Model-Based Systems Analysis & Engineering (MBSA&E) for the Sustainable Flight National Partnership (SFNP)

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Discussion Outline

• Systems Analysis and MDAO

• MBSA&E for the SFNP
  – The Vision
  – The Plan

• MBSA&E Development Efforts
  – The Execution
  – The Future

• Closing Thoughts
Systems Analysis and MDAO
“An explicit **formal inquiry** carried out to help someone **identify a better course of action**...usually employing some combination of: identification of **objectives**, **constraints**, and alternative courses of action; examination of consequences of alternatives in terms of **costs**, **benefits, and risks**; presentation of results in a **comparative framework** so that decision makers can make an informed choice from among the **alternatives**.”

[International Institute for Applied Systems Analysis]
Dual Role of Systems Analysts

OpenMDAO is a key enabler!

"Looking Out"
Vision Vehicle Development, TC Formulation Support

- Stakeholder Discussions & Needs
- New MBSA&E Framework
- System Level Requirements
- Aircraft Conceptual Design Studies
- Identification of Key Technology Needs
- Technology R&D
- Technology R&D Results Integration
- Technology Characteristics
- Integrated SA Verification
- Stakeholder Review & New Guidance
- Stakeholder Validation

"Looking In"
Integrated Technology Assessments

- Project/Subproject Research Activities

Advanced Air Transport Technology
Advanced Air Vehicles Program
SFNP Model-Based Systems Analysis & Engineering
Subsonic Transports: Integrated Technology Development

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**Model Based Systems Analysis & Engineering**
- Sustainable Flight Demonstrator (SFD)
- Transonic Truss Braced Wing (AATT)
- Hi-Rate Composite Aircraft Manufacturing (HiCAM)
- Hybrid Thermally Efficient Core (HyTEC)
- Electrified Powertrain Flight Demonstration (EPFD)
- Electrified Aircraft Propulsion Technologies (AATT)

**Technology Readiness Target**
- Achieve TRL 6 in time for industry product decision-making

**Technology Completion**
- Mfg & Structural Demonstration
- Core Demonstration
- Flight Tests

**“Digital Flight Test” Framework developed**
The MBSA&E Vision for the SFNP

A systems-level, digital integration across SFNP projects which will support the assessment, advancement, and adoption of sustainable technologies for 2030s EIS subsonic transport aircraft concepts

Objectives:
- Develop an open, cross-project/program/external-capable MBSA&E framework building off ARMD investments and capabilities across AAVP/IASP/TACP in support of the SFNP
- Conduct coordinated, integrated systems analysis studies in support of SFNP including:
  - Common, open, reference vehicle models
  - Common, open, vision vehicle models
  - Technology benefit assessments and sensitivity studies informed by the SFNP demos
Advanced Air Transport Technology
Advanced Air Vehicles Program

MBSA&E: A Phased Approach

Phase I: Develop common MBSA&E Framework/Ecosystem
- Create building blocks needed for key disciplinary analyses where lacking
- Integrate building blocks to form coupled MBSA&E framework – leveraging cross-project collaboration (e.g. TTT)
- Evaluate and test the MBSA&E framework with several use cases (conventional aircraft, TTBW, EAP)
- Explore and develop integration between MBSA/MDAO environment and MBSE tools

Phase II: Cross-project integrated model development and coordination
- Development of open, common SFNP reference and vision vehicle concepts and models
- Regular, frequent tech interchange meetings across SFNP systems analysis teams, including external project partners
- Integrated systems analysis studies to incrementally ‘roll-up’ SFNP findings into a consolidated understanding of vision vehicle benefits and trades

* TTT Collaboration Throughout
* Engagement with Projects/Subprojects Throughout

FY22 FY23 FY24 FY25 FY26 FY27

Advanced Tube/Wing MBSA Demo
TTBW and EAP Demos
HyTEC Initial Integration
EPFD/HiCAM Integration
SFD/HyTEC Integration

Future spiral driven by AACES 2050 Concepts/Technologies
Subsonic Transports: Integrated Technology Development

SFNP integrated systems analysis and vision vehicle assessments will require comprehensive cross-project/program/partner coordination efforts, facilitated by MBSA&E.
MBSA&E Development Efforts
**MBSA&E Framework Overview**

- Goal is to provide a rigorous and traceable systems analysis approach with improved interfaces with internal/external tech R&D efforts.
- Developing an OpenMDAO-based framework which will provide advanced capabilities for coupling existing tools and producing optimized, converged solutions.

Disciplinary models are points of engagement with internal/external technology R&D efforts:
- Modifying inputs and assumptions to traditional systems analysis tools
- Integrating high fidelity models

Framework expandable to include additional disciplines.
Propulsion

- **NPSS**
  - Implements OpenMDAO external code components to create wrappers for run both design and off-design propulsion system analysis
  - Includes WATE++ model for computing engine flowpath geometry and weight
  - Output includes full engine deck which will then be interpolated within the mission analysis
  - Implementation within integrated MBSA&E framework is currently limited by issues with NPSS Linux installation

- **pyCycle**
  - Integration with the MBSA&E framework facilitated by pyCycle’s development within the OpenMDAO ecosystem
  - Implementation does not currently include engine flowpath and weight estimation methods
  - Can be configured to output full engine deck for interpolation or directly integrated into mission analysis evaluations
Geometry

- **OpenVSP**
  - Leverages OpenVSP GUI to layout the topology of the geometry model and Python API for geometry manipulation and analysis.
  - Case input file declares and maps OpenMDAO input/output variables and options to OpenVSP parameters, and provides default values, units, description, and min/max bounds for optimization.
  - Capabilities include
    - Geometry model updates
    - Parsing of model parameters
    - Calculations of component wetted areas, volumes, planar slices, area distributions, external file exports, CFD meshing, trimmed IGES/STEP model, center of gravity and moments of inertia, degenerate geometries, parasite drag, etc.
Aerodynamics

• FLOPS/LEAPS Aero
  – Empirical drag buildup based on Delta Method (N79-17801)
• VSPAero
  – Leverages OpenVSP’s Python API
  – Case input file declares and maps OpenMDAO input/output variables and options to OpenVSP parameters, and provides default values, units, and description information
  – Provides Vortex Lattice and Panel aero analysis for sweeps in Mach, angle-of-attack, sideslip, Reynolds number, and derivatives w.r.t. flight conditions and control surfaces deflections
• CART3D
  – Initial wrapper implementation with hooks for Mach, angle-of-attack, reference area and length, moment center, and number of processors
  – Outputs coefficient of lift, drag, and moments
• Future Work:
  – OpenMDAO implementation of Sugar Phase IV TTBW aero prediction surrogate models
  – Integrate VSPAero 2.0 version with adjoint solver implementation that will provide the design sensitivities with respect to flight variables and geometry needed for optimization
  – Integrate MPHYS/FUN3D analysis
Structures

- **HCDstruct**
  - Leverages OpenVSP geometry data and FLOPS/LEAPS weights schedule to build an aeroservoelastic FE model.
  - Structural wing and fuselage weight are optimized using NASTRAN SOL200 as a suboptimization routine within the OpenMDAO framework, returning wing and fuselage weights.

- **SUITCASE**
  - Leverages OpenVSP geometry data and FLOPS/LEAPS system and fuel weights to define static aeroelastic loads and a structural model based on Equivalent Plate structural analysis.
  - Wing structural weight is optimized for strength constraints and returned to OpenMDAO.

- **TACS**
  - Created a general aircraft aerostructural analysis/optimization tool by coupling TACS’s structural solver and OpenAeroStruct’s (OAS) aerodynamic solver into a single workflow using OpenMDAO, benchmark against conventional aircraft concept.
  - Working to couple with VSPAero aerodynamic solver in aerostructural context through Mphys library.

- **Future work**
  - Extend all analysis components to be able to model a TTBW wing configuration.
  - Refactor GT SUGAR Phase IV TTBW wing weight model as OpenMDAO component.
Mission Analysis

• Initial development focused on a refactoring of the LEAPS code (Python FLOPS replacement) in OpenMDAO and Dymos to create a LEAPS2.0
  – Empirical weight correlation module
  – Low-fidelity aerodynamic module
  – Energy-height based equations of motion module
• Completed robust unit testing of LEAPS2.0 to FLOPS output for each module
• Integration with MBSA&E framework facilitated by common OpenMDAO base
• Recognized LEAPS2.0 was similar to the GASPy aircraft sizing and mission analysis tool under development at NASA (GASP replacement)

Unified aircraft sizing and mission analysis tool
• Merges LEAPS2.0 and GASPy into a new tools with OpenMDAO and Dymos as the base
  • Includes empirical weight correlations and aerodynamic calculations from both original software tools
  • Includes unique equations of motion from each tool (energy-height and 2 DOF)
• Targeting open-source release for continued development and adoption
Stability and Control

• Created OpenMDAO components based on Morris and Ashford empirical method for determining horizontal and vertical tail volume coefficients
  – Provides a constraint on the aircraft tail volume coefficients based on empirical aircraft data
• Created OpenMDAO components for static margin and neutral point semi-empirical method for determining longitudinal static stability
  – Mass property inputs are provided by OpenVSP and allows the input of alternative aerodynamic coefficients from external codes like VSP Aero
  – Provides a constraint on the aircraft static margin that results in pitch static stability
• Creating a One-Engine-Inoperative (OEI) mid-fidelity set of components for determining the vertical tail area size required during OEI
  – Provides an estimate of the lowest vertical tail size needed to comply with FAR 14 CFR § 25.149 requirements
• Future work will focus on dynamic stability and control
  – Methods will include modal analysis, control surface sizing based on FAR 14 CFR requirements, flying qualities criteria, etc.
Cost Estimation

- PTIRS Economic Analysis Model is a comprehensive life cycle cost model for development, production, and operations of commercial transport aircraft
- Calculates Direct Operating Cost plus Interest (DOC+I) for technology-enhanced aircraft and corresponding baseline aircraft
- Completed full Python/OpenMDAO implementation of the method (originally Excel-based) for all computational steps for both baseline and technology-enhance aircraft
- Future work
  - Additional testing using different baseline aircraft and technology-enhanced aircraft descriptions
  - Integration into MBSA&E framework (data interface has already been identified using a detailed XDSM)
Model-Based Systems Engineering

- Developing an MBSE model of an example tube and wing concept and exploring the data interfaces required to couple MBSE and MBSA/MDAO models into an integrated framework
  - MBSE parameters will be passed to MBSA model for analysis and design, and output parameters will be passed back to MBSE model for validation
- The MBSE model development is divided into 3 phases
  - Phase 1: Build a descriptive MBSE system, sub-system and component level (physical and functional decomposition) model
  - Phase 2: Develop an executable, parametric MBSE model which will enable mission/design requirements verification, system validation and trade study analysis
  - Phase 3: Couple the vehicle system model using MBSE tool/method (MagicDraw) with a multi-disciplinary, physics-based MBSA model (OpenMDAO) to yield an integrated meta model which can be used for conceptual design of vision vehicles infused with new, sustainable technologies
Closing Thoughts
Recent Highlights

- **MBSA&E framework development initiated in FY22**
  - Disciplinary analysis codes/models have been linked to OpenMDAO and are being coupled to form the overall framework
  - Collaborating with TTT and EPFD on development of Aviary aircraft sizing and mission analysis tool to replace FLOPS & GASP
  - An N+3 Advanced Tube/Wing concept demonstration test case is being used to assess the framework

- Engaging with projects to prepare for MBSA&E application for integrated systems analysis studies in Phase II

- Integrating with the Agency MBSE Community of Practice (CoP) and related NASA MBSE and SE orgs

Initial development efforts have focused on development of an OpenMDAO-based MBSA workflow, creation of disciplinary analysis tools, and exploration of MBSA-MBSE integration approaches
Future Work

- Completion of conventional tube and wing aircraft (N3CC) and TTBW with EAP demonstrations
- Development of initial Aviary capability combining LEAPS2.0 and GASPy aircraft sizing and mission analysis tools
- Continued exploration and implementation of MBSE coupled with MBSA/MDAO framework
- Incorporation of additional disciplinary analysis tools:
  - Acoustics
  - Electrical propulsion components
  - Uncertainty Quantification
- Coordination and integration with SFNP projects to complete systems analysis studies
- Collaboration with industry and academia on framework development and application to SFNP technologies

Future spiral driven by AACES 2050 Concepts/Technologies
OpenMDAO Related Challenges and Observations

• MBSA&E effort is an ambitious development and application of integrated, multidisciplinary aircraft conceptual design tools, with a goal of flexibility and adaptability for SFNP concepts and technologies

• Effort requires coordination, collaboration, and integration of disciplinary expertise of a large team
  – Exploring the implementation of a variable naming convention to facilitate connections and provided consistency across disciplinary tools
    
    aircraft:wing:span, aircraft:fuselage:mass, mission:design:range
  – Addressing limitations of existing software which was not conducive to MDAO integration or execution on Linux HPC systems
  – Evaluating impacts of increasing computational cost as high-fidelity disciplinary tools are integrated
  – Implementing rigorous testing protocols (unit, regression, integration, spec, etc.) has been valuable to the development process, but sometimes challenging for new team members

• Training and teaching OpenMDAO to new users is a persistent challenge
  – OpenMDAO online documentation and tutorials (and now YouTube videos) are a great starting point
  – Paired programming sessions with experienced users are usually required
  – “Homework” problems (not in tutorials) are valuable for checking understanding (e.g. ideal normal shock)
Model Based Systems Engineering

**Model Development Phases**

1. **Descriptive Model**
   - Model Management
   - Requirements
   - Behavior
   - Structure
   - Requirements verification
   - System-level validation
   - Trade study using instances
   - Analytical views and reports
   - MBSE-MBSA-link/simulation
   - MBSE-Meta-model (conceptual)
   - MBSE-Meta-model (parametric)
   - Data exchange/format

2. **Executable Meta Model**
   - Requirements
     - Wing sizing, weight, aerodynamic performance
   - Functional Decomposition (Behavior)
     - Generate lift, store fuel, control roll / stability, distribute aerodynamic loads
   - Physical Architecture (Structure)
     - Wing structure, skin material, control surfaces, mechanical, electrical, storage
   - Parametrics (V&V)
     - Wing size ($S_{\alpha}$, AR), weight as constraint (block fuel, CG); aerodynamic performance (coefficient WSU/R and aircraft (GW, TWR) in use case (performance) and instances (trades))

3. **Integrated Model**

**MBSA&E Vision for SFNP**

A systems-level, digital integration across SFNP projects which will support the assessment, advancement, and adoption of sustainable technologies for 2030s EIS subsonic transport aircraft concepts.

**Descriptive System Model**

- Advanced Aerodynamic Ground & Flight Tests (AATF & SF3)
- High-Rate Composite Manufacturing Processes (HCAM)
- MBSA&E Digital Integration & Knowledge Capture on Vision Vehicles
- Electric Propulsion Ground & Flight Tests (AATF & EPSF)

**Conceptual Integrated Model**

- Stakeholder Needs
  - MBSE
  - Digital twins
  - MBSA
  - Design Variables
  - Multi-disciplinary Analysis
  - Aero. Disciplines

**Functional Decomposition**

- Airframe
- Engine
- Avionics
- Landing Gear
- Fuel System
- Actuation
- Powerplant
• Uncertainty Quantification
  - Developing and testing integration of Uncertainty Quantification using Polynomial Chaos Expansion (UQPCE) with OpenMDAO (https://github.com/nasa/UQPCE)