National Aeronautics and Space Administration

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

Eric Hendricks, NASA GRC

OpenMDAO Workshop

October 24, 2022

www.nasa.gov

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

Systems analysis defined...

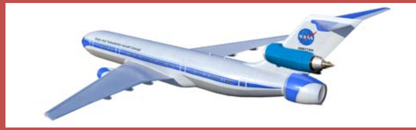
"An explicit **formal inquiry** carried out to help someone **identify a better course of action**...usually employing some combination of: identification of **objectives**, **constraints**, and alternative courses of action; examination of consequences of alternatives in terms of **costs, benefits, 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 Validation

Stakeholder Discussions & Needs

Stakeholder Review & New Guidance

New MBSA&E Framework

System Level Requirements

System Level Metrics Assessment

Integrated SA Verification

Aircraft Conceptual Design Studies

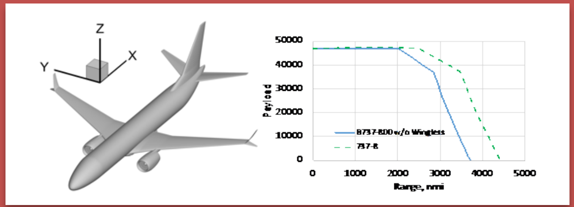
Technology R&D Results Integration

Identification of Key Technology Needs

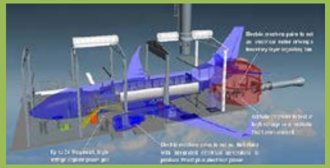
Technology Characteristics

Technology R&D

"Looking In"
Integrated Technology Assessments

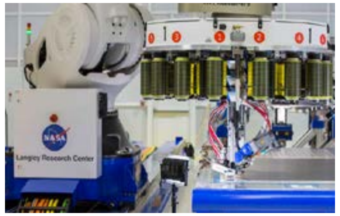


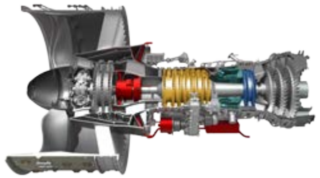
Project/Subproject Research Activities

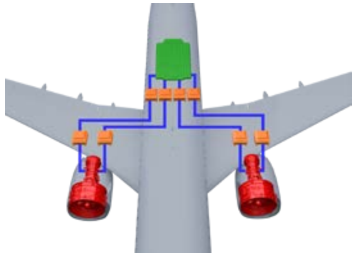


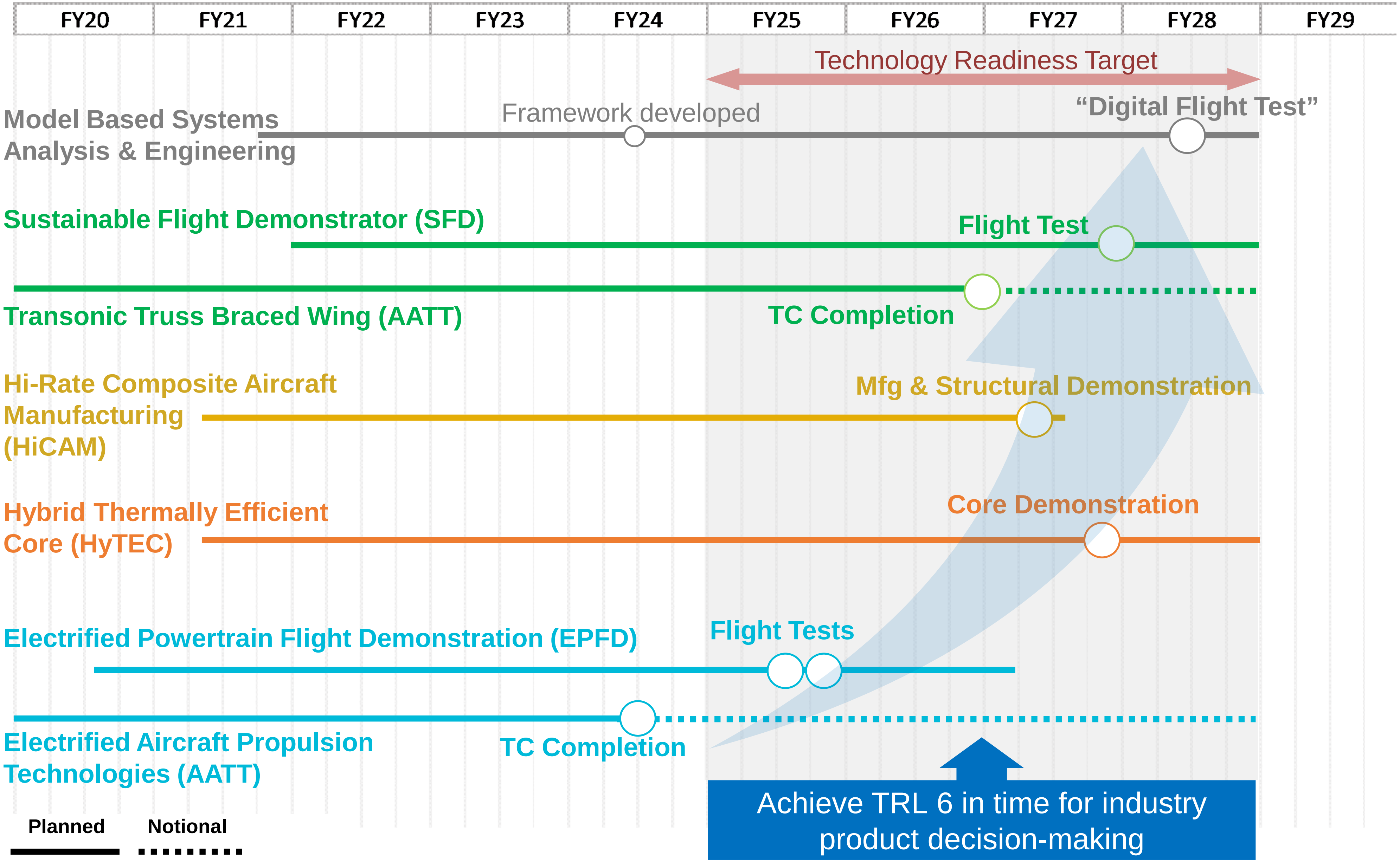
SFNP Model-Based Systems Analysis & Engineering

Subsonic Transports: Integrated Technology Development









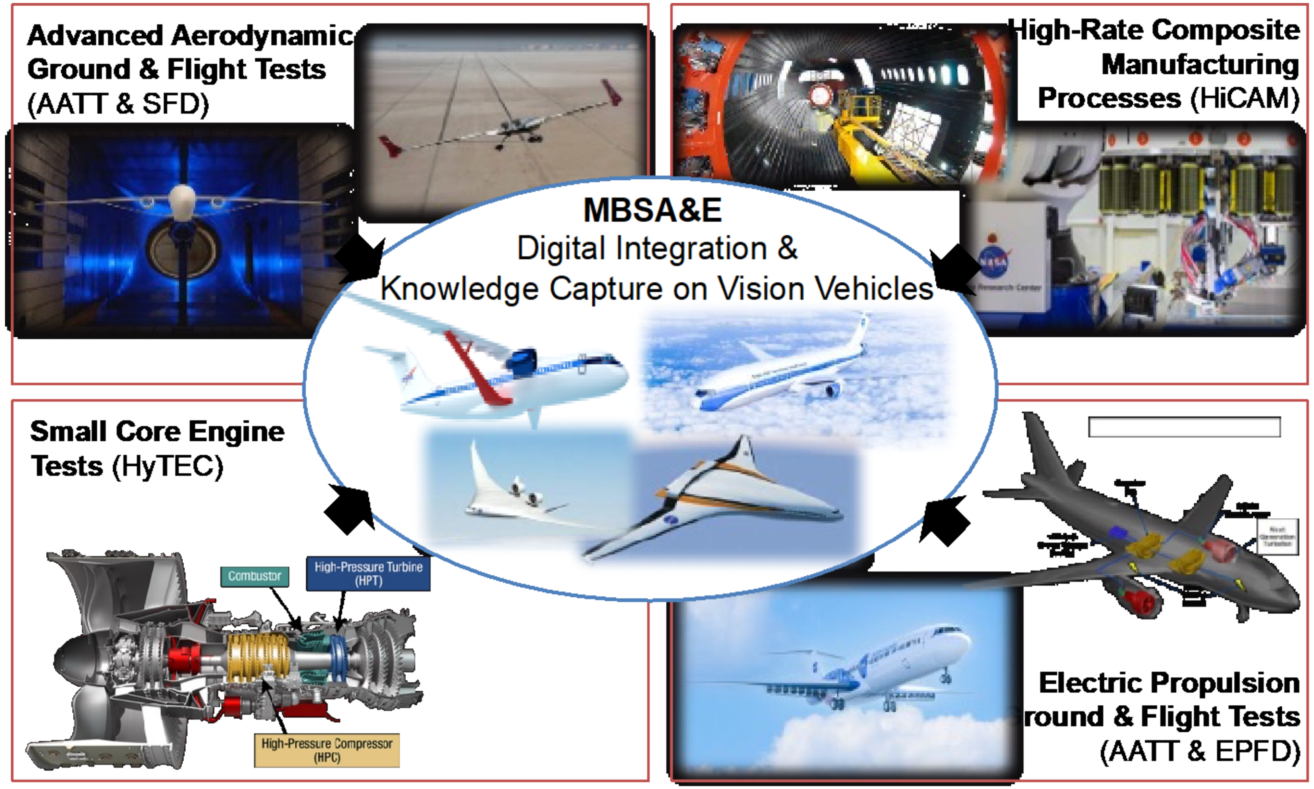
The MBSA&E Vision for the SFNP

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

<u>**Objectives:**</u>

- 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



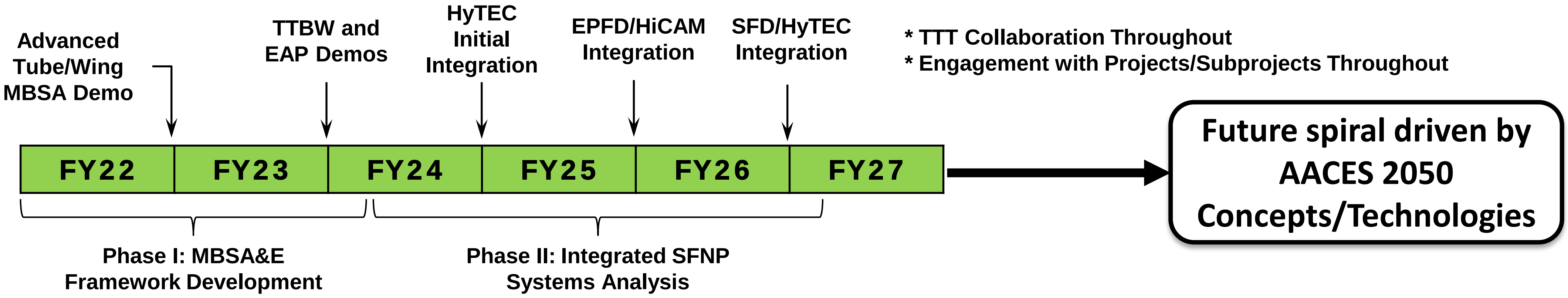
MBSA&E: A Phased Approach

Phase I: Develop common MBSA&E Framework/Ecosystem

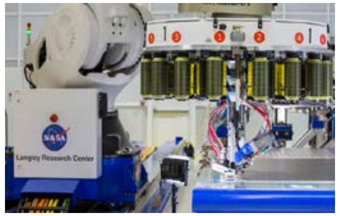
- Create building blocks needed for key disciplinary analyses where lacking
- Integrate building blocks to form coupled MBSA&E framework – leveraging cross-project collaboration (e.g. TTT)
- Evaluate and test the MBSA&E framework with several use cases (conventional aircraft, TTBW, EAP)
- Explore and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

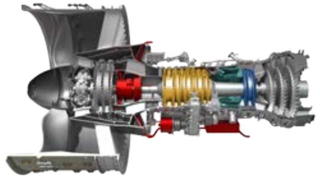
Phase II: Cross-project integrated model development and coordination

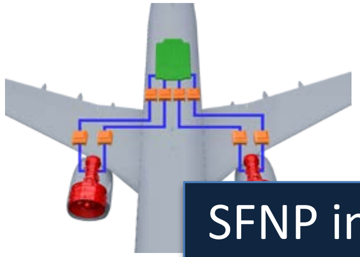
- Development of open, common SFNP reference and vision vehicle concepts and models
- Regular, frequent tech interchange meetings across SFNP systems analysis teams, including external project partners
- Integrated systems analysis studies to incrementally ‘roll-up’ SFNP findings into a consolidated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

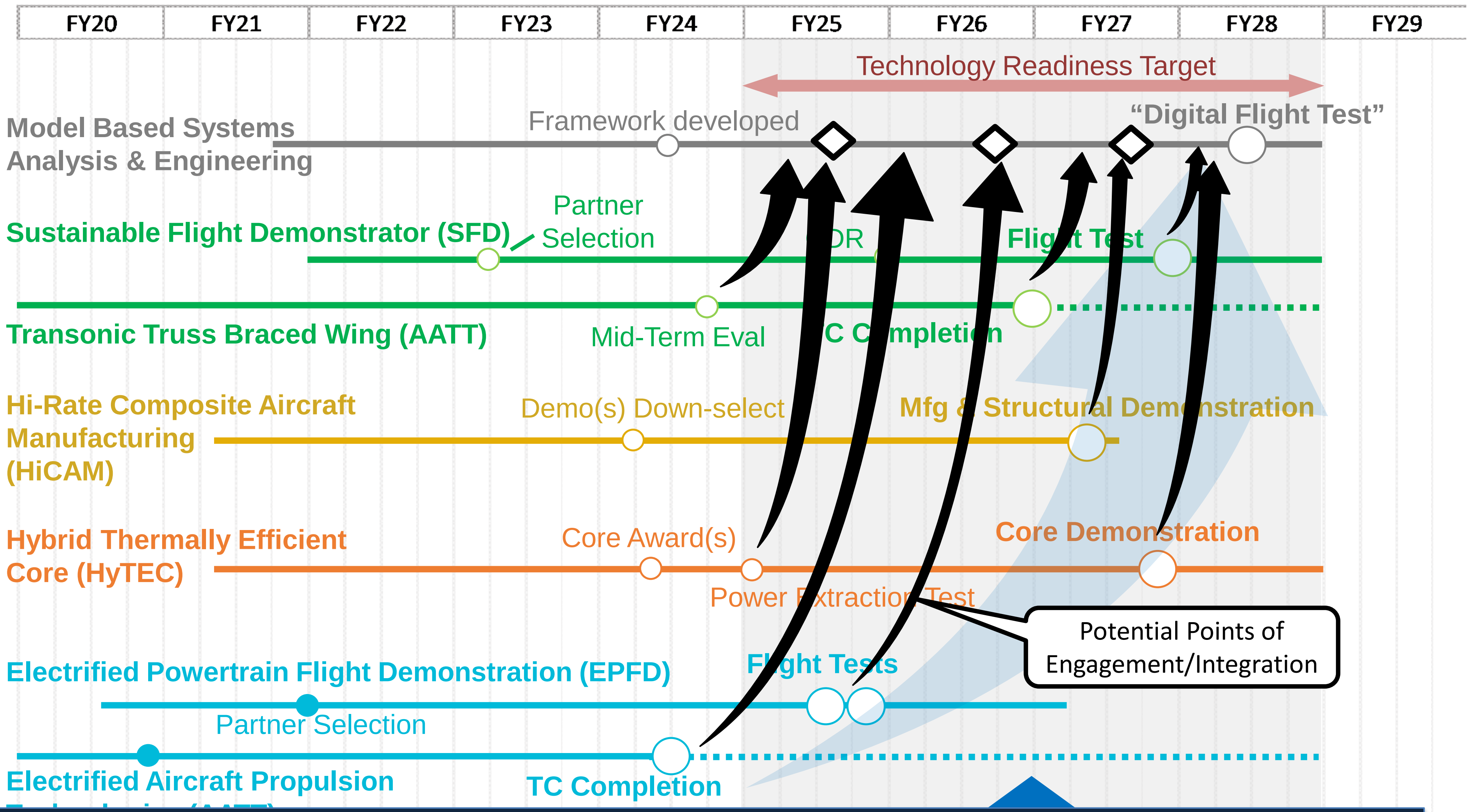


Subsonic Transports: Integrated Technology Development







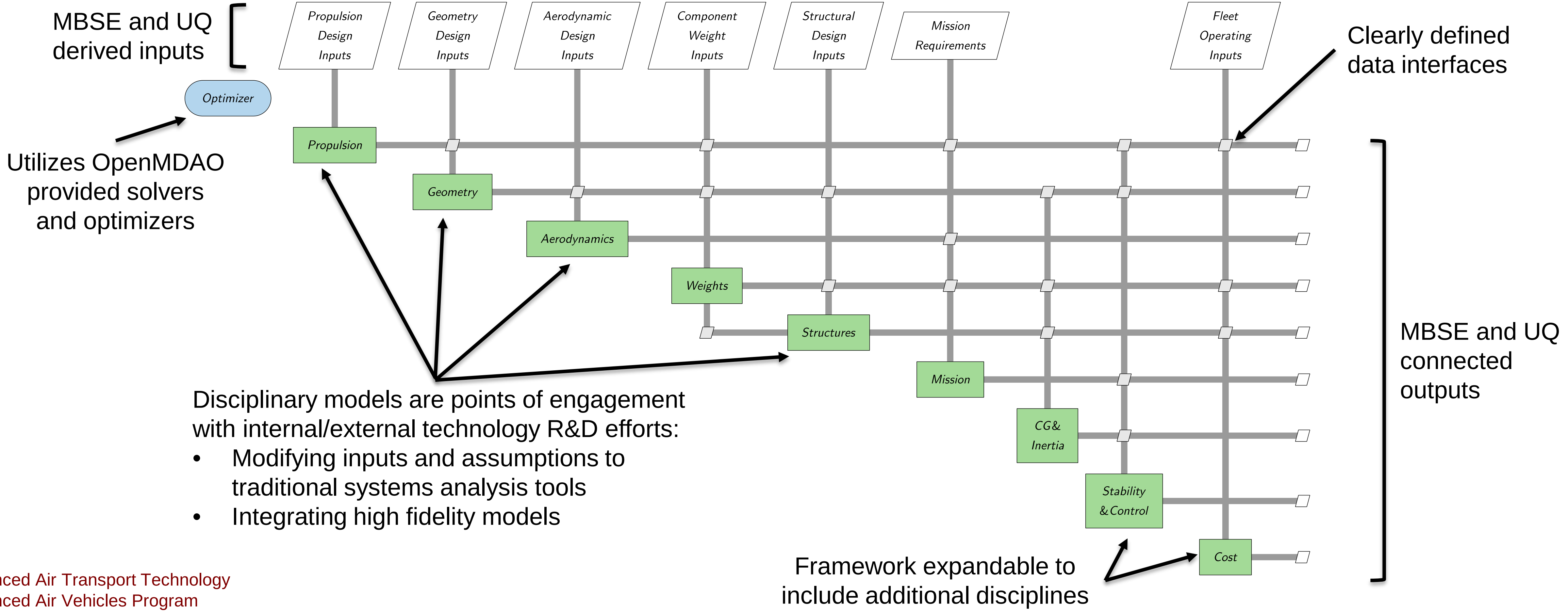


SFNP integrated systems analysis and vision vehicle assessments will require comprehensive cross-project/program/partner coordination efforts, facilitated by MBSA&E

MBSA&E Development Efforts

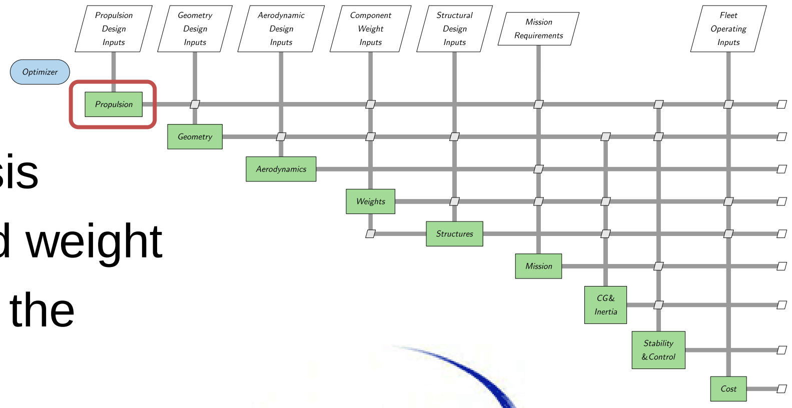
MBSA&E Framework Overview

- 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



Propulsion

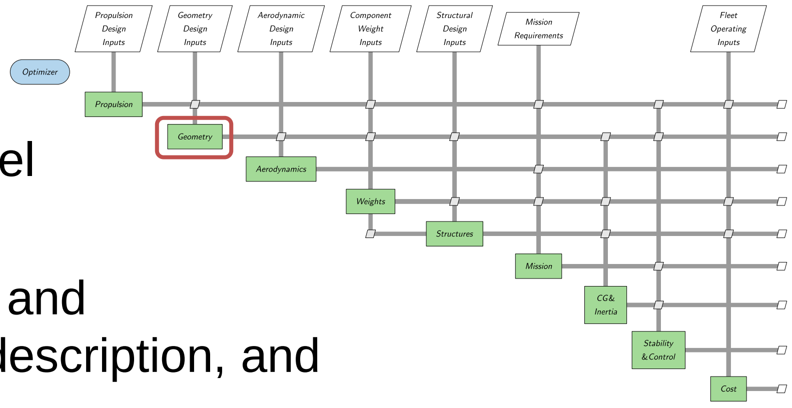
- NPSS
  - Implements OpenMDAO external code components to create wrappers for run both design and off-design propulsion system analysis
  - Includes WATE++ model for computing engine flowpath geometry and weight
  - Output includes full engine deck which will then be interpolated within the mission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

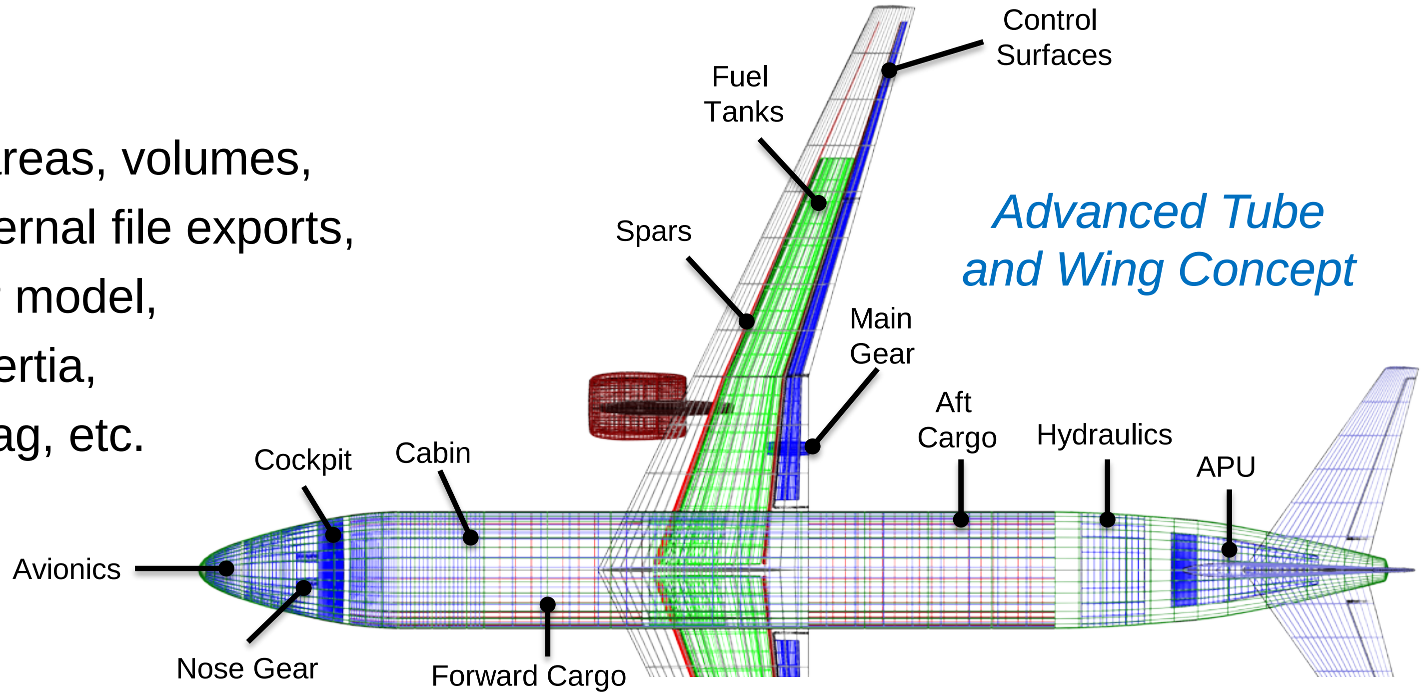


- pyCycle
  - Integration with the MBSA&E framework facilitated by pyCycle's development within the OpenMDAO ecosystem
  - Implementation does not currently include engine flowpath and weight estimation methods
  - Can be configured to output full engine deck for interpolation or directly integrated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

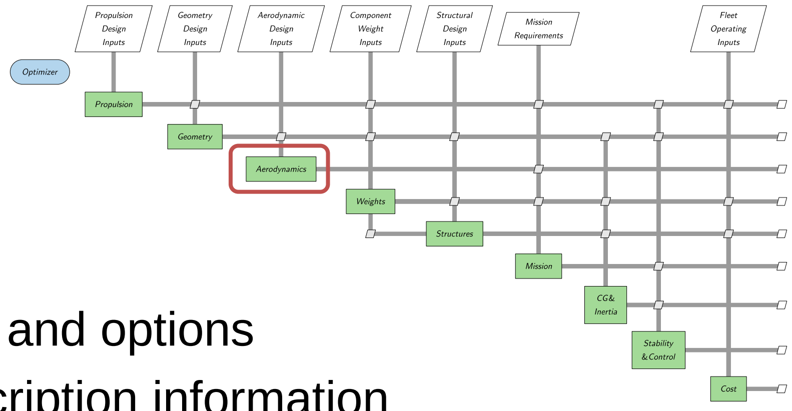
Geometry

- 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.





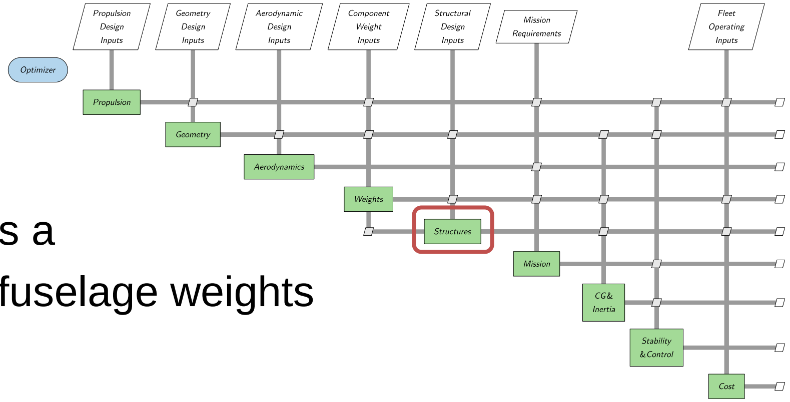
Aerodynamics



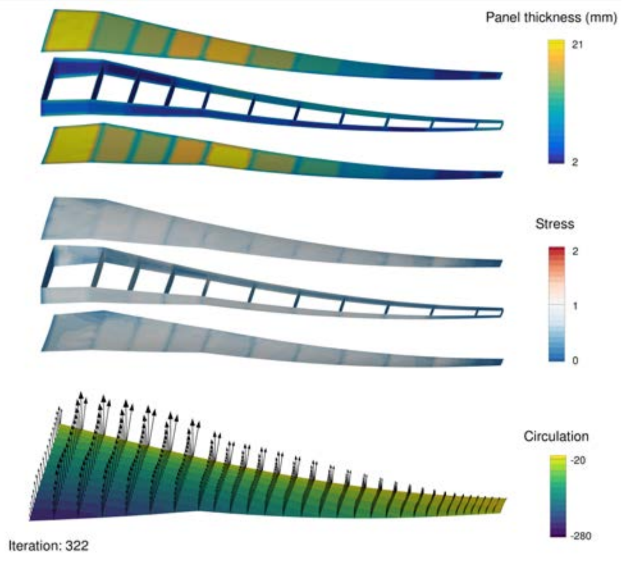
- FLOPS/LEAPS Aero
  - Empirical drag buildup based on Delta Method (N79-17801)
- VSPAero
  - Leverages OpenVSP’s Python API
  - Case input file declares and maps OpenMDAO input/output variables and options to OpenVSP parameters, and provides default values, units, and description information
  - Provides 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

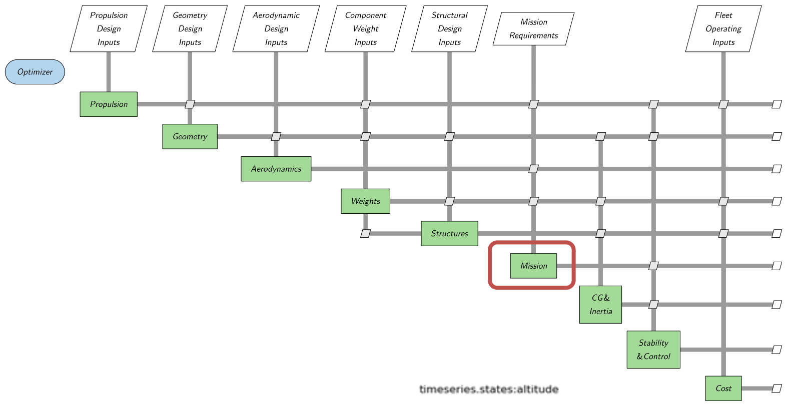


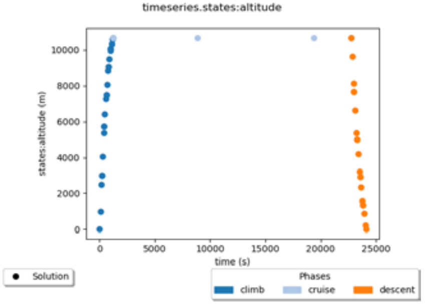
- SUITCASE
  - Leverages OpenVSP geometry data and FLOPS/LEAPS system and fuel weights to define static aeroelastic loads and a structural model based on Equivalent Plate structural analysis.
  - Wing structural weight is optimized for strength constraints and returned to OpenMDAO.
- TACS
  - Created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



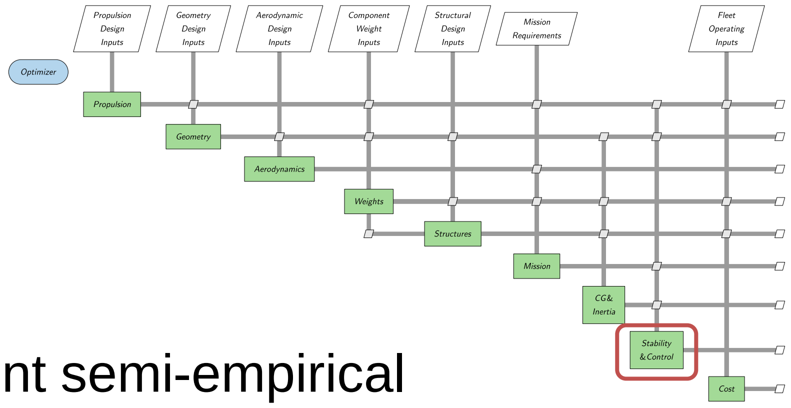


Unified aircraft sizing and mission analysis tool

- 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

AVIARY

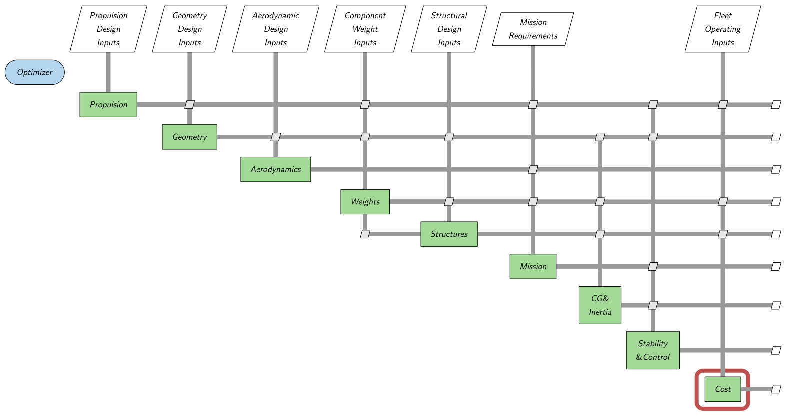
Stability and Control



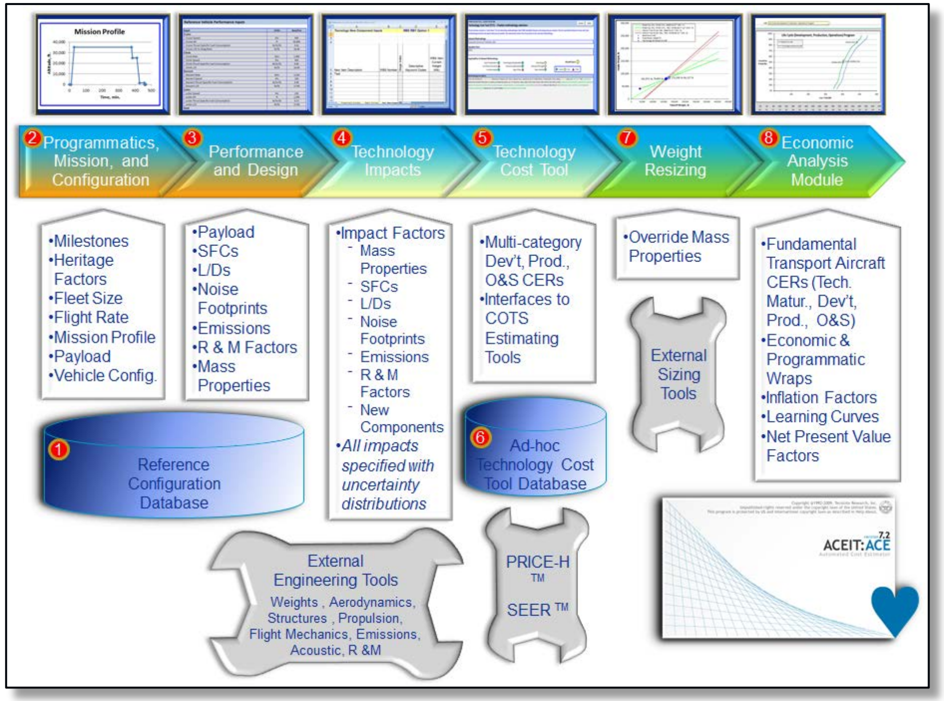
- Created OpenMDAO components based on Morris and Ashford empirical method for determining horizontal and vertical tail volume coefficients
  - Provides a constraint on the aircraft tail volume coefficients based on empirical aircraft data
- Created OpenMDAO components for static margin and neutral point 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 VSPAero
  - 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)

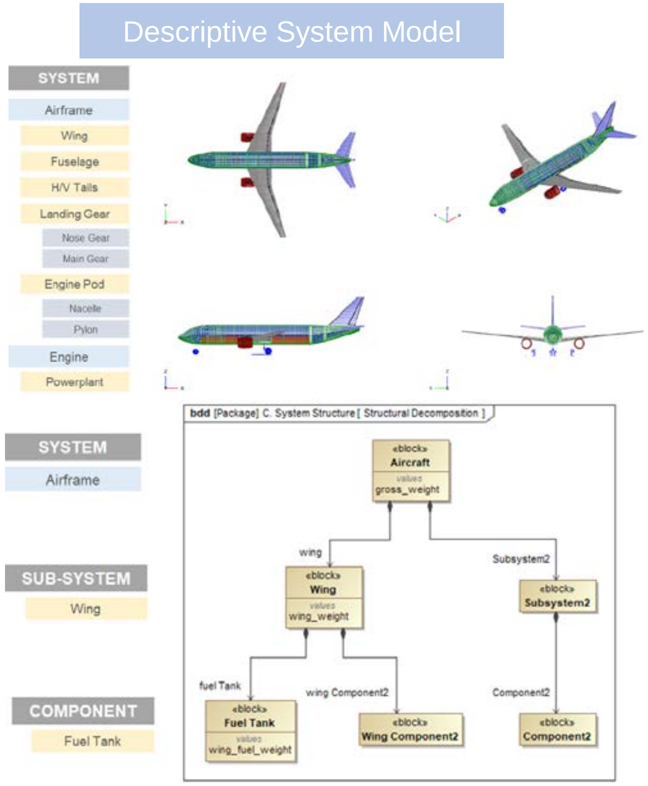


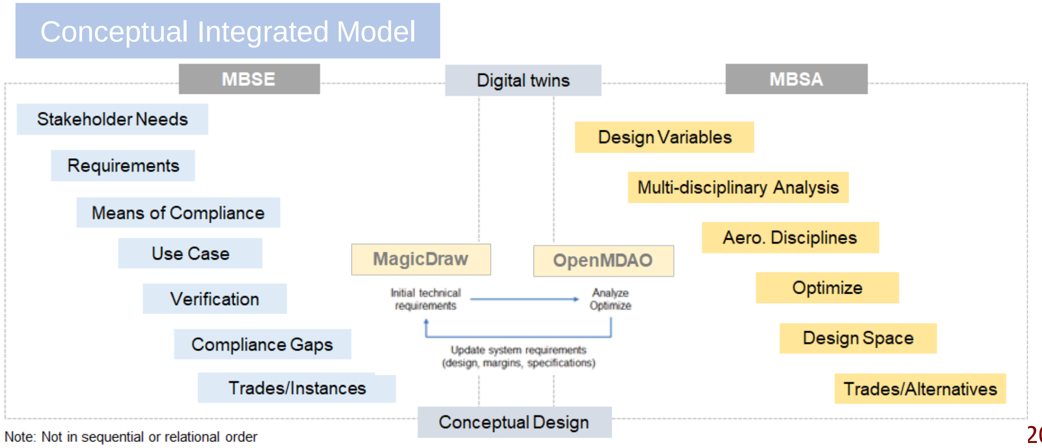
PTIRS Workflow



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



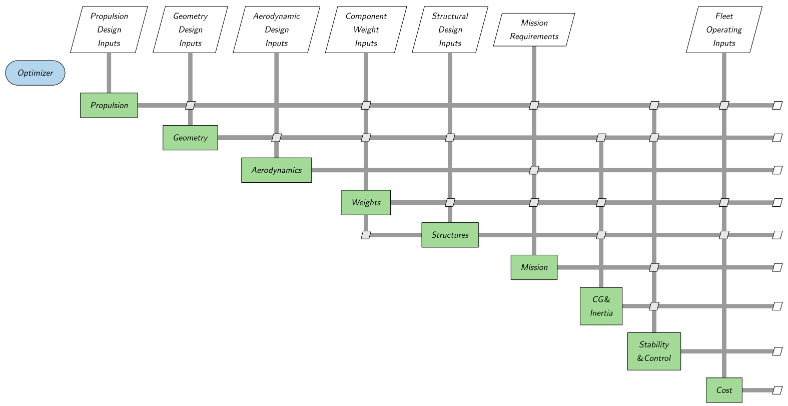


Closing Thoughts

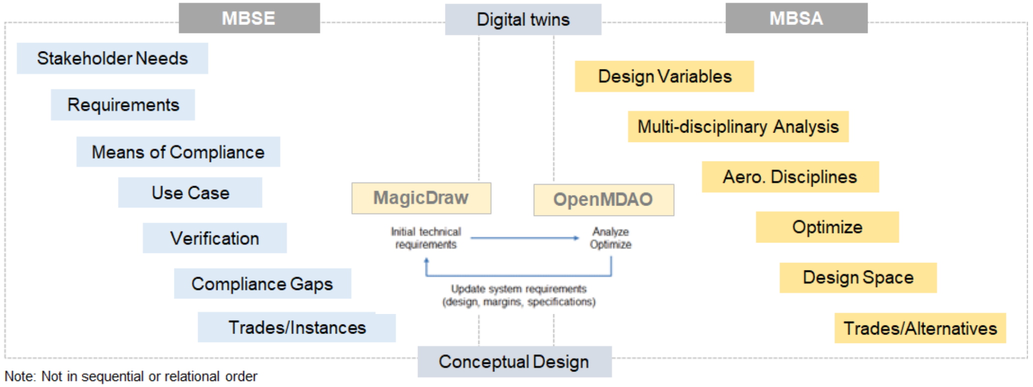
Recent Highlights

- 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



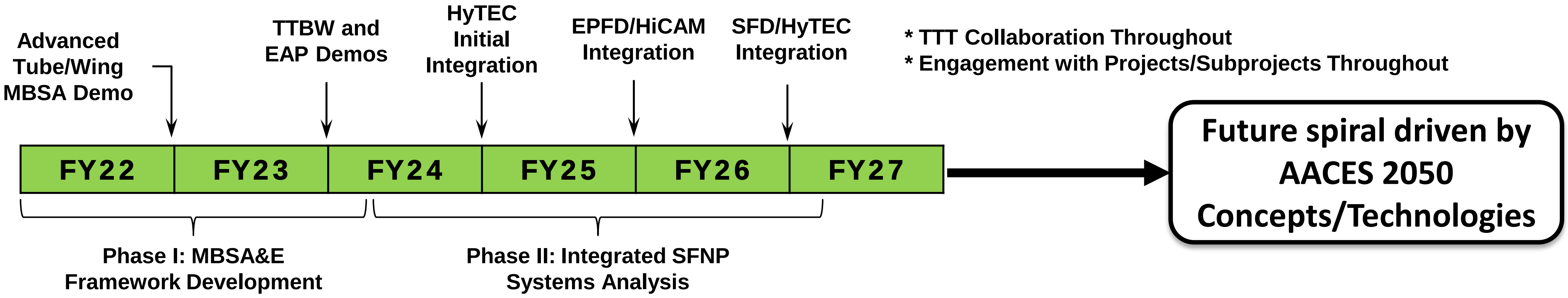
OpenMDAO based MBSA Framework in Development



Initial Approaches for MBSA-MBSE Integration Being Explored

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



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

Phase	
1 Descriptive Model	Model Management
	Requirements
	Behavior
	Structure
2 Executable Model	Requirements verification
	System-level validation
	Trade study using instances
	Analytical views and reports
3 Integrated Model	MBSE-MBSA link/simulation
	MBSA&E meta-model (conceptual)
	MBSA&E meta-model (parametric)
	Data exchange/format

2 Executable Meta Model

Requirements
Wing sizing, weight, aerodynamic performance

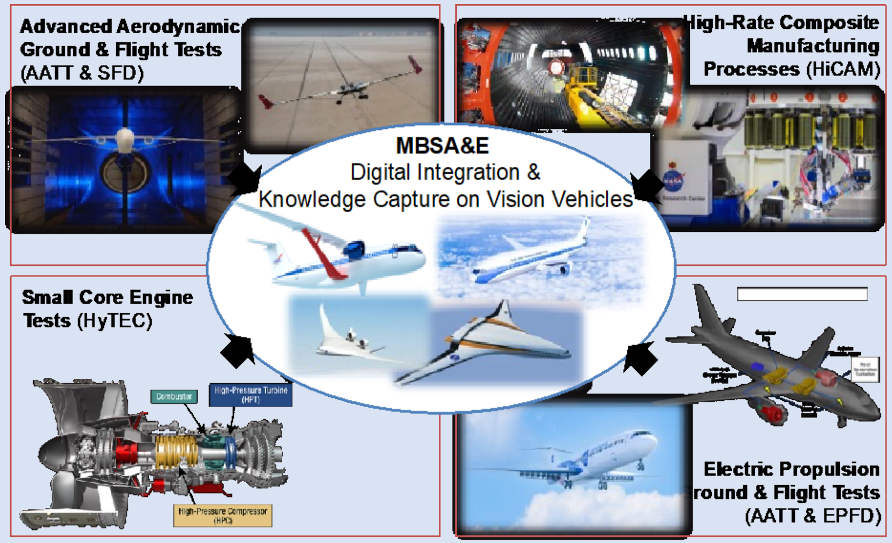
Functional Decomposition (Behavior)
Generate lift, store fuel, control roll / stability, distribute aerodynamic loads

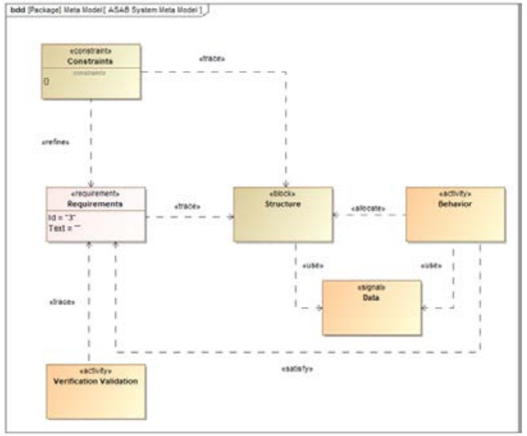
Physical Architecture (Structure)
Wing structure, skin material, control surfaces, mechanical, electrical, storage

Parametrics (V&V)
Wing size (S_{ref}, AR), weight as constraint (block fuel, CG); aerodynamic performance (coefficients/WSR) and aircraft (GW, TWR) in use case (perform mission) and instances (trades)

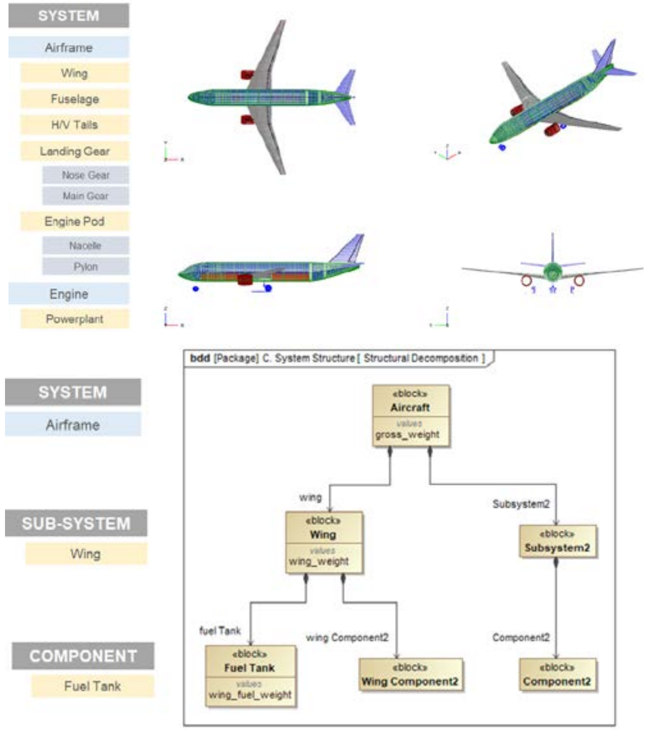
MBSA&E Vision for SFNP

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.

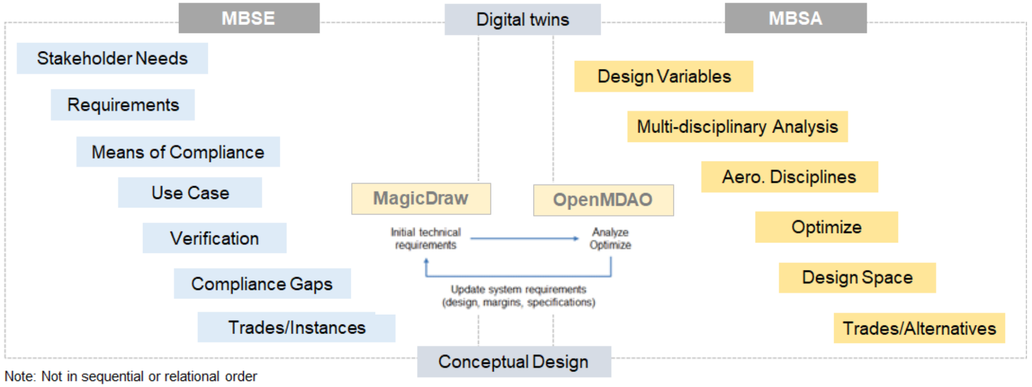




1 Descriptive System Model



3 Conceptual Integrated Model



Note: Not in sequential or relational order

UQ

- Uncertainty Quantification
  - Developing and testing integration of Uncertainty Quantification using Polynomial Chaos Expansion (UQPCE) with OpenMDAO (https://github.com/nasa/UQPCE)

Detailed XDSM