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Model-based Systems Analysis and Engineering: Aircraft and Component/Subsystem Models

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August 2025

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Abstract

The National Aeronautics & Space Administration (NASA) Model-Based Systems Analysis & Engineering (MBSA&E) effort developed a toolset for system-level vision-vehicle performance and technology assessments in support of the Sustainable Flight National Partnership (SFNP). NASA sponsored a set of projects to stimulate innovation and develop industry partnerships supporting the MBSA&E effort. The Aircraft and Component/Subsystem Models project was one of six projects performed by Boeing. The project generated open models of a commercial transport study aircraft and its engine. General Electric (GE) provided a customer model of an engine based on a cycle from the Numerical Propulsion Simulation System (NPSS) Consortium. Boeing modeled a conventional transport from the Subsonic Ultra-Green Research (SUGAR) study modified with the engine from GE in the MBSA&E toolset. The MBSA&E model was compared and calibrated to match Boeing results. The experience working with the MBSA&E toolset provided opportunity to form observations on the capability.

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Nomenclature

AATT	–	Advanced Air Transport Technology
ACM	–	air cycle machine
API	–	application programming interface
C_D	–	drag coefficient
C_L	–	lift coefficient
CLIN	–	contract line item number
Dymos	–	multidisciplinary optimal control library
ECS	–	environmental control system
FLOPS	–	Flight Optimization System
GASP	–	General Aviation Synthesis Program
GE	–	General Electric
MBSA	–	model-based systems analysis
MBSA&E	–	Model-Based Systems Analysis & Engineering
MBSE	–	model-based systems engineering
MDAO	–	multidisciplinary design analysis & optimization
N+3	–	third next generation technology timeframe
N3CC	–	N+3 conventional configuration
NASA	–	National Aeronautics & Space Administration
NPSS	–	Numerical Propulsion Simulation System
OpenMDAO	–	Open Multidisciplinary Design Analysis & Optimization
SE	–	systems engineering
SFNP	–	Sustainable Flight National Partnership
SUGAR	–	Subsonic Ultra-Green Aircraft Research
TF01	–	turbofan engine cycle established by the NPSS Consortium
TSFC	–	thrust specific fuel consumption
VLD _{es}	–	Vertical Lift Design
VSP	–	Vehicle Sketch Pad
VSPAERO	–	Vehicle Sketch Pad Aerodynamics
WingMOD	–	Wing Multidisciplinary Optimization Design

Introduction

National Aeronautics & Space Administration (NASA) Aeronautics engaged with industry, academic, and other agencies through the Sustainable Flight National Partnership (SFNP) to accomplish the aviation community’s goal of net-zero carbon emissions by 2050. The Advanced Air Transport Technology (AATT) Project was a contributing member of the SFNP and was tasked with integrating simulation data, ground test data, and flight demonstration data for system-level vision-vehicle performance and technology assessments. The effort toward collating and integrating technology and vehicle data across the SFNP led by the AATT Project was dubbed Model-Based Systems Analysis & Engineering (MBSA&E). NASA sponsored a set of projects to stimulate innovation and develop industry partnerships supporting the MBSA&E effort. The Aircraft and Component/Subsystem Models project described in this report was one of six projects performed by Boeing.

The project aimed to evaluate a commercial transport with existing NASA MBSA&E tools. The MBSA&E model would be matched to industry evaluations, and delivered with unlimited rights. By delivering a model with unlimited rights, Boeing would provide NASA the flexibility to distribute the model openly across government, industry, and academia. Wide distribution could allow the model to be used as a reference for the multidisciplinary design analysis & optimization (MDAO) community. Developments in analysis and optimization capabilities could be checked against results of this model. Modeling the transport with MBSA&E tools and comparing results with internal analysis tools provided Boeing the opportunity to assess the MBSA&E capabilities and report observations.

Since the transport model would be openly available, a conventional configuration with current technology levels was selected to be modeled. The model resembles a Boeing 737 but is based on an airplane concept from the Subsonic Ultra-Green Aircraft Research (SUGAR) study (Reference 1). Using a study aircraft similar to an existing one was a way to produce an open model with high confidence in the results of the model. Boeing partnered with General Electric (GE) to provide an open engine model for the aircraft. To create an open model, the engine based on the TF01 turbofan engine cycle established by the Numerical Propulsion Simulation System (NPSS) Consortium. High level information on the vehicle is provided in Figure 1.

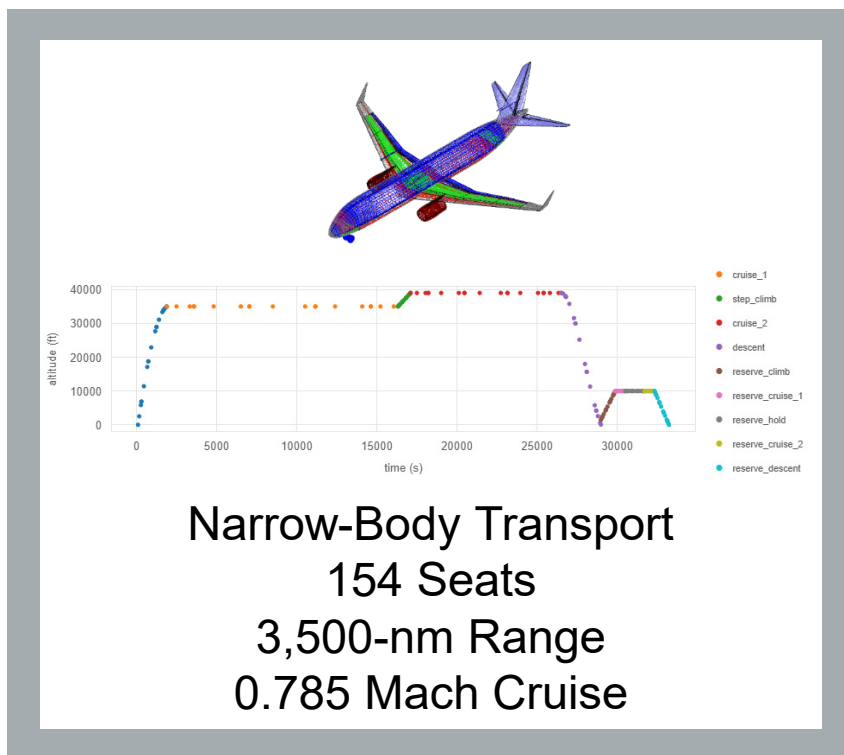


Figure 1. Commercial transport model developed in study

Approach

NASA previously developed a model of a commercial transport with technologies anticipated for the third next generation timeframe (N+3), circa 2035 (Reference 2). This vehicle was called N3CC for N+3 conventional configuration. The N3CC model provided a working setup for the MBSA&E toolset that was built on OpenMDAO (Open Multidisciplinary Design Analysis & Optimization). The toolset included Aviary, which adopted methods from Flight Optimization System (FLOPS) and General Aviation Synthesis Program (GASP) (Reference 3). Aviary also integrated with the Dymos multidisciplinary optimal control library for mission performance analysis. The MBSA&E toolset also included Vehicle Sketch Pad (VSP), VSP Aerodynamics (VSPAERO), and NPSS.

Boeing received the N3CC MBSA&E model from NASA and made modifications to model the Sugar Free configuration from the SUGAR study. The Sugar Free configuration represented vehicles from the N baseline generation technology timeframe, circa 2005. The Sugar Free was originally modeled with technologies consistent with the 737NG vehicle and CFM56 engine. The MBSA&E model used the Sugar Free geometry but switched propulsion to the TF01 engine provided by GE. The MBSA&E model also adopted composite wing and tail weights.

Geometry

The Sugar Free geometry was modeled in VSP by making modifications to the N3CC VSP model. The fuselage height, width, and length were matched to the Sugar Free. The passenger area and forward and aft cargo areas were also adjusted. The wing planform, thickness, and position were adjusted to match. The control surface planforms were also matched. VSP could only locate spars at a constant fraction of chord, so it was not possible to match spar location. In the wing carry through section, where the wing is inside the fuselage, the actual spars run perpendicular to the fuselage. In the VSP model, the spars in the carry through section follow the wing and are swept. In the VSP model, the sweep causes the front spar to end at the aircraft center line significantly forward of where it should be. The forward cargo area is kept ahead of the front spar, so it does not go as far aft as it should. The horizontal and vertical tail planforms were set to match. Nacelle diameter, length, and position were set to match the Sugar Free geometry. The Sugar Free and N3CC VSP geometry models are compared in Figure 2.

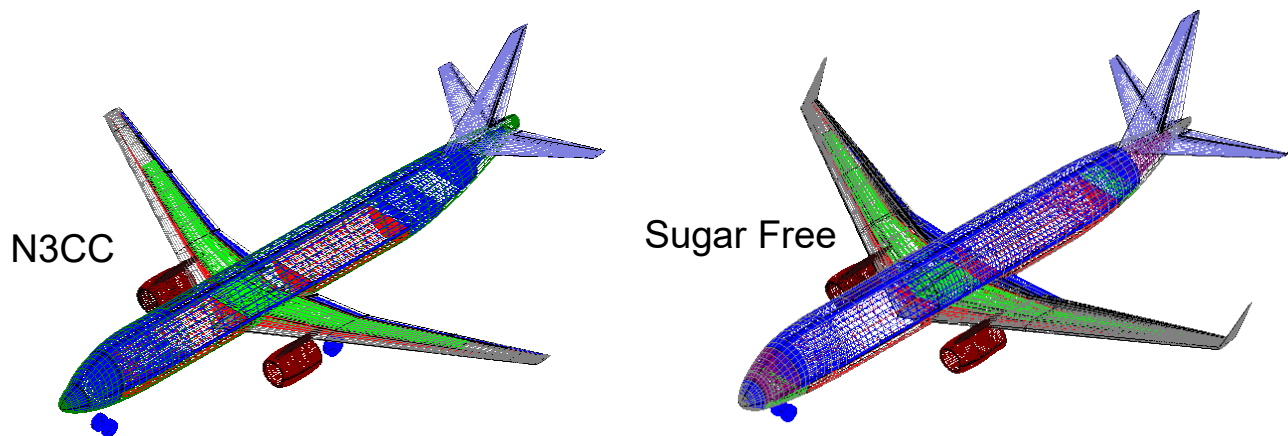


Figure 2. Sugar Free geometry generated from N3CC.

To allow the Sugar Free MBSA&E model to be openly available, the N3CC airfoils were retained instead of using Boeing airfoils. While airfoils would affect results of higher fidelity computational fluid dynamics (CFD) analysis, they were not expected to have significant effects on the analysis performed with VSPAERO. The Sugar Free geometry had a winglet that was not on the N3CC. The wing tip airfoil was extended over the winglet.

To control twist and model the winglet and control surfaces, input stations were added to the N3CC VSP geometry, as indicated in Figure 3. At the winglet root, there are two input stations that are close together. The input stations allow setting the winglet root twist independently from the wing tip twist.

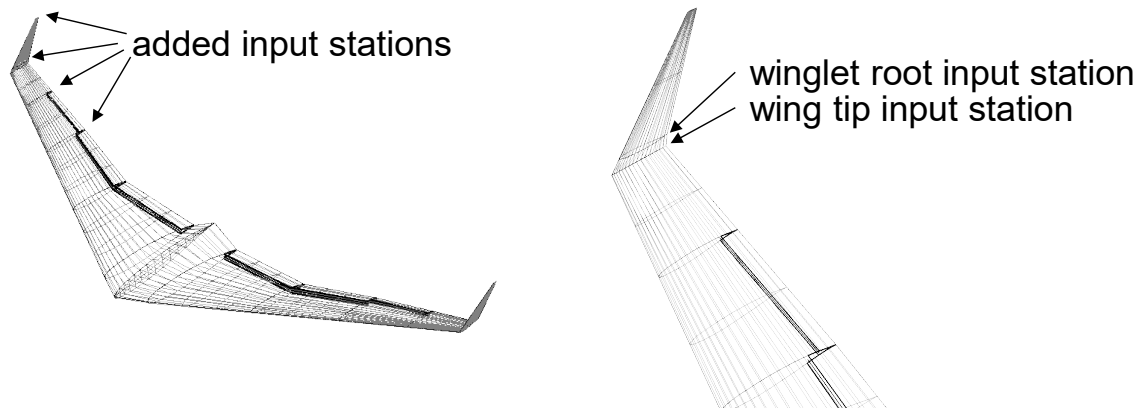


Figure 3. Input stations added relative to N3CC to model Sugar Free.

The twist across the wing would be adjusted to match span loading from Boeing analysis. During that process, it was observed that the wing root modeling on N3CC resulted in a drop off in lift at the centerline because the geometry was not sealed. Figure 4 shows a gap in the lower surface and overlap in the upper surface in the N3CC geometry where the left and right wings come together. While VSP handled dihedral changes in the middle of a wing, notably at the winglet, it did not adjust for left and right wings coming together. To correct the gap and overlap, the Sugar Free geometry was set to zero dihedral inboard of the side of body. This change caused the left and right wings to come together smoothly as indicated in Figure 4.

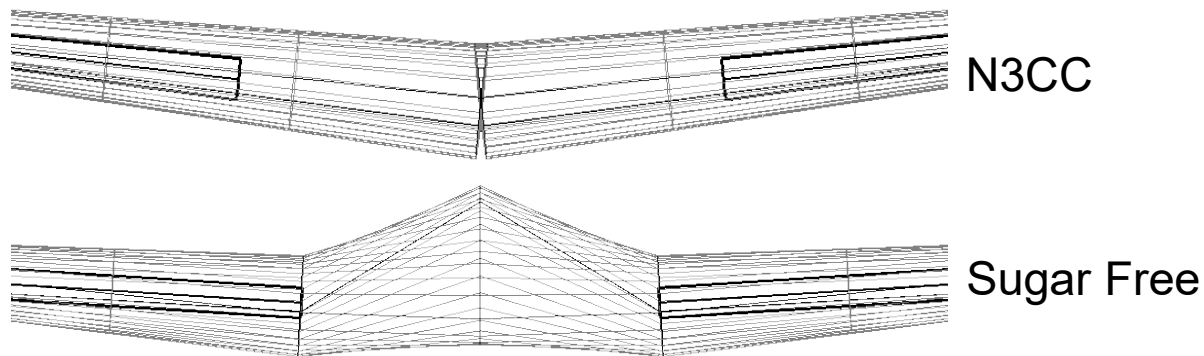


Figure 4. Differences in modeling of wing root section between N3CC and Sugar Free.

The Boeing Wing Multidisciplinary Optimization Design (WingMOD) code was previously applied to the Sugar Free geometry in the Adaptive Compliant Trailing Edge (ACTE) study (Reference 4). A WingMOD span load was used as a target for setting the twist on the Sugar Free VSP model. The Sugar Free model was run in VSPAERO and twist on the VSP model was manually adjusted to get a match with the WingMOD span load. Matching span load was used instead of matching geometric twist because it took out any differences from using N3CC airfoils and it set up the best match for induced drag calculations in VSPAERO.

Characteristics of the twist in the Sugar Free MBSA&E model are indicated in Figure 5. The two closely spaced input stations at the winglet root allow for a rapid twist change. This rapid change allows the winglet to be at a higher incidence and take on more load than if a smoother transition was taken between wing tip and winglet root. At the side of body, there was no attempt to create a discontinuity in the twist

distribution. In the WingMOD model, the wing inside the fuselage was modeled at zero incidence with a step change to the incidence at side of body. Matching the WingMOD span loading required a noticeably negative incidence for the centerline airfoil in the MBSA&E model. While this feature achieved essentially equivalent span load, the MBSA&E model may have looked better with discontinuous twist at the side of body.

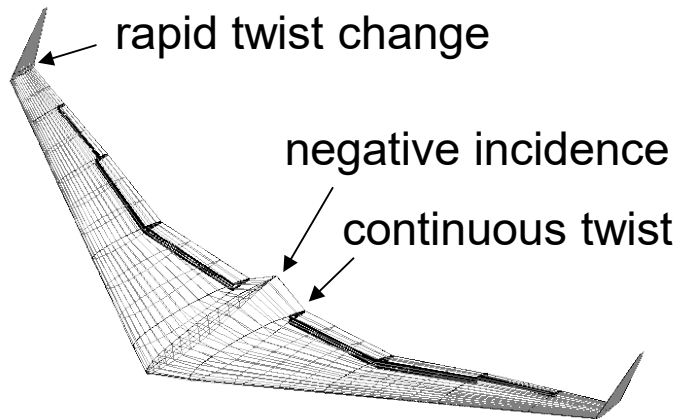


Figure 5. Twist modeling for Sugar Free.

Aerodynamics

The Sugar Free MBSA&E model was set up with both VSPAERO and Aviary aero models. Aviary uses conceptual design methods while VSPAERO uses vortex lattice model or panel methods.

VSPAERO was tried initially, but it proved too expensive for sizing optimization. The MBSA&E tool set calls VSPAERO to generate tables of lift coefficient (C_L) and drag coefficient (C_D) versus Mach number and angle of attack. The aerodynamic tables are used for mission performance analysis. For fixed geometry, the tables can be calculated once. For sizing wing area via optimization, the aerodynamic tables had to be calculated repeatedly, and the computational time was impractical.

Aviary aero was used to allow sizing optimization. While the MBSA&E toolset made the aerodynamic tables calculated by VSPAERO readily available, Aviary aero data had to be extracted from the output of the mission performance analysis. When the mission was solved through OpenMDAO, details of the solution were stored in a file that could be read with an OpenMDAO CaseReader object. OpenMDAO Case objects could be retrieved from a CaseReader, and there was a final case that detailed the final solution. There was a method to list output parameter names from a Case, and there was a method to get values from a Case given the name of the parameter being extracted. Lift and drag coefficients were fortunately outputs that could be extracted from the trajectory solution.

The approach for calibrating Aviary aero against Boeing data involved extracting lift and drag data from a cruise segment and interpolating to get the drag coefficient at a pair of calibration lift coefficients. Parameters for aerodynamic calculations were mostly inherited from the N3CC model. Two adjustment factors from the MBSA&E tool set were used to adjust Aviary aero to match Boeing estimates for cruise: `lift_dependent_drag_coeff_factor` and `zero_lift_drag_coeff_factor`. The calibrated values for Aviary aero are shown in Table 1. A third adjustment factor, `subsonic_drag_coeff_factor`, was set to 1 for Aviary aero but used to adjust VSPAERO. Aviary aero data extracted from the initial 35,000 ft altitude cruise segment in the mission performance analysis for the baseline vehicle are shown in Figure 6. The Aviary aero model closely matches Boeing results.

The MBSA&E toolset provided a single adjustment factor for VSPAERO: `subsonic_drag_coeff`. The values of `lift_dependent_drag_coeff_factor` and `zero_lift_drag_coeff_factor` did not seem to affect VSPAERO, so the VSPAERO version of the model kept the values for Aviary aero as indicated in Table 1. To minimize differences between the VSPAERO and Aviary aero versions of the model, the `subsonic_drag_coeff_factor` on the VSPAERO model was set to match mission fuel burn on the baseline aircraft. VSPAERO data extracted from the initial 35,000 ft altitude cruise segment in the mission performance analysis for the baseline vehicle are shown in Figure 6. Having a single adjustment limited the ability to match the trend of drag versus lift in the VSPAERO model with the Boeing data.

The adjustment factors used for Aviary aero seemed reasonable. Accounting of excrescence and interference drag could be expected to result in a zero lift drag adjustment slightly over 1. Lift dependent viscous drag and compressibility drag could be expected to drive the lift dependent drag adjustment slightly over 1.

It was not clear what components of drag VSPAERO was accounting for. A breakdown between skin friction drag and pressure or induced drag would have been helpful. The value for `subsonic_drag_coeff_factor` may seem too high if VSPAERO accounted for skin friction drag and it may seem too low if it did not account for skin friction drag. Combined with the mismatch in the trend of drag coefficient with lift coefficient, a deeper look at the VSPAERO drag methodology may be warranted.

Table 1. Drag adjustment factors applied to Sugar Free model.

	Aviary Aero Calibrated Values	VSPAERO Calibrated Values
lift dependent drag coeff factor	1.09	1.09
zero lift drag coeff factor	1.05	1.05
subsonic drag coeff factor	1.00	1.45

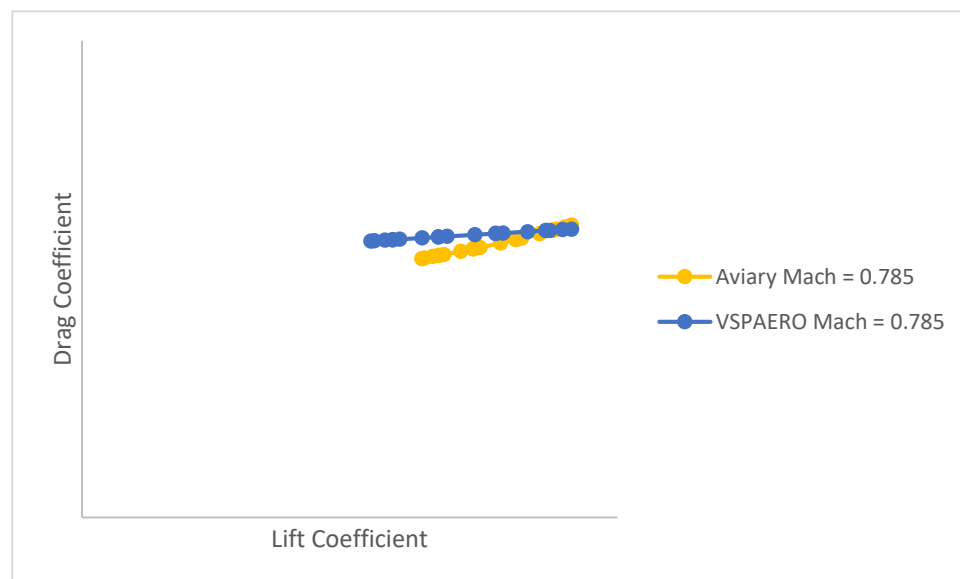


Figure 6. Comparison of calibrated Aviary aero and VSPAERO models against Boeing results.

It did not look like VSPAERO or Aviary aero captured compressibility drag. VSPAERO captures some compressibility effects via Prandtl-Glauert transformation. The key component of compressibility drag is from shocks creating a loss of total pressure that causes pressures aft of the shock to be lower than pressures ahead of the shock. The difference between fore and aft pressures creates a drag that requires a separate analysis model. An example of a compressibility drag analysis is provided by Shevell (Reference 5). For this study, the aircraft was operated in conditions where compressibility drag was low, so the effects were absorbed in the calibration of the aero models. At other than the 0.785 cruise Mach number, the MBSA&E Sugar Free model will show differences relative to the Boeing aero model.

Another missing compressibility related analysis is buffet. Shocks induce flow separation that reduces the usable maximum lift coefficient relative to flight at low Mach number. Cruise altitude can be limited by buffet: the aircraft should be able to pull a load factor of 1.3 before reaching deterrent buffet. Buffet was not a limiting constraint in the Boeing analysis of the Sugar Free configuration, so its omission in the MBSA&E toolset did not affect the analysis of this configuration; however, a means for estimating buffet may be needed for other aircraft configurations.

Propulsion

A loosely coupled demonstration connected five of the Boeing MBSA&E projects and affected the engine model developed by GE. Key activities of the demonstration are indicated in Figure 7. The projects addressed different contract line item numbers (CLINs) and were referred to by those numbers.

In a pair of projects dealing with narrow and comprehensive model sharing (CLIN 004 & CLIN 005), Collins Aerospace provided an analytical model and systems engineering (SE) models of an air cycle machine (ACM). The analytical model was shared as a functional mockup unit (FMU) as a form of narrow model sharing, where details of the model are hidden. SE models were shared with the ACM as a black box, simulating narrow model sharing, and with lower level components of the ACM exposed, simulating comprehensive model sharing. The SE models were integrated in a Boeing vehicle level SE model. The analytical ACM model was integrated in a Boeing model for an environmental control system (ECS). Other components of the ECS were modeled by Boeing, simulating comprehensive model sharing, where the details of the analysis script were available. The ECS model was used to determine the amount of air that was bled off the engine for performance estimates.

The project dealing with the connection between model-based systems analysis (MBSA) and model-based systems engineering (MBSE) (CLIN 003) was responsible for developing a vehicle SE model and also a software MBSA-E connector that could transfer information between Magic Draw (used for MBSE) and the Aircraft Data Hierarchy (ADH) (developed for MBSA). The University of Michigan was primarily responsible for developing the MBSA-E connector.

For the project that developed the ADH (CLIN 001), the University of Michigan demonstrated using the ADH in running a PyCycle engine model and loading propulsion data for vehicle performance through the ADH into the N3CC MBSA&E model. Connecting the PyCycle ADH to Magic Draw through the MBSA-E connector was also demonstrated.

GE prepared the TF01 engine model with modifications to handle bleed and power offtake requirements. GE ran the conditions needed for vehicle performance. For this project focused on generating an open commercial transport MBSA&E model (CLIN 006), Boeing converted the GE engine performance data into the Aviary format used in the MBSA&E toolset. Boeing also ran Weight Analysis of Turbine Engine++ (WATE++) on the GE model to generate an engine weight for the MBSA&E toolset.

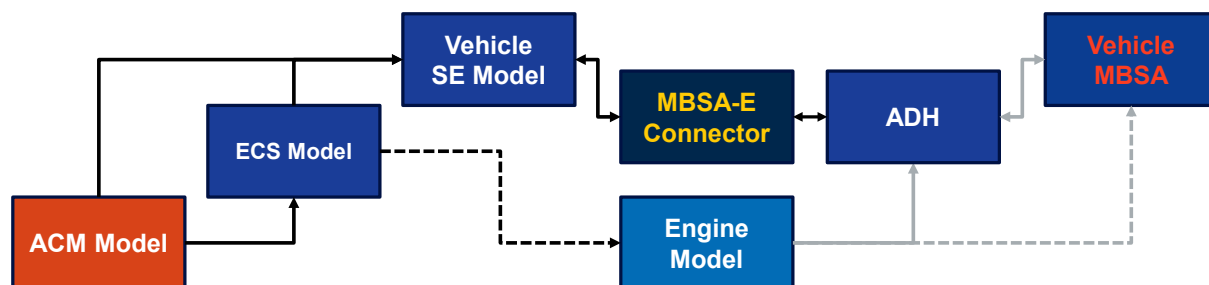


Figure 7. Related activities across MBSA&E project.

The bleed and power offtake used for engine performance are shown in Table 2. The power offtake is primarily for running the electrical system and is typical for this size of commercial transport. The bleed from the engine core primarily powers the ECS. The fan flow bleed taken from the fan casing provides fresh air for the cabin and cool air for heat exchange. Both bleed and fan flow were taken from the ECS model. The cruise condition is nominally standard day at 35,000 ft. The ground condition is warm day at

sea level. The anti-ice system may draw additional bleed, but it was assumed anti-ice would not be used on a warm day for this study. The intent was for the cruise bleed to be used for engine performance and the ground bleed to be used as a check on engine design.

Table 2. Bleed and power offtake used for engine performance.

ECS Configuration	Power Offtake (hp)	Bleed (ppm)	Fan Flow (ppm)
Conventional Cruise	150	59.5	46.9
Conventional Ground	150	59.5	52.1

GE developed a non-proprietary engine model for MBSA&E. The model was based on the NPSS Consortium generic high bypass turbofan (TF01) cycle because it was non-proprietary, had representative full range component maps, and had been extensively used for training purposes by many organizations. The baseline model lacked features required for this study such as the option for bleed locations for aircraft systems, power extraction options, and usability features such as a throttle input. These features were added in a non-proprietary form with demonstration run files so the updated model could be openly used in later efforts.

In addition to being non-proprietary, it was desirable for the demonstration model to be easily installed and used in the MBSA&E environments. Although the model could still be used in the NPSS environment by those using this software for other efforts, this demonstration model was configured as a small footprint customer model that could be run without any additional software installation. In addition to the command line execution model chosen for the demonstration, the model could be executed via an application programming interface (API) from many computer languages, including Python. This API execution also allowed data to be handled programmatically in addition to file-based input and output. The model could be configured as an FMU, similar to the ACM model. Flexible viewer options were provided to organize and format the data as required.

The delivered model included information to support development of the ADH (CLIN 001). A viewer was provided that included additional outputs recommended for the ADH to address the propulsion information required for other aircraft design efforts on a conventional narrow body aircraft. An example viewer, with just added variable names and no parameter values, was also provided for a hybrid electric and open rotor configuration.

For the demonstration problem, the engine was sized to a thrust requirement at take-off and evaluated over a mission. The cycle design choices such as fan pressure ratio, bypass ratio, and overall pressure ratio plus technology choices of turbine inlet temperature, cooling flow levels, and component efficiencies were selected as reasonable default values typical of current engines for this application. They were not selected to meet aircraft requirements at other conditions or to provide the best fuel burn at the target cruise conditions. The geometry and weight information for the engine was based on a WATE model that was roughly consistent with the technology and component design of the cycle. Changes to better match the aircraft mission could be easily made but would not be meaningful without a corresponding change to the information in the WATE model to be consistent with these design choices and with the component technology. The schedule in this study did not allow for iteration that would have allowed generating a better match between engine and airplane.

The GE TF01 engine model represents a 2-spool turbofan with 9 bypass ratio, 1.3 fan pressure ratio, and 3,200 R turbine temperature. The airflow and bypass ratio were sized to allow the engine to meet the thrust target at takeoff and have a thrust lapse similar to the N3CC Turbofan 22k. The performance of the TF01 engine near the cruise point is shown relative to the N3CC Turbofan 22k engine in Table 3. The points are taken at max thrust from the engine performance tables. The cruise Mach unfortunately lies between points in the table. The TF01 engine was set up to match the Turbofan 22k thrust points, which simplifies comparison. The TF01 cycle is not as advanced as Turbofan 22k, which partially accounts for the higher thrust specific fuel consumption (TSFC). The power offtake and bleeds applied to TF01 also affected TSFC.

Table 3. Cruise performance of TF01 engine compared to N3CC Turbofan 22k.

Description	Turbofan 22k		TF01	
	0.75	0.80	0.75	0.80
Altitude (ft)	35,000	35,000	35,000	35,000
Thrust Net (lb)	3,927	3,976	3,927	3,976
Fuel Flow (lb/h)	1,836	1,930	2,911	3,038
TSFC (1/h)	0.468	0.485	0.741	0.764

The original Sugar Free configuration was based on a CFM56 engine model. Table 4 compares the TF01 takeoff with the Turbofan 22k and CFM56-7B22 data from Reference 6. All the engines are in the 22,000 lb thrust class. Public information on the CFM56 in cruise was not found to enable comparison. The takeoff TSFC shows the TF01 falling in between the efficiency of the CFM56 and the Turbofan 22k.

Table 4. Sea level static performance of TF01 engine compared with other engines.

	Takeoff TSFC (1/h)
CFM56-7B22 ⁶	0.366
TF01 conventional bleed	0.281
Turbofan 22k	0.232

Boeing evaluated the weight of the TF01 engine using WATE++ in NPSS 3.2. The GE model was generated in NPSS 3.1, so some modifications were made to run WATE++. The outputs of WATE++ are shown in Table 5.

Table 5. WATE++ analysis results for TF01 engine.

Weights (lb)		Dimensions (in)	
Bare Engine Weight	5,264.3	Engine Length	168.7
Accessories Weight	789.6	Engine Pod C.G.	63.2
Engine Weight	6,053.9	Engine Max Diameter	68.4
Inlet/Nacelle Weight	732.0	Nacelle Max Diameter	83.1
Total Engine Pod Weight	6,785.9	Total Engine Pod Length	198.0

The bare engine weight from WATE++ is compared with CFM56 family weights from Reference 6. The weight is very close to the CFM56-7B22. The weight of the CFM56-7B27 is reported to be the same as the 7B22, despite the higher thrust. That indicates the ability to extract more thrust with little modification to the engine. It also suggests a higher thrust to weight may be achievable. The same might apply to the TF01 if it had been designed to the higher thrust.

Table 6. Comparison of TF01 engine weight with other engines.

Engine	Thrust (lb)	Weight (lb)
TF01	22,200	5,264
CFM56-7B22 ⁶	22,700	5,234
CFM56-7B27 ⁶	27,300	5,234

Weights

A model of the original Sugar Free configuration was built in the Boeing Vertical Lift Design (VLDes) performance analysis. VLDes was originally developed for electrified propulsion rotorcraft studies (Reference 7), but it had been modified and applied to transport aircraft studies. The TF01 engine performance data and weight were substituted into the VLDes model to form the modified Sugar Free configuration that would be modeled in the MBSA&E toolset.

Table 7. MBSA&E inputs used to calibrate modified Sugar Free baseline weights compared with N3CC inputs.

Description	N3CC	Sugar Free
aircraft:wing:mass scaler	0.7412	1.06
aircraft:fuselage:mass scaler	0.69981	0.98
aircraft:design:empty mass margin scaler	0.01498	0.00
aircraft:crew and payload:cargo container mass scaler	1.00	0.00
aircraft:horizontal tail:mass scaler	1.42225	1.21
aircraft:vertical tail:mass scaler	1.42225	1.21
aircraft:wing:surface ctrl mass scaler	1.77696	1.58
aircraft:air conditioning:mass scaler	0.98094	1.01
aircraft:anti icing:mass scaler	0.53202	0.55
aircraft:apu:mass scaler	1.02321	1.02
aircraft:avionics:mass scaler	1.123226	0.81
aircraft:electrical:mass scaler	1.1976	1.28
aircraft:fuel:fuel system mass scaler	0.93202	1.13
aircraft:furnishings:mass scaler	0.81859	0.63
aircraft:hydraulics:mass scaler	0.95543	0.88
aircraft:instruments:mass scaler	1.66955	1.21
aircraft:landing gear:main gear mass scaler	0.8846	0.88
aircraft:landing gear:nose gear mass scaler	0.8846	0.88
aircraft:crew and payload:passenger service mass scaler	1.00	1.59
aircraft:engine:mass scaler	1.15	2.11
aircraft:engine:reference mass	6,293.8	5,264
aircraft:engine:reference sls thrust	22,200	22,200
aircraft:engine:scaled sls thrust	22,200	32,600
mission:design:gross mass	135,000	186,400

The thrust on the modified Sugar Free was sized in VLDes with an optimization including engine diameter providing guidance on thrust sizing. The engine size was driven by a 20-minute time to climb to initial cruise altitude that the original Sugar Free performed with a scaled CFM56 engine with 28,200 lb thrust. Based on the optimization guidance, the engine diameter on the modified Sugar Free was manually set to yield 32,600 lb takeoff thrust. The TF01 was modeled to match the thrust of the Turbofan 22k engine, which likely had a higher lapse rate than the CFM56 because of higher bypass ratio. The reduction in thrust at higher altitudes created the need for a larger engine size.

The aircraft was run with this engine sizing in VLDes to establish component weights and mission fuel burn. The aircraft was then run in the MBSA&E toolset and inputs were adjusted to match the VLDes results. Adjusting the weights was an iterative process because of the influence of vehicle level weights on many of the component weights. To limit the number of iterations, the inputs for the Sugar Free configuration were selected to match Boeing results to about 1%. Input parameters used to match results for the modified Sugar Free are shown in Table 7, with inputs for N3CC provided for comparison.

The adjustment factors for wing and fuselage structure are significantly larger on the modified Sugar Free than on N3CC. The N3CC wing weight was reportedly matched to a FEM based sizing. A concern with FEM based weights is whether all the sizing criteria were applied. Minimum gauge and buckling would cause significant portions of structure to be heavier than indicated by a material stress allowable. Factors for non-optimal material would also bump up the weight. Similar concerns may apply to the fuselage adjustment. The original and modified Sugar Free fuselage was aluminum rather than composite, which may be an actual difference relative to N3CC. The original Sugar Free wing was aluminum but the modified Sugar Free assumes composite wing and tails.

The Sugar Free MBSA&E model calibrated all the component weights, so the empty_mass_margin_scaler was not used. The Sugar Free did not use cargo containers, so that component was zeroed. The Sugar Free furnishings adjustment was lower than N3CC while passenger service mass was higher. Differences in accounting may have created a shift of items between the two categories. The

engine_mass_scaler was set rather high to match Boeing engine pod mass. After the work on study was complete, it was noted that engine_mass_scaler alters the exponent that scales the engine mass with thrust. The behavior is different from the other scalers, which are multiplied with raw component weight estimates to get calibrated component weights. In the study, the bare engine mass was used as the reference mass with expectation that the weight method would fill in engine systems and propulsion structure weight. With the understanding of engine_mass_scaler following the study, it would have been better to use engine_reference_mass to calibrate the engine pod weight.

Results

Performance Evaluation and Sizing

Weights for the modified Sugar Free configuration modeled in the MBSA&E toolset are compared in Table 8 with results for the original configuration evaluated in the SUGAR study (Reference 1) and the configuration evaluated in the ACTE study (Reference 4). The ACTE study had more optimistic weights and used an advanced engine that was similar in performance to the N3CC Turbofan 22k. The MBSA&E configuration is closer to the original SUGAR study. The TF01 engine used for MBSA&E is more efficient than the CFM56 used in SUGAR, which is reflected in the lower fuel burn. The TF01 had less thrust at higher altitudes, which then required the larger takeoff thrust indicated in the table. The larger engine added weight, reflected in the operational empty weight in the table. The increase in engine weight was greater than reductions for switching wing and tail structure to composite from aluminum. The changes in fuel burn and empty weight left the MBSA&E configuration slightly heavier than the result from the original SUGAR study.

Table 8. Results of modified Sugar Free evaluated in MBSA&E compared with prior studies.

Description	SUGAR¹	ACTE⁴	MBSA&E (Boeing)	MBSA&E
Takeoff Weight (lb)	184,800	153,973	186,432	186,061
Operational Empty Weight (lb)	96,000	87,412	99,335	98,964
Payload (lb)	30,800	30,800	30,800	30,800
Total Fuel (lb)	58,000	35,761	56,297	56,297
Engine Thrust	28,200	24,700	32,600	32,600

A sizing optimization was tested with the MBSA&E toolset. For a fixed vehicle configuration, the MBSA&E toolset performs an optimization that solves mission performance and weights needed to fly a specified mission. Sizing wing area and engine thrust involved adding two parameters as design variables in the optimization: aircraft:wing:detailed_area and aircraft:engine:scaled_sls_thrust. This approach for wing sizing scales the dimensions of the wing while preserving the shape, including aspect ratio, sweep, span fractions for planform breaks, ratios between chords at the planform breaks, and thickness to chord ratios.

Adding wing area to the optimization was too computationally expensive when VSPAERO was used, but sizing wing area was readily handled with Aviary aero. The result of the sizing optimization is shown in Table 9. The detailed_area parameter corresponds with total wing area, which includes the planform area of each wing section in its reference plane, including the winglet and the portion of the wing buried in the fuselage.

Table 9. Comparison of results between baseline and takeoff weight sized configurations.

Description	Baseline	Takeoff Weight Sized
Total Wing Area	1,596	1,497
Engine Thrust	32,600	29,088
Operational Empty Weight	98,964	93,169
Fuel Burned	50,335	49,106
Reserve Fuel	5,963	5,637
Takeoff Weight	186,061	178,712

Since the baseline was previously sized, it was expected that the sizing would not move far from the baseline. The baseline wing area had been kept the same relative to prior studies so that comparisons would be made on consistent geometry, so there was opportunity for resizing the wing to improve the configuration. A larger opportunity came from a relaxed time to climb constraint that was used in the MBSA&E toolset. While the engine on the baseline was sized for a 20-minute time to climb to match the capability of the original Sugar Free, the mission profile entered in MBSA&E allowed a 30-minute time

to climb, which is a more typical requirement. In the MBSA&E toolset, the baseline aircraft used the full 30 minutes for reduced fuel burn although it could have climbed faster. When optimized in MBSA&E, the engine size could be reduced until the 30-minute time to climb became critical. The combination of non-optimally sized wing and oversized engine in the baseline provided room for the MBSA&E sizing optimization to improve the aircraft.

The optimization in the MBSA&E toolset was able to reduce both engine size and wing area to reduce takeoff weight. The baseline and takeoff weight sized geometries are compared in Figure 8. The reduction in wing area is visually small. It may be perceived by judging the relative location of the end of the fuselage and the wing tip.

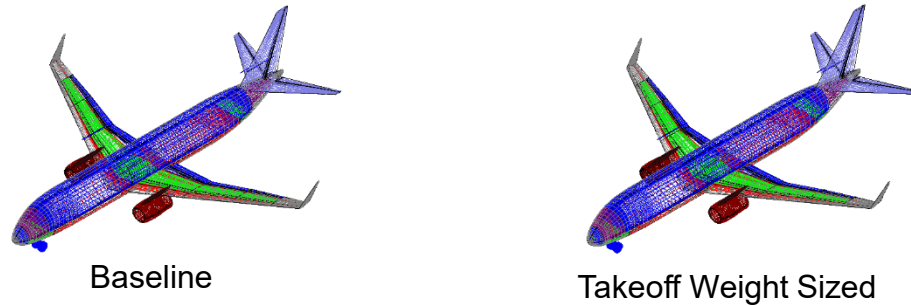


Figure 8. Comparison of baseline and takeoff weight sized geometries.

Mission profiles showing altitude versus time are shown for the baseline in Figure 9 and the takeoff weight sized configuration in Figure 10. The profiles included a climb to 35,000 ft initial cruise altitude, a step climb to cruise at 39,000 ft, descent, and reserve segments. The time to climb to initial cruise altitude was limited to 30 minutes. A 300-fpm minimum climb rate capability was required in both cruise segments. The climb rate capability drove the timing of the step climb. With a smaller wing and engine, the takeoff weight sized configuration had to wait until later in the mission, after it had burned more fuel, before it was able to make the step climb to 39,000 ft.

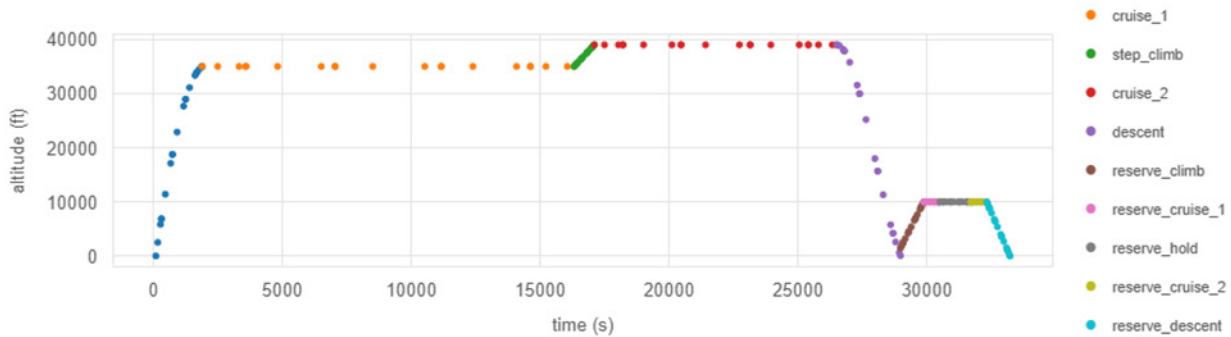


Figure 9. Mission profile for baseline configuration.

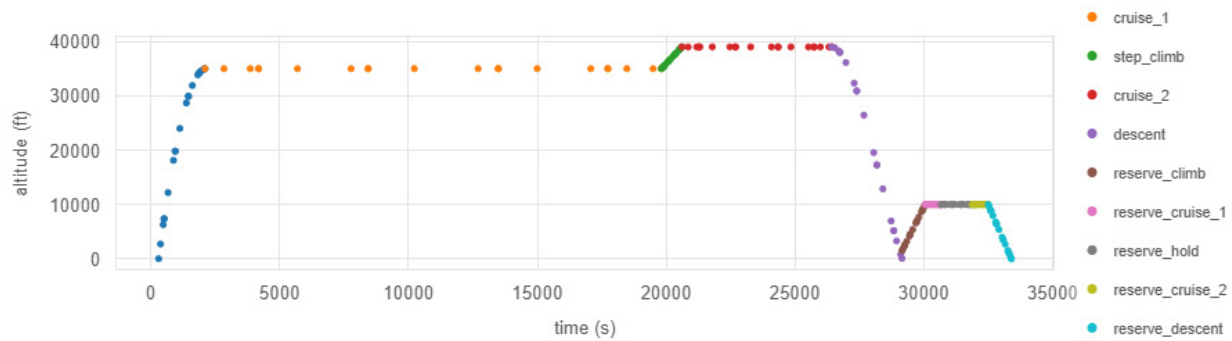


Figure 10. Mission profile for takeoff weight sized configuration.

Observations

This project provided Boeing an opportunity to experience MBSA&E toolset. Observations on the capabilities and workflow of the toolset are provided here.

VSP was found to be able to model most geometry features. Spar locations were limited to a constant chord fraction across the span of the wing. Spar locations in the Sugar Free MBSA&E model are approximate. Notably, the spars in the wing carry through structure buried in the fuselage should have zero sweep, but they follow close to the wing leading and trailing edges given the limitation in locating the spars. As modeled, the front spar intrudes in a space that should be occupied by cargo, and the load paths on both spars are longer than if the spars had been able to cut straight across the fuselage.

VSP models components internal to the airplane. Examples include passenger cabin, cargo bays, and fuel tanks. In the early development of the Sugar Free MBSA&E model, analysis failures were encountered that were traced back to overlaps or intersections between components. The component geometries had to be modified slightly to avoid these analysis failures.

The setup of MBSA&E models could be confusing because inputs were spread over multiple locations. Geometry could be input in VSP, the `aviary_inputs.csv` file, or the `case_setup.py` script. The `aviary_inputs.csv` file held most of the inputs that needed to be modified in the MBSA&E toolset, and it was the most inviting location to make changes. The `case_setup.py` script contained inputs for interacting with VSP geometry. Inputs in `case_setup.py` were needed to enable some inputs to `aviary_inputs.csv`. It would have been difficult to know what to change in `case_setup.py` without examples or help from the MBSA&E team. While a base geometry would be set up in VSP, the VSP inputs could be overridden by a default value in `case_setup.py` or the value in `aviary_inputs.csv`, so it was necessary to set some inputs in multiple locations to get the desired geometry.

Additional confusion came from `aviary_inputs.csv` file containing more parameters than were actually being used as inputs. While it was good to see a fairly complete set of parameters that could be inputs, it was difficult to know which inputs were actually controlling the analysis. For instance, there were parameters for wing area, span, and aspect ratio, so it would be difficult for a user working only with `aviary_inputs.csv` to know which two of the three to use. The `case_setup.py` script controlled what parameters were active, so a user had to understand and be able to manipulate both files to get the desired effect. It would be preferable to control the active parameters from the `aviary_inputs.csv` file. One approach would be to treat everything in `aviary_inputs.csv` as an input and warn if the setup is over specified. Another approach would be to maintain the list of active parameters in `aviary_inputs.csv`.

Some analysis gaps were identified. There did not appear to be analysis methods for compressibility drag or buffet. The conceptual weight methods in the MBSA&E toolset were used in this project, but the adjustment factors for the N3CC wing weight suggest the higher fidelity analysis used to set the target weight may have missed structural sizing considerations, such as minimum gauge, buckling, and non-optimal weight. Low-speed aerodynamics and performance were not addressed in this study; it would be good to address these in the future.

It was hoped that wing area optimization could be performed using VSPAERO tabular aero data. If the MBSA&E drag accounting could separate induced drag, wing parasite drag, and non-wing parasite drag, it would have allowed scaling portions of drag with the wing. Without this feature, it was not reasonable to scale the tabular aero data. Aviary aero was then used because VSPAERO was too computationally expensive to use directly in optimization.

If the aero data tables were expanded to include wing area and a small number of planform changes, it should be possible to create the tables at acceptable computational cost and use the tables for optimization. NASA developed a feature for MBSA&E that could provide this capability, but this project did not test the feature.

Another option for enabling planform optimization would be to use the Boeing design space exploration approach with the MBSA&E model as an analysis. Implementing this option would require changing the optimization in the MBSA&E to provide information needed for the outer design space exploration. For example, the ability to get to cruise altitude in 20 minutes would be handled in the outer design space exploration, but this formulation would require the MBSA&E toolset to report what altitude the aircraft could reach in the 20 minutes plus the vehicle sizing and fuel burn for flying the nominal 35,000 ft initial cruise altitude mission profile.

The MBSA&E toolset provided automation for running VSPAERO to generate aero data tables. Once the information is generated, the data is written to a Python script that can be used for subsequent work. This capability seemed useful and would grow in importance if the aero tables were extended to include planform variations.

The setup for mission performance analysis was largely handled in the `flops_phases.py` script. Having another file controlling inputs is not desirable; however, it was relatively straightforward to set up the mission in the `flops_phases.py` script. There is an automated setup of the optimization used to solve mission performance. The automation was appreciated because the problem to solve mission performance was on the order of a hundred variables and constraints.

In running the mission solution optimization, it was observed that getting a solution was fairly reliable when a solution was possible. The optimization would fail when the mission could not be performed, for example when there was insufficient thrust. There was some adjusting of initial guesses to get solutions, but this type of activity was typical for those used to working with similar codes. The inputs for initial guesses were at the flight segment level, like how long a flight segment was expected to last, as opposed to tweaking a particular time step within a segment. The optimization to size wing area and engine thrust using Aviary aero went well, converging in a reasonable amount of time.

During the project, there was ongoing development of the MBSA&E toolset. The initial N3CC model received by Boeing was not compatible with the version of Aviary that was current at the time. This experience led Boeing to work with specific versions of the MBSA&E toolset and N3CC model provided by NASA, ensuring compatibility between the toolset and model. OpenMDAO was outside the MBSA&E package Boeing received from NASA, and toward the end of the project, changes to OpenMDAO created issues with the MBSA&E version Boeing was using. As the user base for the MBSA&E toolset grows, it will be increasingly important to minimize the effort needed to bring existing models into updates of the MBSA&E toolset. Making more formal releases of the toolset may help.

Beyond changes in the NASA tools, there was an update to the Bokeh data visualization Python package in the middle of the project that made it incompatible with the MBSA&E toolset. NASA provided a script for building a Python environment for MBSA&E with the initial N3CC model, which was very helpful for getting started. Boeing adopted the practice and found it increasingly important to specify versions or upper limits on versions.

Assistance from the NASA developers was needed to work with the MBSA&E toolset. The knowledge for doing many tasks resided in people and not in documentation. Aviary documentation provided short descriptions of parameters, but it could miss points, such as explaining the difference between area and detailed area. Expanding the available documentation is desired. The documentation would ideally

describe all available parameters and how they are used. It would be good to document how to make common setup changes. For instance, having to activate a parameter in `case_setup.py` before setting it elsewhere is not an obvious procedure.

Future Possibilities

From working this project, several ideas arose for activities that could further the MBSA&E toolset and models. The activities fell beyond the scope or schedule of the project and may be candidates for future work.

The Sugar Free MBSA&E model ended with a significantly larger engine than in prior studies. The GE TF01 engine had not been designed to be best for the aircraft. Iterating on the engine and aircraft design may be expected to match the engine better with the airplane and result in a model that is more representative of how this aircraft would be designed. An automated process in the MBSA&E toolset could be used to match engine and airplane as part of a future effort.

To support matching engine and airplane, an integrated parametric propulsion model is preferred by most engine manufacturers at the conceptual design phase. Such a model provides consistent performance, weight, and geometry data for the selected technology level based on the thrust requirements as well as the expected aircraft mission and life requirements. The model options typically include required thrust at multiple conditions, including takeoff, top-of-climb, and one or more cruise conditions. This approach allows for consistent selection of component sizes to best achieve target thrust levels for the specified engine technology level, mission, and target life with the best mission fuel burn. These models are typically highly proprietary and expensive to create and were beyond the scope of this effort. However, the TF01 model and the WATE model are a reasonable starting point to create this type of model either within OpenMDAO or entirely within NPSS.

The University of Michigan was able to connect propulsion data into the N3CC MBSA&E model through the ADH. Conversion of additional components of the MBSA&E to use the ADH and Standard Evaluator would provide a good test of capabilities developed by Boeing in the larger MBSA&E effort.

Some analysis gaps were observed when comparing results between the MBSA&E toolset and Boeing analyses. Compressibility drag and buffet analysis should be added to the MBSA&E toolset, particularly if it is used for transports that fly at higher Mach numbers. Higher fidelity structural sizing used to calibrate the MBSA&E toolset resulted in relatively low values for the correction factors applied to the conceptual weight methods in the toolset. This observation suggests making sure important structural sizing criteria are included, including minimum gauge, buckling, and non-optimal weight.

This project matched MBSA&E and Boeing results for one airplane configuration. It would be a stronger test of the MBSA&E methods to compare results for vehicles across a relevant portion of the design space.

The use of higher dimensional aero models to capture the effects of wing area and other geometric variables is seen as a way to use higher fidelity analysis (such as VSPAERO) when optimizing geometry in the MBSA&E toolset. An alternative would be to use design space exploration approaches commonly applied by Boeing. Testing either of these approaches would show how the MBSA&E toolset could be employed to optimize more of the vehicle.

Conclusion

A modified Sugar Free configuration was modeled by Boeing using the NASA MBSA&E toolset. The configuration incorporates an open engine model from GE that is based on the NPSS Consortium TF01 cycle. The modified Sugar Free with TF01 engine was evaluated in both Boeing and NASA tools, and the MBSA&E model was calibrated to match Boeing results. The GE TF01 engine model and the Boeing Sugar Free MBSA&E model delivered to NASA are openly distributable.

The experience working with the MBSA&E toolset provided opportunity to form observations on the capability. The user experience could be refined, which was not surprising for a toolset that was still under development. Some analysis gaps were identified, notably compressibility drag. The capability to optimize geometry with higher fidelity aero was desired. While there were areas for improvement, many features of the MBSA&E toolset worked well. With knowledge of the tools residing mostly in people, NASA collaboration was important for being able to use the MBSA&E tools.

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