shown in the figure. The design/input parameters including the geometric parameters of the wings, fuselage and engine performance parameters are obtained from publically available data including the airport planning guides of the aircraft (reference 6). These design/input parameters as well the performance estimates obtained using SUAVE for all five baseline aircraft are shown in Figure 12. Typical Suave performance plots for the B737-800 Example Mission.

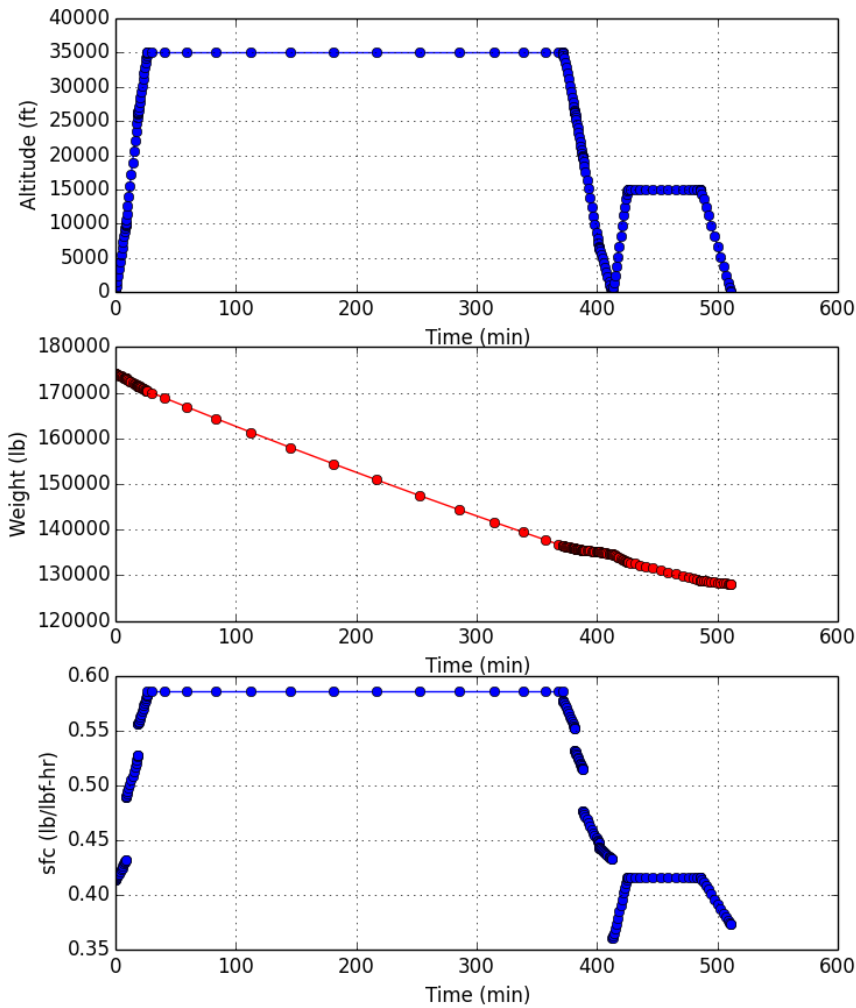


Figure 12. Typical SUave performance plots for the B737-800 Example Mission.

Mission/Operation Parameters

Parameter	Units	Value at Design Point				
		CRJ900	B737-800	B767-300ER	B777-200ER	B747-400
Cruise Mach	~	0.8	0.78	0.8	0.84	0.85
Range	nm	2,011	2,960	5,920	7,530	7,060
Payload weight	lbs	18,000	37,170	54,810	64,050	87,570
Reserve fuel	lbs	4,251	6,229	11,325	16,400	29,037
Block fuel	lbs	16239	39125	163600	280563	347151

Total mission fuel	lbs	20,490	45,354	174,925	296,963	376,188
Take off length	ft	8,280	10,298	10,212	10,212	9,801
Landing length	ft	6158	6236	6776	6776	6417

Aircraft geometry and dimensions

Parameter	Units	Value	Value	Value	Value	Value
Wing aspect ratio	~	10.2	9	10.63	8.6	7.38
Wing reference area	ft ²	651.841	1344	3049.42	4602	5972
Wing projected span	ft	81.5289	117	156.1	199.1	211.4
Wing sweep at 1/4 chord	deg	26.8	25	31.5	31	38.4
Airfoil t/c ratio at wing root	~	0.12	0.1	0.11	0.1	0.106
Wing inner taper ratio	~	0.204	0.16	0.24	0.182	0.222
Fuselage max width	ft	3	10.3018	18.4	22	
Fuselage max height	ft	3	10.3018	18.4	22	28.6
Fuselage length	ft	21.56	124.73753	116.01	197.44	24.01
Horizontal tail aspect ratio	~	4.58	6.16	4.61	4.928	3.6
Horizontal tail area	ft ²	208.58	349.698	811.2	1238	367.2
Horizontal tail span	ft	30.9	46.4108	61.15	78	65.61
Horizontal tail sweep	~	40	30	33	32	39
Vertical tail aspect ratio	~	1	1.91	1.77	1.1	1.146
Vertical tail span	ft	9.737	25.82021	40.3	31.8	29.82
Vertical tail area	ft ²	97.77	349.698	582.5	923	776
Vertical tail sweep	~	40	25	40.3	40.5	44

Engine geometry and design parameters

Parameter	Units	Value	Value	Value	Value	Value
Max SLS thrust	lbf	16 148	27 303	57266	94804	57 603
TSFC(design point)		0.553	0.585	0.576	0.52	0.565

Weight breakdown

Parameter	Units	Value	Value	Value	Value	Value
OEW	lbs	41105	88100	185414	299861	389025
MTOW	lbs	83269	174200	412000	676000	875000
MZFW/MTOW	~		0.9	0.7	0.7	0.7

TABLE 3. SUMMARY OF PERFORMANCE ESTIMATES FOR AIRCRAFT IN THE FIVE CLASSES

The performance of these aircraft for the design mission and the off-design missions are compared with results obtained during an earlier effort as part of PARTNER Project 43 (2011-2013) with the FAA and using results obtained from Georgia Tech using the Environmental Design Space (EDS) tool as part of Ascent Project 10. **Figure 13** shows a comparison of the performance of the B737-800 modeled using SUAVE for a variation of mission range with results from EDS. The results clearly

indicate that the aircraft model in SUAVE not only accurately predicts the design performance for the baseline aircraft but also predicts accurately the aircraft performance for off-design missions. Similar trends are observed for the aircraft as well. The database of aircraft thus created can now be easily imported in AEDT using the interface and used for fleet level analysis.

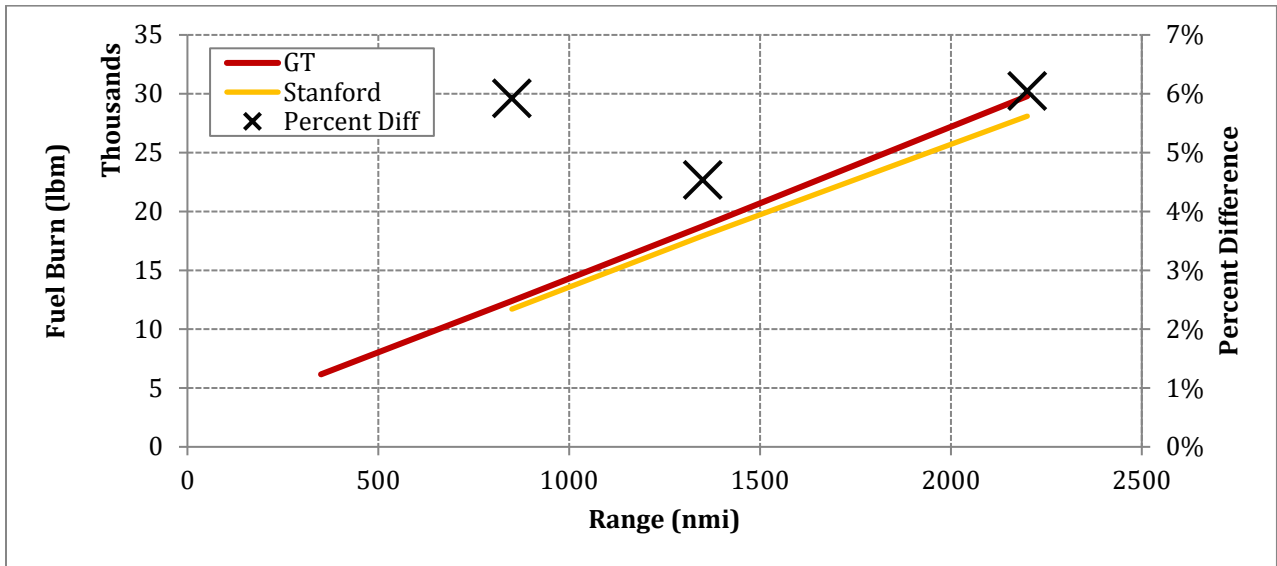


Figure 13. Performance Comparison Between SUAVE (yellow) and EDS (red) for Different Range Missions for the B737-800 Aircraft.

Task 3: Modeling Unconventional Aircraft Configurations – Strut-Braced Wing Aircraft

An important motivation of creating a SUAVE-AEDT interface is to leverage SUAVE’s ability to easily model/simulate unconventional aircraft/engine configurations to build AEDT models for futuristic aircraft configurations and study their fleet level impact. In order to test the ability of the framework to translate complex/unconventional aircraft configurations into the AEDT format, we model a strut-braced wing configuration in SUAVE and describe how translating the model into AEDT format is a trivial exercise.

Modeling the aircraft in SUAVE

Aircraft

The aircraft model is setup in SUAVE exactly like the conventional aircraft described in Section 7. The aircraft is build up of a combination of wing, fuselage and engine components (SUAVE objects) with the input geometric parameters for each component specified exactly like the conventional aircraft. The strut-braced wing differs from the conventional aircraft in that it has four wing components, the main wing, horizontal and vertical tails and a strut. For the strut, a strut location needs to be specified but otherwise is identical to the setup of a conventional wing component. The fuselage and propulsion are set up in the exact same way as a conventional aircraft.

Mission

Setting up the mission is identical to the conventional aircraft. The mission is broken down in to segments and each segment is modeled using a SUAVE segment object. These segments are then assembled together into a mission that is then used to evaluate the aircraft performance.

Physics-Based Design Modules

For the estimation of the aerodynamic properties and the primary structural weight of the aircraft, computational fluid dynamics (CFD) using SU2 (a CFD solver developed at the Aerospace Design Lab, Stanford) and an in-house finite element based weight estimation framework are used. The results from these analyses are then fed back into SUAVE and used to analyze the performance of the aircraft over the design mission

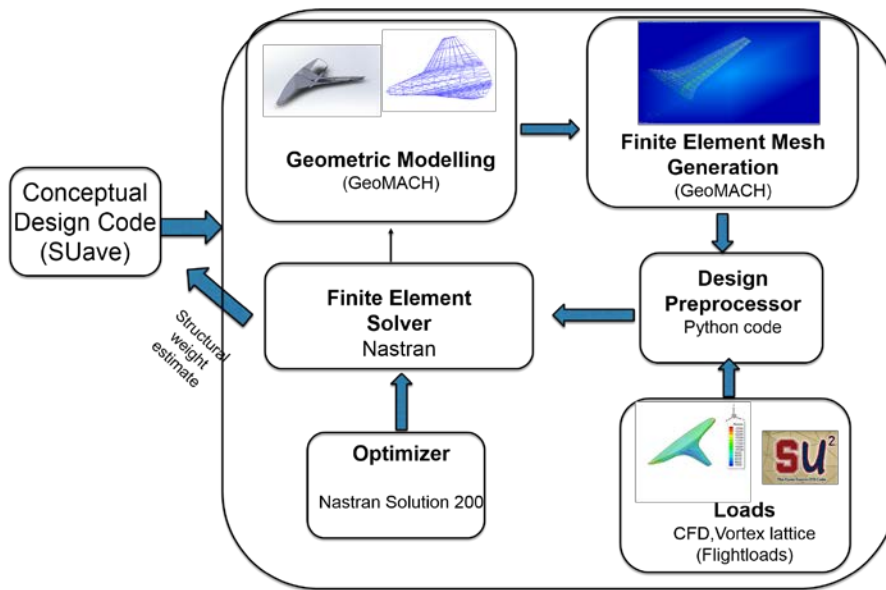


Figure 14. Interfacing of high-fidelity analysis modules in SUAVE environment.

FEA based weight estimation

FEA based weight estimation entails a number of steps as shown in Figure 14. First the vehicle’s geometric data (dimensions and positions of the fuselage and wings) are imported from SUAVE and stored in a local data structure.

Geometry Generation

Next, a geometric (CAD) model/ outer mold line of the aircraft is generated in an automated fashion. GeoMACH, a geometry generation framework developed at the University of Michigan, Ann Arbor is used for this purpose. The outer mold line generated is fed to a volume mesh generator (Pointwise) for generation of the unstructured volume mesh for computational fluid dynamic calculation (described in Section 8.1.8). The outer mold line is used to build a structural model (finite element mesh) of the aircraft consisting of fuselage and wing skins as well as spars, ribs and stringers for the internal structure. These elements are approximated as shell elements.

Sizing loads

Structural sizing using a finite element method requires the definition of sizing loads. For aircraft configurations, this includes the flight loads acting on the structure as well as fuel loads on the wing internal surface and cabin pressurization loads on the fuselage. The fuel and cabin pressurization loads can easily be added as a constant distributed pressure loading on the structural elements. The flight loads are obtained using lift distribution functions that specify the span-wise and

chord-wise distribution of lift on the wings. Loads obtained from computational fluid dynamic simulations or panel methods if available can also be used.

FEA based sizing/Optimization

Once the structural mesh and the sizing loads are obtained, sizing optimizations are performed on the structure. The thicknesses of the shell elements are used as design variables with the optimizer aiming to minimize the weight of the structure while ensuring that stress constraints are met during optimization. For the current study, the design sizing and optimization is performed using Nastran. Nastran is a commercial finite element structural solver that contains an optimization module Solution 200. Solution 200 is used to solve the design problem specified above and its returns the weight of the feasible structure. More detailed descriptions of the weight estimation framework will be presented at SCITECH 2016. **Figure 15** shows the results of the steps described above for the strut-braced wing aircraft configuration modeled (going from the geometry to the optimal structural solution).

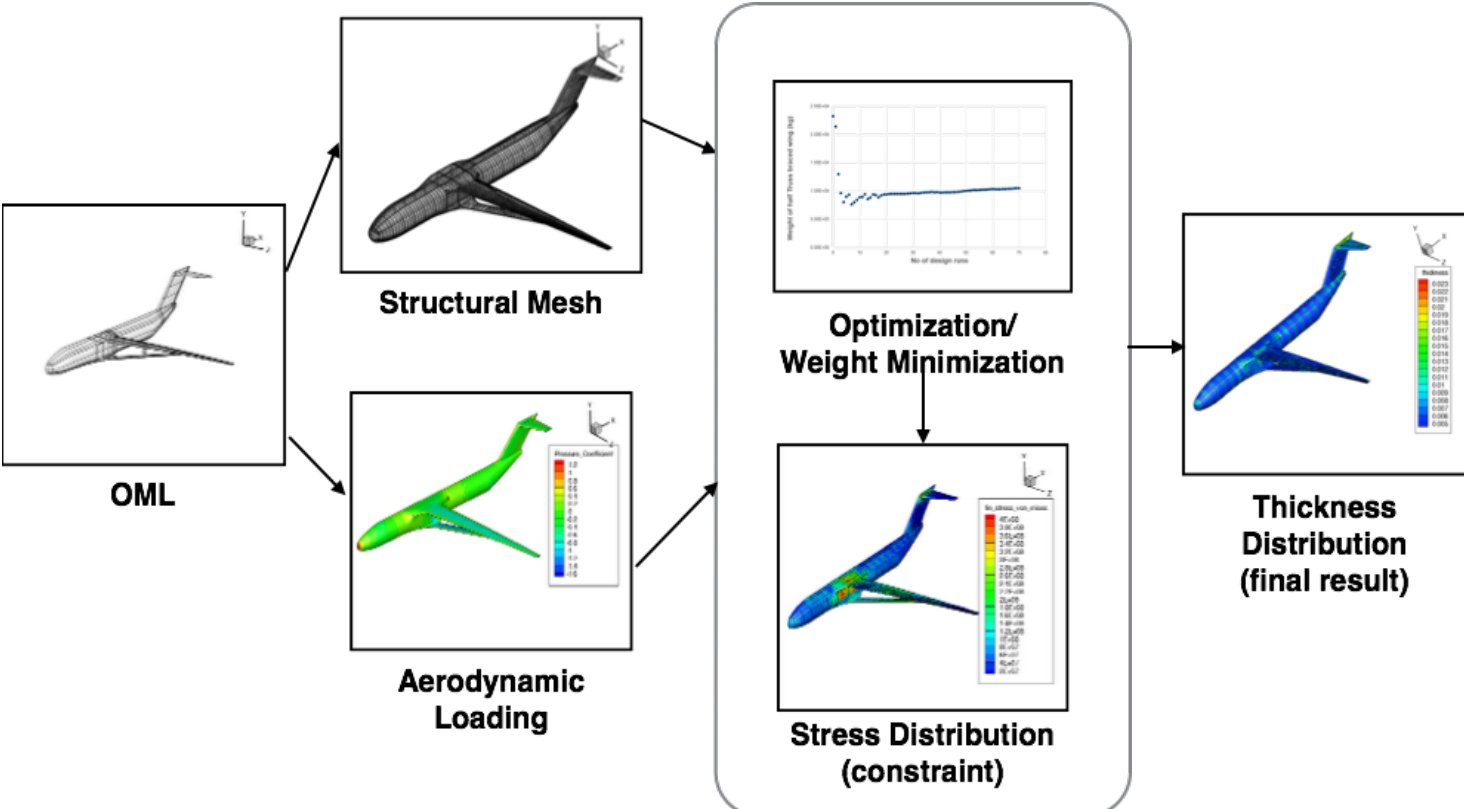


Figure 15.Schematic of entire FEA-based weight estimation procedure, including computation of critical aerodynamic loads.

Improved Aerodynamic Prediction

In order to get an accurate estimate of the lift of the aircraft in cruise, an Euler solution (as shown in **Figure 16**) is computed using the SU2 computational fluid dynamics suite developed at the Aerospace Design Lab at Stanford. The outer mold line (OML) obtained from GeoMACH is used to build an unstructured volume mesh using Pointwise. This mesh is then used for the CFD solution with SU2 returning the lift and inviscid drag of the aircraft. These results are fed back into SUAVE and used to build surrogates for the lift and drag of the aircraft, which are then used during the mission evaluation.

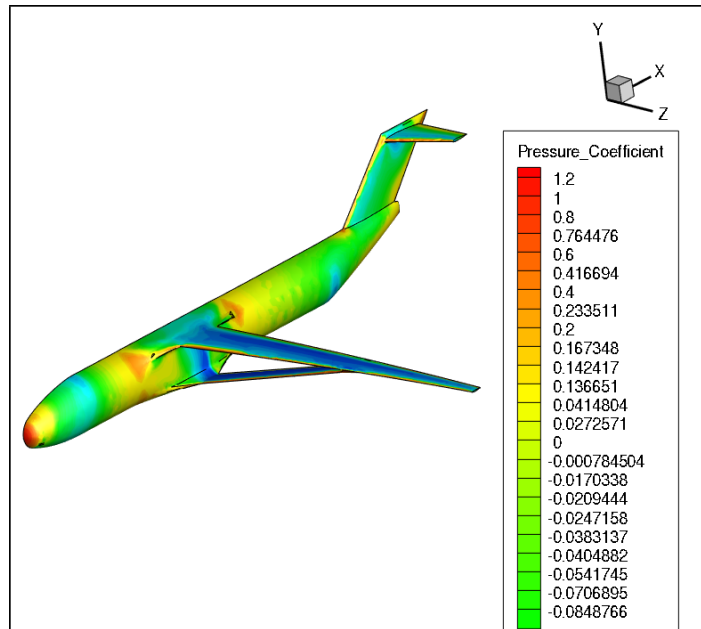


Figure 16. Sample strut-braced wing aircraft solution using the SU2 CFD analysis capability.

Overall performance analysis

The overall mission solver functions in the same way as for conventional aircraft with equation of motion solved at each time step using the performance estimates obtained from the individual analysis modules. The aerodynamics and the primary structural weight are obtained from physics based models as described in Sections 8.2.1 and 8.2.2. The stability and landing and takeoff modules use correlation-based methods to compute estimates.

Given that the aircraft models/component breakdown and output data structures used for the strut-braced wing are consistent with those used for conventional aircraft configurations, the results obtained from simulating the performance of the strut-braced wing for a set of conditions can be used to generate an AEDT input file without any modification to the SUAVE-AEDT interface.

Outreach Efforts

N/A

Awards

N/A

Student Involvement

N/A

Publications

N/A

Conclusions & Future Work



In summary, all the objectives of Project 12 (in the three separate Tasks described in this report) were completed during the period of performance of this grant. More specifically, we have created a software module, pySUAVE-AEDT, that is now maintained as part of the SUave open-source distribution (see <http://github.com/suavecode>), that can transfer any aircraft that is modeled in SUave to a format that can be understood by AEDT. The module is based on the BADA3 format but, as we gain access to the new and improved BADA4 representation, we will make the necessary changes to enable BADA4 models to be created as well. In addition, we have created a library of representative existing aircraft (at least one aircraft in each of the aircraft classes) in SUave that can be analyzed and optimized in SUave, but that can also be transferred to AEDT for future use. Finally, we have demonstrated the SUAVE-AEDT connectivity for an advanced aircraft (a truss-braced wing aircraft model) that has been modeled and optimized in SUave as a way to show that future advanced aircraft developed in SUave could be provided to AEDT for additional impact assessment of new technologies and new configurations.

As part of the effort, and although not required by the grant, we have developed an acoustic source characterization and propagation module for SUave that accounts for both engine and airframe noise sources. Although this model has not been described here and is not yet integrated with AEDT, we intend to include this capability in future releases of pySUAVE-AEDT.

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