



# Model-based Systems Analysis and Engineering Phase I Overview: Defining Aspiring Standards for the Next Generation of MDAO Collaboration

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## Abstract

This paper provides an overview of the results of the Model-Based Systems Analysis and Engineering (MBSA&E) Phase I program funded by NASA, which aims to support NASA's Phase I efforts developing their MBSA&E framework while also addressing industry-wide problems inherent in building, maintaining and collaborating with MBSA and MBSE models internal to and between organizations. This work proposes open standards for systems analysis and systems engineering solutions to improve collaboration and modeling best practices between organizations when executing design activities. Key results to further these goals include the development of a comprehensive Aircraft Data Hierarchy (ADH) for storing and persisting configuration data, a standard interface for integrating disciplinary models and storing Multidisciplinary Design Analysis and Optimization (MDAO) workflow information, effective model sharing processes that protect intellectual property while enhancing collaboration, and an aircraft benchmark exercise to assess NASA's MBSA&E tool against industry equivalents, compare results, and offer feedback. The software products from this work including the ADH, standard interface, and MBSE-ADH connector are all available open-source on GitHub. The model sharing process is described in detail in its own paper. These activities, including a benchmarking activity, were tested successfully on NASA's MBSA&E framework, developed in Aviary and OpenMDAO, as the first use case. These advancements are expected to facilitate a more cohesive aerospace design ecosystem, ultimately leading to more efficient and innovative aircraft development for the NASA MBSA&E model and other industry equivalents. Outside of NASA, this work is a starting place to begin a wider discussion and collaboration with the broader aerospace industry to grow, mature, and perpetuate these aspiring standards.

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## Nomenclature

ADH	- Aircraft Data Hierarchy
AGILE	- Aircraft 3rd Generation MDO for Innovative Collaboration of Heterogeneous Teams of Experts
API	- Application Programming Interface
BCA	- Boeing Commercial Airplanes
CFD	- Computational Fluid Dynamics
CMDOWS	- Common MDO Workflow Schema
CLIN	- Contract Line Item Number
CPACS	- Common Parametric Aircraft Configuration Schema
ECS	- Environmental Control System
EPFD	- Electrified Flight Powertrain Demonstrator
FLOPS	- Flight Optimization System
FMU	- Functional Mockup Unit
GASP	- General Aviation Synthesis Program
GE	- General Electric
HiCAM	- Hi-rate Composite Aircraft Manufacturing
HDF5	- Hierarchical Data Format, version 5
HyTEC	- Hybrid Thermally Efficient Core
IP	- Intellectual Property
KADMOS	- Knowledge- and graph-based Agile Design with Multidisciplinary Optimization System
MBSA	- Model-Based Systems Analysis
MBSA&E	- Model-Based Systems Analysis and Engineering
MBSE	- Model-Based Systems Engineering
MSoSA	- Model-Based Systems Architecture
NASA	- National Aeronautics and Space Administration
NPSS	- Numerical Propulsion Simulation System
NRA	- NASA Research Announcement
OEM	- Original Equipment Manufacturer
R&D	- Research and Development
SFD	- Sustainable Flight Demonstrator
SFNP	- Sustainable Flight National Partnership
SEF	- Supplier Engagement Framework
SUGAR	Subsonic Ultra-Green Aircraft Research
SysML	- Systems Modeling Language
N+3	- Third next generation technology timeframe
TACS	- Tool for Aerodynamic and Control Surface Sizing
TDP	- Technical Data Package
TTBW	- Transonic Truss-Braced Wing
WATE++	- Weight Analysis of Turbine Engine
WBS	- Work Breakdown Structure
VSP	- Vehicle Sketch Pad

# Introduction

The aerospace industry is currently navigating a transformative period characterized by increasing pressure to develop more efficient, sustainable, and innovative aircraft designs. This evolution is driven by a confluence of factors, including environmental regulations, rising customer expectations for fuel efficiency, cost-effectiveness and performance, and the growing complexity of modern aircraft systems. This pressure pushes designers to need tools that can handle the increasing complexities on the analysis as well as system definition sides. As the industry grapples with these challenges, the integration of advanced methodologies that are targeted at aiding in the development of complex systems such as Multidisciplinary Design Optimization (MDAO) and Model-Based Systems Engineering (MBSE) has become essential for achieving the ambitious goals set forth for next-generation commercial and military aircraft.

## Model-Based Systems Analysis and Engineering (MBSA&E)

MBSA&E is a project within the Sustainable Flight National Partnership (SFNP) program that aims to develop and demonstrate technologies enabling next-generation subsonic commercial aircraft. The SFNP encompasses large technology development efforts, including ground and flight demonstrations, such as the Sustainable Flight Demonstrator (SFD) program, which involves constructing and testing a full-scale transonic truss-braced wing (TTBW) configuration, as well as other initiatives including Hybrid Thermally Efficient Core (HyTEC), Hi-rate Composite Aircraft Manufacturing (HiCAM), and Electrified Flight Powertrain Demonstrator (EPFD).

The overarching goal of MBSA&E is to build an aircraft design and sizing framework capable of analyzing and sizing next-generation commercial aircraft concepts using state-of-the-art MDAO techniques. It aims to enable systems-level digital integration across the multiple SFNP technology development areas as show in Fig. 1 by incorporating simulation, ground test, and flight demonstration data, as well as technology models and methods into MBSA&E models. This integration is crucial for supporting vision-vehicle performance and technology assessments. To achieve these goals, MBSA&E seeks to leverage the strengths of both Model-Based System Analysis (MBSA) and MBSE in combination.

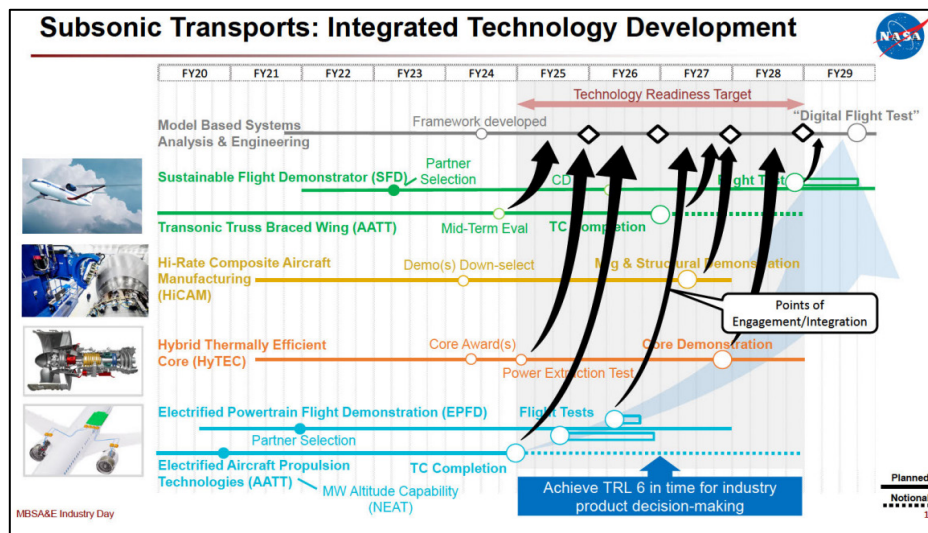


Fig. 1: Integrated Technology Development with Integration of All Programs into MBSA&E [Credit: NASA]

## The Need for MBSA and MBSE

MBSA is a process involving the development of analytical or computational models, often using MDAO, for assessing vehicle or system-level performance. Due to its similarity to MDAO in this paper’s context, the terms MBSA and MDAO will be used interchangeably in this paper. MDAO provides a framework that integrates various engineering disciplines – such as aerodynamics, mass properties, propulsion, and mission effectiveness – enabling a holistic approach to aircraft design sizing and ensuring that all relevant coupling between disciplines are considered simultaneously. This integration is essential for optimizing complex, highly coupled novel aircraft designs that must meet stringent performance, effectiveness, and regulatory requirements [1]. And

can be used to uncover interdependencies and design drivers of these novel configurations [2]. The ability of MDAO to handle complex interactions has become increasingly beneficial as more subsystem-level and novel configuration design drivers emerge in next-generation aircraft. This ability has led to the incorporation of higher-fidelity analyses into early design MDAO models, allowing for the consideration of critical factors earlier in the design process and reducing the downstream risk of rework and costly mistakes. Moreover, MDAO studies not only produce go-forward optimum vehicles, but also can explore trends and data across a vehicle design space, enabling decision makers to make informed decisions that enhance the overall aircraft design and program.

In parallel, MBSE has become increasingly important in aircraft design as a key avenue for effectively managing the complexity of interconnected systems and allowing engineers to visualize the entire system comprehensively, making it easier to identify potential issues earlier in the design process [3]. The increased focus on digital engineering and digital integration means introducing MDAO into MBSE is both desired and inevitable. By utilizing formalized, structured models, MBSE supports vehicle design, analysis, verification, and validation throughout the lifecycle of complex systems [4]. It leverages universal modeling languages, such as SysML, as well as published modeling and architectural standards to improve traceability of requirements and enhance communication among discipline teams.

One key area of investigation with MBSE is its ability to improve the traceability of requirements by linking them to specific design elements within the model, allowing engineers to track how changes to the design impact requirements or vice-versa. This traceability is critical to ensure that all stakeholder needs are met and the final product aligns with the initial objectives. This improved communication extends to discipline teams by providing a common framework and language for discussing design concepts and systems. Using a common language ensures these teams are on the same page [5].

### *NASA's MBSA&E Framework*

NASA developed a new software platform for aircraft modeling called Aviary [6] to enable the analyzing and sizing next-generation commercial aircraft concepts. Aviary is an open-source MDAO tool that enables the modeling of aircraft concepts with analytic gradients. Built on the OpenMDAO framework [7] which features a gradient-enabled architecture to speed up the optimization process, Aviary facilitates tightly coupled, simultaneous design across various built-in aircraft subsystems, including weights and sizing, aerodynamics, propulsion, and mission analysis. This capability integrates two NASA legacy aircraft design tools, Flight Optimization System (FLOPS) [8] and General Aviation Synthesis Program (GASP) [9] while also allowing for the incorporation of external analysis tools to customize workflows within the Aviary framework, making it a versatile platform for exploring unconventional aircraft configurations.

Building on the Aviary framework, MBSA&E has embarked on an ambitious process to integrate and exercise NASA's aircraft conceptual/preliminary design analyses within Aviary. Many popular NASA-developed analyses such as OpenVSP, PyCycle, Dymos, VSPAero, TACS, and Suitcase have already been integrated, with Aviary's base FLOPs or GASP methods filling any analysis gaps as required. A transonic truss-braced wing configuration was developed and analyzed by Arteskin-Hariton et al. using the Aviary framework with many integrated external subsystems to showcase the capabilities of Aviary for aircraft design and optimization [10]. This same MBSA&E TTBW model was also used to connect into MBSE and integrate with uncertainty quantification [11].

### *MBSA&E's NASA Research Announcement*

To accelerate and mature the development of the MBSA&E framework, NASA issued the MBSA&E NASA Research Announcement (NRA), which encompasses eight different technology areas. The NRA was intended to solicit innovative ideas to support the on-going development of the MBSA&E framework in specific technology areas and improve the application of it to the assessment of SFNP technologies and concepts. NASA was particularly interested in building partnerships with industry and academia to incorporate lessons learned and best practices into MBSA&E as well as develop critical advanced concept and technology-based model components for digital integration and vehicle performance assessments. The eight research areas are below:

1. **Aircraft Data Hierarchy:** Develop a logical, adaptable, and rigorous aircraft data hierarchy within

- OpenMDAO to facilitate comprehensive conceptual and preliminary aircraft design and analysis
2. **Standard Interface Definition Between Disciplinary Models:** Create and implement standard data interfaces for each discipline to ensure consistent and efficient integration of multiple disciplinary analysis tools within the MBSA&E framework
3. **Systems Analysis and Systems Engineering Integration:** Bridge the gap between MBSA and MBSE to enable the integration of systems engineering models within the MBSA&E framework
4. **Comprehensive Model Sharing and Collaboration Approaches:** Develop methods for sharing of complete models between industry and government partners while addressing concerns related to information security and IP
5. **Narrow Model Sharing and Collaboration Approaches:** Explore limited (obfuscated) sharing methods that protect sensitive information while allowing for model execution
6. **Aircraft and Component/Subsystem Models:** Develop relevant aircraft and component/subsystem models using integrated software tools to enable comprehensive system-level evaluations of technologies within the SFNP
7. **Disciplinary Tool Integration with OpenMDAO:** Create integrations and example models for disciplinary analysis tools within OpenMDAO to support the assessment of technologies being developed under the SFNP.
8. **Discipline Tool Development within OpenMDAO:** Develop and validate new disciplinary software tools as a library layer on top of OpenMDAO, ensuring they implement analytic derivatives to enhance the efficiency of system-level analyses.

### *Broader Vision*

Boeing recognizes that the challenges faced by NASA in developing their MBSA&E framework as demonstrated through these technology focus areas, especially the first five, are not isolated to NASA but are shared across the entire industry, including Boeing. Boeing's vision for the MBSA&E program recognizes this fact and consequently extends beyond NASA's objectives, striving to set new standards for systems analysis and systems engineering solutions to include and benefit the entire aerospace sector.

Currently, there are no accepted US-industry standards or processes for aircraft data hierarchy, interface, MBSE-MBSA interactions, and model sharing. This vacuum presents a significant barrier to collaboration between organizations when trying to execute joint design activities or studies and is a major reason why none are usually proposed. By developing and promoting new aspiring standards, Boeing aims to create a more cohesive and integrated aerospace design ecosystem where information and models can be shared freely and be understood between organizations. This paradigm shift will reduce the time necessary to analyze vehicle concepts and facilitate the sharing and integration analysis modules that may be using different MDAO frameworks and analysis models but utilize the same MBSA&E standards. These standards would also allow the creation of a modern MDAO benchmark configuration where participating institutions could compare their tools and frameworks against one another for the first time, similar to the canonical Common Research Model for Computational Fluid Dynamics (CFD) analysis [12].

The European Union's AGILE program contains the closest parallel to Boeing's vision for MBSA&E. AGILE has made significant strides in establishing pseudo-standards for a central data hierarchy and MDAO workflow interfaces as part of its efforts to develop a collaborative 3rd generation distributed collaborative design environment [3]. Through the development of the Common Parametric Aircraft Configuration Schema (CPACS), AGILE has created a unified data structure that facilitates the interdisciplinary exchange of product and process data among various analysis codes and tools. This central data hierarchy not only streamlines the integration of diverse disciplinary analyses but also promotes interoperability among different MDAO frameworks. By emphasizing the importance of a standardized interface through different packages such as KADMOS [13] and CMDOWS [14] for a distributed ecosystem, AGILE enables communication between disparate heterogeneous systems and MDAO frameworks, thereby enhancing collaboration across organizations as these configuration files are exchanged. However, the AGILE products are not fully suited to this MBSA&E vision. For example, the CPACs hierarchy makes no accommodation for MBSE, a critical requirement for modern systems, is based on an older XML standard, and has a geometry-focused architecture. Additionally, the

CMDOWS definition was designed with the KADMOS package and other European tools in mind which are not prevalent in the US and may have issues being accepted without being developed specifically for the nuances of the US-based use-cases where organizations are more independent and collaboration is less likely. Nevertheless, these state-of-the-art AGILE products offer many ideas and lessons learned that can be gleaned and investigated to improve the solutions created for MBSA&E.

Elevating the focus to an aerospace-wide solution with MBSA&E requires the addition of supplementary requirements to achieve this wider impact. These requirements are illustrated in Fig. 2. The center of this figure displays the NASA MBSA&E model with a depiction of how the Boeing CLIN efforts align and interact with the MBSA&E framework. This diagram emphasizes that these are additional requirements of the MBSA&E effort to align with the wider mission, but the MBSA&E use-case remains the initial use-case for all MBSA&E standard development efforts.

Fig. 2 is surrounded by six additional requirements/focus areas. The first is the implementation of vendor neutral and tool agnostic principles. This approach recognizes the diverse landscape of tools and technologies currently in use across the aerospace industry and the unrealistic expectation that an organization will stop using their tool/framework to pick up another that may be compatible with these new standards. By ensuring that developments such as the data hierarchy and standard interface can integrate seamlessly with a variety of existing systems and coding languages, this work aims to facilitate collaboration among organizations without imposing rigid requirements on the tools they use. This flexibility is crucial for encouraging widespread adoption and ensuring that organizations can leverage their current capabilities while benefiting from the advancements offered by the MBSA&E initiative.

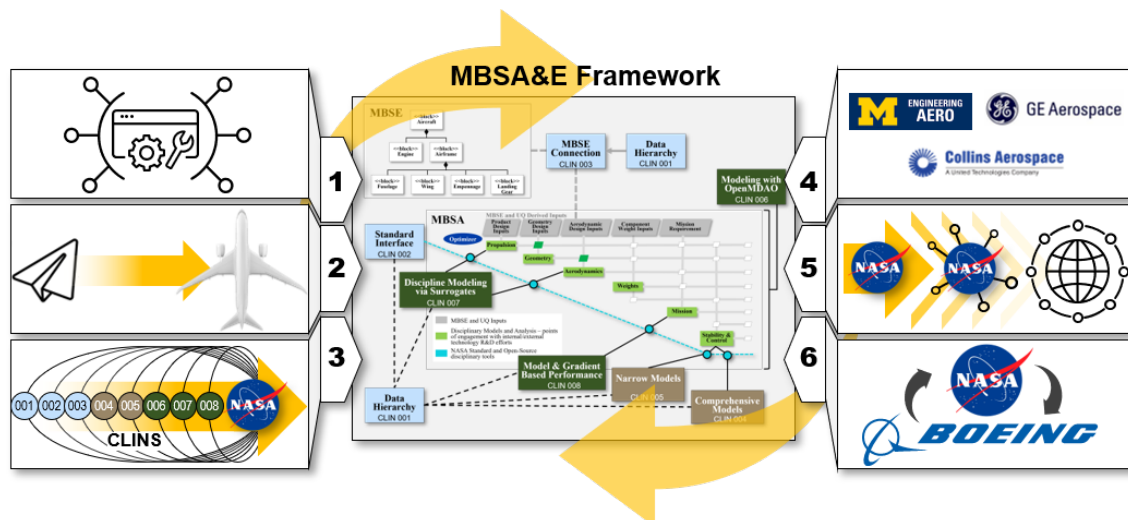


Fig. 2: Boeing’s broad vision for MBSA&E technology focus areas that: 1) Implement vendor neutral architectures; 2) Emphasize development across design phases; 3) Exploit synergies between CLINs for superior products; 4) Leverage academic & industry perspective for broader perspective/alignment; 5) Employ permissive data rights (open source); and 6) Coordinate closely with NASA

Boeing envisions the MBSA&E solutions as a comprehensive solution that spans multiple design phases, from conceptual design to detailed design, and from research and development (R&D) to production. This multi-phase approach allows for a holistic view of the aircraft development process, enabling teams to consider the implications of design decisions at every stage. It also allows these solutions to grow and move with the design process as it matures, reducing the need to switch between different data representations or storage systems, and opens up a larger potential pool of users. As a starting place, this project uses the conceptual design, R&D use-case that matches NASA’s current state. However potential future growth into other phases must be considered upfront to enable development into later design phases as the project matures.

Co-developing technology areas that leverage overlap and exploit synergies among different disciplines is another critical focus area. By identifying common goals and shared challenges across various technology domains, this project aims to foster collaboration that enhances the overall effectiveness of the MBSA&E

framework. This approach allows for the pooling of resources and expertise, leading to more efficient development processes and innovative solutions. By working together on overlapping technology areas, Boeing and its partners can accelerate the maturation of critical technologies and ensure that they are effectively integrated into the MBSA&E process.

Recognizing the complexity of modern aircraft design, Boeing emphasizes the importance of incorporating diverse opinions early in the development process. This project seeks to gather insights and expertise from various disciplines and perspectives from across the design phases by engaging with a wide range of industry, government and academic partners. This collaborative approach not only enriches the development process but also fosters innovation by ensuring that all relevant voices are heard and bringing together experts from different fields. Boeing brought together a group of aerospace leaders for MBSA&E from different parts of the aerospace landscape including Collins Aerospace, GE Aerospace and University of Michigan to capture this range of inputs as early as possible.

The application of permissive data rights, specifically embracing an open-source philosophy, is critical to the goals of this approach. Boeing aims to encourage collaboration and transparency of these efforts within the aerospace community, by making the technologies and methodologies developed through the MBSA&E initiative accessible to a broader audience. This open-source approach not only facilitates knowledge sharing but also allows for collective contributions to the development of the MBSA&E framework. By fostering a culture of openness, Boeing aims to gather a diverse range of inputs and insights that can enhance the overall quality and effectiveness of the aircraft design process while also increasing the user-base and reach that is necessary to reap the full benefits of these approaches.

Finally, the vision does not forget that the first use-case of this project is centered around the NASA MBSA&E framework. Boeing will work with NASA tightly to address their needs while considering the broader focus that this vision demands.

## Boeing MBSA&E

This section describes the six technical focus areas under the Boeing MBSA&E project. These include CLINs (Contract Line Item Numbers) 001 – 006 as described in the NASA MBSA&E NRA including development of aircraft data hierarchy, standard interface definition between disciplinary models, systems analysis and systems engineering integration, comprehensive and narrow model sharing and collaboration approaches, and aircraft model for benchmarking. The period of performance for this contract was 19 months starting in October 2023 and extending until April 2025.

All of the CLIN technology focus areas are aligned with different parts of the MBSA&E framework. The Boeing MBSA&E concept architecture that visually portrays how each CLIN is a part of the MBSA&E framework can be seen in Fig. 3. General summaries of the results of each CLIN are described below.

- **CLIN 001:** Developed a modern configuration data definition standard for the vehicle design studies. The ADH enables the exchange information between tools using a common data structure and a schema that can be validated. Created with MBSE in mind using Model-Based Systems Architecture (MSoSA) and other standards.
- **CLIN 002:** Updated OpenMDAO to enable programmatically tracking of all the inputs, outputs, and options going into and out of a component. Created an API to allow the saving and loading of an entire MBSA assembly/workflow in a neutral format (i.e. json). Architected the updated code to enable backwards compatibility to all existing OpenMDAO models.
- **CLIN 003:** Defined the metamodel, system model, profiles necessary to represent an aircraft MBSA model and configuration in MBSE. Created a series of Cameo plugins that bi-directionally connect MBSE into the ADH without mapping, enabling more generalized and flexible integration into MBSE.
- **CLIN 004/005:** Defined a detailed process flow to perform comprehensive (i.e. no model obfuscation) and narrow (i.e. containing some obfuscation to protect IP) model sharing between two organization. Demonstrated this exchange process between Boeing and Collins using Boeing software.
- **CLIN 006:** Modeled a conventional commercial aircraft called “Sugar Free”, used in previous Boeing-NASA studies [17], in the MBSA&E model. Compared the results of these studies and optimizations

against Boeing sizing results. Generated lessons learned to help guide continued MBSA&E development.

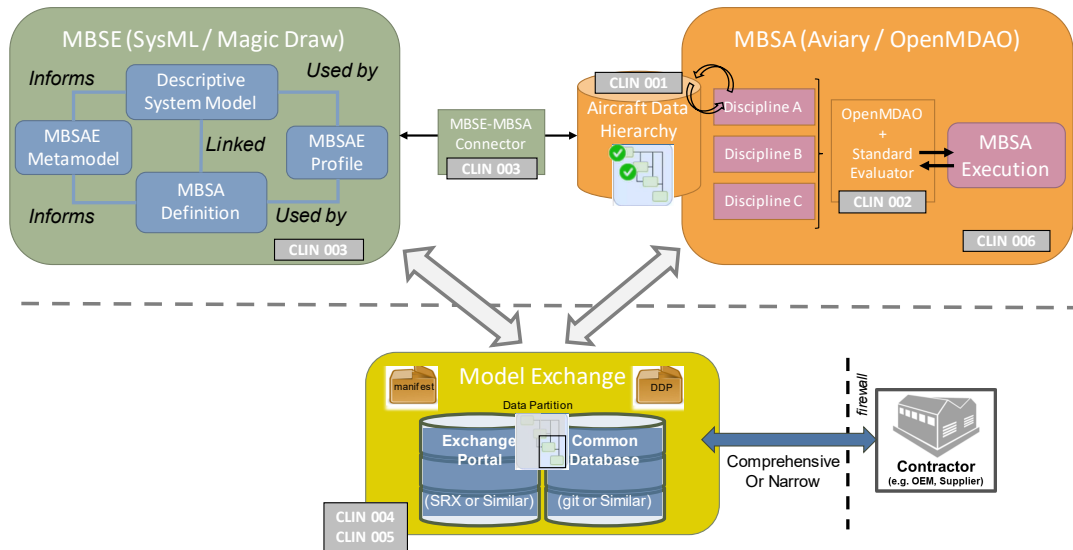


Fig. 3: Boeing MBSA&E Concept Architecture

Collins Aerospace, the University of Michigan, and General Electric were enlisted as subcontractors in this effort so they could provide general guidance, insight and support in accomplishing the goals of MBSA&E. These participants helped Boeing engage industry and academia early in the development process to incorporate their diverse opinions into the products. The general roles of each supplier are summarized as follows:

- Collins Aerospace: Industry-leading component supplier provided expertise in subsystem design and OEM – supplier collaboration projects
- University of Michigan: Experts in OpenMDAO implementation and model development as well as Python programming and MBSE-MBSA interfaces for use in aircraft design models
- General Electric: Industry-leading propulsion supplier providing a non-proprietary engine for aircraft benchmarking exercise as well as a propulsion supplier perspective

The six CLINs are discussed in more detail in the following sections. These sections are summaries of the full reports which can be read separately for more details.

### Aircraft Data Hierarchy (CLIN 001)

The aerospace industry has long faced challenges related to data management, particularly in the context of multidisciplinary design processes. Many MDAO systems link variables directly between workflow analyses. The complexity of linking in this type of system scales significantly with the total number of unidirectional connections around  $N*(N-1)$  between  $N$  analyses, leading to excessive setup time, maintenance cost, framework flexibility, and error rates. A central data solution or data hub, solves this issue by having each analysis grab their inputs from and put their outputs into the data hub, reducing the amount of possible connections to  $2*N$  (Fig. 4).

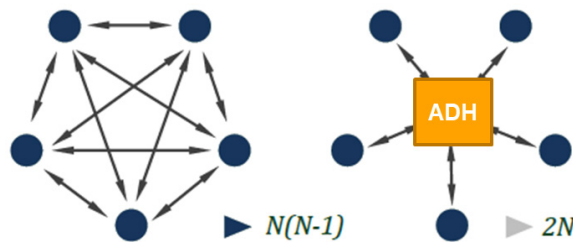


Fig. 4: Traditional (Left) vs. Central Data Hub Solution (Right)

Issues still exist even after implementing a central data hub since exchange infrastructures often exhibit significant limitations, including a lack of standardization, tool-oriented data hierarchies, and a pronounced bias toward systems analysis over systems engineering. These challenges create inefficiencies, increase project costs, hinder innovation, and reduce collaboration. In one specific example, NASA noted that their Aviairy data hierarchy was heavily biased toward legacy tool and MBSA, had no common hierarchy between MBSE and MBSA, was decentralized, and generally NASA-centric. The ADH initiative was conceived to address these fundamental issues by becoming an industry-wide modern data definition standard for the aerospace vehicle design studies (including MBSE).

The ADH had four main objectives: Standardization, interoperability, flexibility, and efficiency. Through standardization, it aims to establish consistent and clear a common language for aircraft design and analysis to eliminate ambiguity and reduce misinterpretation that often plague cross-disciplinary collaborations. This includes establishing common data standards between MBSA and MBSE. Interoperability enables seamless integration of various systems, tools, and processes across workflows and organizations to facilitate efficient data exchange and collaboration. This inherently means the ADH should be vendor neutral and tool agnostic to be utilized in a variety of systems. Flexibility allows the ADH to adapt to evolving design methodologies and accommodate all aircraft types and categories, providing a comprehensive solution for aerospace data management. Efficiency streamlines data management processes to minimize manual effort and enhance the overall productivity of engineering teams. The development process involved extensive stakeholder engagement, including interviews and discussions with key aerospace organizations such as NASA, Boeing, General Electric Aerospace, Collins Aerospace, and the University of Michigan. This collaborative approach and adherence to the Boeing vision ensured that the ADH addresses diverse needs and leverages industry expertise at the beginning of the development process when input is the most valuable.

The development of the ADH employs a sophisticated technical architecture designed to meet the rigorous demands of aerospace data management. A comprehensive set of requirements was gathered through extensive discussions with stakeholders, informing the design and functionality of the data hierarchy. Next, research into the primary programming language, data validation methodology, and data/persistence formats were performed. The primary programming language used for implementing the ADH is Python, chosen for its versatility, extensive library ecosystem, and widespread adoption in scientific and engineering communities. The choice aligns favorably with NASA's preferred usage of OpenMDAO, a python-based MDAO integration framework.

A key innovation in the ADH implementation is the use of Pydantic v2 for schema definition and validation, chosen after a robust and thorough exploration of options for data validation. This validation is critical for maintaining data integrity and consistency, particularly in complex, collaborative design environments. The ADH supports multiple data formats for persistence and exchange, including JSON, YAML, and XML. This flexibility allows engineers to choose the format that best suits their specific needs and existing toolchains, reducing barriers to ADH adoption. Each format offers specific advantages, such as human readability, parsing efficiency, and integration capabilities.

The ADH is organized based on existing standards to align it with industry best-practices where possible (Fig. 5). The organizational structure is based on MIL-STD-881F with modification to align with the SAWE RP A-8 work breakdown structure (WBS). This WBS provides logical, hierarchical organization for data, facilitating efficient navigation and access. Though a military standard, this structure is expected to work across commercial and defense applications. Each line item in the WBS is implemented as a recursive MSoSA object, representing air vehicle components, systems, and equipment. This recursive structure with the architecture view as the parent and requirements, performance, and behavior as child views enabling consistent representation of complex, nested systems while maintaining clarity and organization. The parent-child relationship ensures that all analysis, requirements, and behavioral characteristics are derived from and traceable to the fundamental architectural definition. This structure aligns MBSA and MBSE data allowing for seamless transfer between the two without mapping.

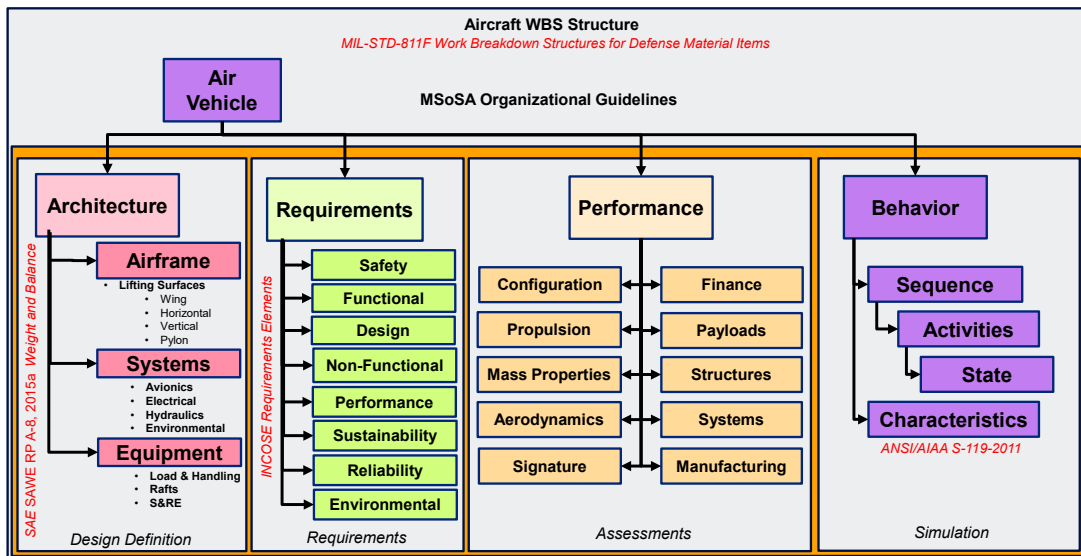


Fig. 5: Architecture of Aircraft Data Hierarchy

Significant progress has been made in the development of the ADH, with key milestones achieved in foundational development, stakeholder engagement, architectural decisions, and prototyping.

A draft ADH Pydantic schema has been delivered, defining the structure and relationships of the ADH data objects as defined in Fig. 5. Prototyping efforts have included schema development, API implementation, and integration testing, validating the interaction of the ADH with OpenMDAO as the first use case. An API was developed for accessing and managing data within the ADH providing essential functionality for interacting with the data hierarchy. Basic helper functions have been implemented and documented for initial testing, demonstrating the practical utility.

Demonstrations of the ADH's capabilities at the subsystem/discipline analysis level have showcased its functionality in real-world scenarios, providing tangible evidence of its value. These demonstrations highlighted the ADH's ability to represent and manage data for specific aircraft components, facilitate integration with existing analysis workflows and integration with MBSE.

One such propulsion-focused demonstration involved defining the ADH architecture, behavior, and performance branches to facilitate zero-dimensional engine performance analysis using the pyCycle tool in collaboration with GE Aerospace. The architecture branch includes Pydantic classes for engine components, while the behavior branch captures off-design performance, and the performance branch specifies solver settings for analysis. A generalized propulsion analysis builder tool was developed to generate an OpenMDAO pyCycle model from the ADH, allowing users to run analyses with customizable flight conditions. This integration showcased the ADH's capability to support single-disciplinary workflows in propulsion system design and analysis with

The ADH code is currently hosted on public GitHub including documentation, demonstrations, and unit tests. This open-source approach leverages the collective expertise and resources of the aerospace community, creating a more robust, comprehensive framework than would be possible through isolated development.

The ADH has been positioned as a fundamental component of modern aerospace engineering, with ongoing collaboration with key aerospace stakeholders. However, much work is still to be done to meet these lofty goals. The future vision involves a multi-faceted approach aimed at continuing development to enhance its capabilities and ensure its widespread adoption within the aerospace engineering community. A critical next step is to add detail to the "leaves" of the ADH, which will create a standard set of non-duplicate parameters for each part of the architecture to facilitate the integration of various engineering tools and ensure comprehensive coverage of all relevant aircraft design parameters. A full aircraft ADH will be populated and integrated into an MDAO model to showcase the full potential of the capability and act as a guide for others. Engaging with the aircraft design community will be essential to gather insights feedback. To further enhance the ADH's functionality, the

integration of uncertainty quantification will be prioritized, allowing for more robust design decisions that account for variability in design parameters. The development of rollups for mass properties, cost, and other critical metrics, such as parasite drag, and generating detailed reports will facilitate comprehensive system-level assessments. The python API will continue to be improved along with documentation and demonstrations to ensure ease of use for all users.

The Aircraft Data Hierarchy represents a critical advancement in aerospace data standardization, providing a comprehensive framework for aircraft data management, exchange, and collaboration. Its successful implementation is expected to transform aerospace engineering practices at NASA and throughout the industry, enabling more efficient, effective, and innovative approaches to aircraft design. Continued investment and industry participation in the ADH are essential for realizing its full transformative potential, ensuring that it becomes a cornerstone of modern aerospace engineering.

### Standard Evaluator (CLIN 002)

The CLIN 002 Standard Interface/Evaluator project was a collaborative effort involving Boeing and Collins Aerospace, focusing on the development of a standard evaluator that enables the programmatic definition of MDAO assemblies by developing a Python library that allows for the independent definition of component assemblies and optimization problems. The overarching goal was to facilitate the integration of various analyses and optimization processes while ensuring compatibility across different MDAO frameworks (i.e. a vendor neutral paradigm). Fig. 6 shows the vision that was outlined at the beginning of the project, and highlights the two main capabilities in purple currently implemented during CLIN 002 work in the standard evaluator Python open-source library. Other aspects of this vision are left for future development.

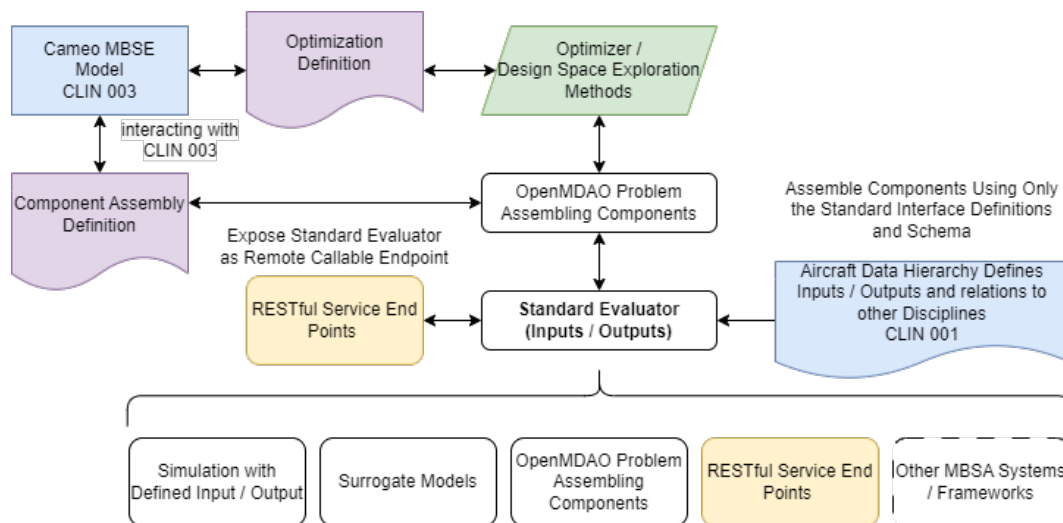


Fig. 6: Overview of the functionalities implemented and their context

The primary objectives of this project were to:

- Develop a standard evaluator that allows for the full description of discipline analyses used in MDAO assemblies, including inputs, outputs, and options for each component.
- Enable the assembly of MDAO frameworks from textual descriptions, compressed files, and optimization definitions, independent of specific MDAO frameworks.
- Facilitate the replacement of computationally expensive analyses with surrogate models or simplified analyses, enhancing efficiency in MDAO studies.
- Create a programmatic interface for defining options for components in MDAO assemblies, particularly for components hosted remotely.
- Establish a foundation for version control and integration with the digital thread in modern development processes.
- Make the project open-source to facilitate development and usage across the aerospace industry

The project developed the standard evaluator as a Python library, leveraging the NASA OpenMDAO framework as its initial integration case. This development process involved several key steps, including creating a component assembly definition, where the team defined a standard way to describe components and their interactions within an MDAO assembly using Pydantic classes. This enabled storage of assembly information in JSON format, facilitating version control and ease of use. This storage method is a platform-independent description of MDAO assemblies, allowing for seamless transitions between different MDAO frameworks within an organization or between them. A robust API was created to enable developers to programmatically define options for components within OpenMDAO, including default values, ranges, and descriptions, permitting users to access required options without needing to delve into source code or documentation. The project emphasized the importance of explicitly defining the inputs and outputs of components within an MDAO assembly, ensuring that changes to internal variables do not impact external users. All of the additions to OpenMDAO for this capability are backwards compatible with any existing models meaning that the implementation of this approach is entirely optional for users, keeping with OpenMDAO's user-oriented ethos.

The project successfully delivered a standard evaluator that meets the outlined objectives. Key results include enhanced MDAO assembly definition, allowing for the easy assembly, editing, and re-assembly of MDAO workflow definitions from various sources, including textual descriptions and HDF5 files. The team conducted multiple demonstrations in an easy-to-follow Jupyter Notebook format to showcase the functionality of the standard evaluator, including the creation of components, groups, and optimization problems. One demonstration took an OpenMDAO assembly, saved off the assembly in JSON format, edited the assembly, then loaded the modified assembly back into OpenMDAO and ran the model (Fig. 7). These demonstrations highlighted the ease of use and flexibility of the developed library. Another demonstration illustrated how one can replace computationally intensive analyses with surrogate models and facilitate the assembly of MDAO frameworks. The standard evaluator code is currently hosted on public GitHub including documentation, demonstrations, and unit tests. It is available on PyPI.

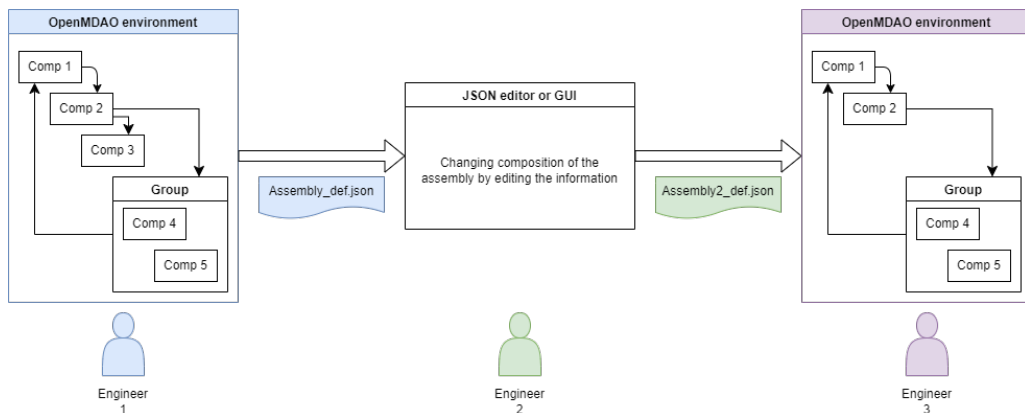


Fig. 7: Pictorial description of the process to take an assembly, edit it via the JSON file, and create a new assembly

One unexpected result of the standard evaluator development was the conversation it spurred with the NASA Aviary and OpenMDAO development teams about Options and their usage in OpenMDAO. These conversations are spurring conversations to streamline and improve the best practices for specifying Options to be able to support a more well-defined interface. The groundwork laid by this project opens avenues for future integration with other frameworks and the development of graphical user interfaces (GUIs) for assembly creation and editing.

The Standard Interface/Evaluator project has made strides in advancing the capabilities of MBSA frameworks within the context of NASA's MBSA&E initiative by developing software that allows for the programmatic description of MBSA assemblies and optimization problem definitions. The standard evaluator's ability to facilitate interoperability across different frameworks and its potential for integration with digital threads and modern development processes position it as a critical tool for the future MBSA&E systems and their

collaboration between and within organizations.

### MBSA-MBSE Bridge (CLIN 003)

This project focused on creating a framework that integrates disciplinary analysis tools with systems engineering artifacts. The plan included developing a metamodel to guide the systems engineering model's structure, creating a descriptive system engineering model that adheres to this metamodel, and integrating this model with disciplinary analysis tools. The project also built a connector for MBSE-MBSA coupling to effectively pass information between MBSE and MBSA. The traditional methods of data transfer often leads to errors and inefficiencies, particularly when dealing with large design problems that involve numerous variables and configurations. The project aimed to automate the data transfer process and generalize the transfer setup, allowing designers to focus on analysis and decision-making rather than manual data handling and integration. The systems engineering modeling environment utilized MagicDraw 2022x Refresh 1 and the Systems Modeling Language (SysML) version 1, with the digital connectivity implemented using MagicDraw plugins coded in Jython.

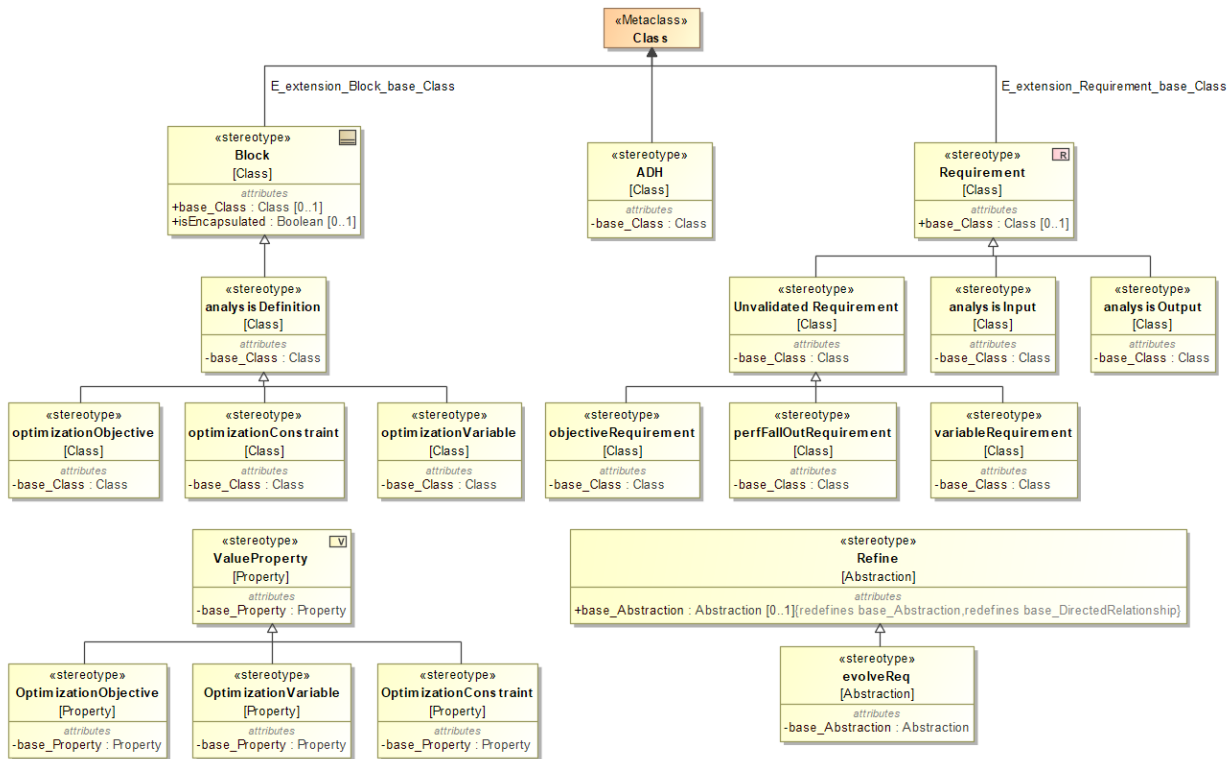


Fig. 8: MBSA&E Profile

The methodology involved several key steps. The systems engineering model was designed to derive requirements, establish validation and verification relationships, and facilitate communication with suppliers. Effective communication with partners, such as Collins Aerospace, was critical for developing and testing out the airplane system model, ensuring that requirements and performance metrics were clearly conveyed. The collaborative efforts between Boeing, Collins, and NASA resulted in a comprehensive workflow that integrates various elements of model sharing, including the creation and definition of model manifests and metadata. The development of a metamodel, SysML profile (as shown in Fig. 8), and systems engineering model provides a framework for integrating MBSA information into MBSE, enabling traceability between disciplinary analysis and systems engineering artifacts. The systems engineering models include a logical model, a requirement model, and a performance model. These systems engineering models follow the developed metamodel and sysML profile so that the data structure, requirement, and system hierarchy in MBSE are consistent with the disciplinary analysis. With such consistency established, data can be exchanged between MBSE and MBSA following the metamodel and the sysML profile, where the traceability is created.

The project emphasized the importance of traceability between design decisions and disciplinary analysis, allowing designers to evaluate the implications of their choices. The bi-directional data exchange between MBSE and MBSA uses the ADH file as the exchange medium, which represents a single airplane configuration instance, including requirements, architecture, performance, and behavior, and is based on the MSOSA guidelines. The ADH is described in more detailed in the “Aircraft Data Hierarchy (CLIN 001)” section. A Jython-based API was developed within MagicDraw to enable bi-directional data exchange between MBSE and an ADH. The general workflow is depicted in Fig. 9. The API functions are integrated into a larger engineering workflow, which begins with the creation of an ADH to represent the system architecture/airplane configuration. The workflow involves importing the ADH into MagicDraw to instantiate a systems engineering model (including requirements, architecture, and performance), making design decisions/updates to the SysML systems model, exporting the updated model for analysis, and then updating the system model based on the results of the analysis. This iterative process enhances collaboration between systems engineers and disciplinary analysts, allowing for more efficient design optimization.

The API consists of five Jython scripts that serve as plugins within MagicDraw, each designed to perform specific functions related to data import and export. These API scripts include

- ReadADH: Reads a JSON file and creates a SysML model in MagicDraw, establishing the initial system architecture
- WriteADH: Exports the SysML model from MagicDraw to a JSON file, allowing for further analysis and modifications.
- UpdateADH: Compares the SysML model with a JSON file, updating any conflicting values in the system model.
- ImportStereotypes: Reads a JSON file to create a stereotype profile for components based on their Work Breakdown Structure (WBS) numbers.
- WriteInstance: Exports an Instance Specification in MagicDraw to a JSON file, facilitating the analysis of multiple configurations.

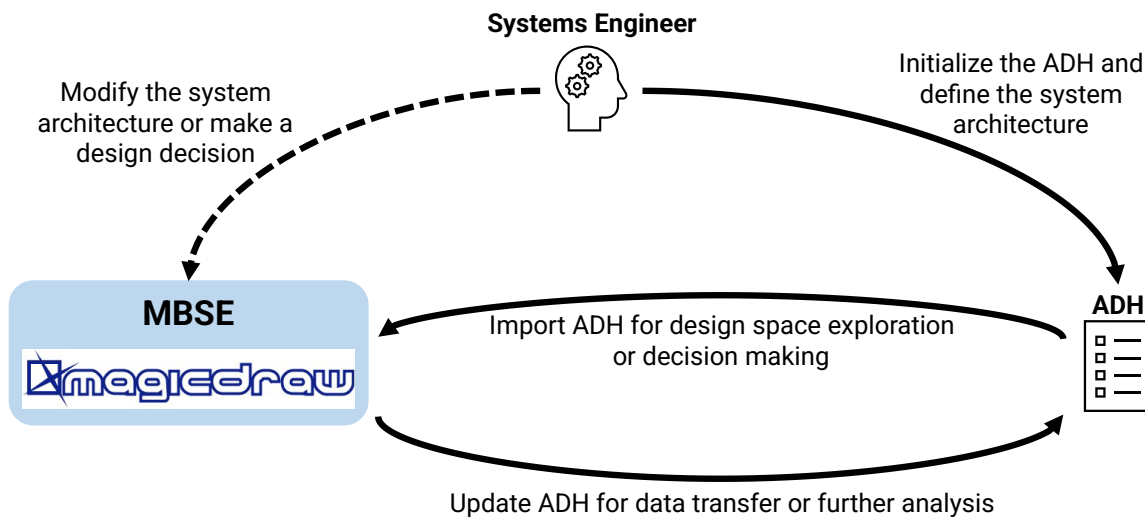


Fig. 9: Using ADH to pass data between MBSE and MBSA tools

Demonstrations of the capabilities including ones that follow the generalized workflow (Fig. 9) were included in the GitHub repository, showcasing how the systems engineer and disciplinary analysts may interact with the ADH. Future enhancements may include optimizing the integration of uncertainty quantification, refining the metamodel, and expanding the capabilities of the API to facilitate even more seamless data exchange between MBSE and MBSA tools.

By developing a comprehensive framework that supports digital connectivity, the project enhances the ability to manage complex systems and facilitates effective communication among stakeholders. Continued

advancements in this area will further strengthen the integration of MBSA and MBSE, driving innovation in aerospace engineering and ensuring that the industry can effectively respond to future challenges. The successful implementation of the project lays the groundwork for future initiatives aimed at enhancing the exchange of digital information in complex systems development, ultimately contributing to the overarching goals of the MBSA&E program.

### *Comprehensive & Narrow Model Sharing (CLIN 004 & 005)*

The transition from traditional documentation and 2D drawings to digital engineering models has introduced various challenges in the aerospace industry. Boeing, in collaboration with its partners, has been actively addressing these challenges through the development of model sharing approaches with its suppliers. As part of the MBSA&E contract with NASA, Boeing has tailored and expanded these processes to support the NASA MBSA&E use-cases. This summary outlines the comprehensive and narrow model sharing strategies that have been established to facilitate collaboration and exchange of models while ensuring the management of model identity information, protection of intellectual property (IP), version control, change propagation, and other considerations. Many of these processes were pioneered in these previous efforts that Boeing is now building on for NASA. Comprehensive model sharing involves the complete exchange of models, including all input files, output files, and associated data in their native formats, allowing both parties to access, analyze, and modify the models collaboratively. In contrast, narrow model sharing focuses on providing limited access to models, often obscuring sensitive information while still enabling execution within a framework, thereby protecting IP while facilitating necessary collaboration. The focus of this project is on creating a framework/process that allows for effective communication and data sharing between two organization in either form, thereby enhancing and accelerating the overall sharing and engineering process.

The methodology employed in this project involved several key steps. The Boeing-developed Model-Based Engineering Supplier Engagement Framework (SEF) was utilized to define the level of collaboration with Collins, a key supplier, as an example case for MBSA&E. The SEF outlines various engagement levels, with Level 3A selected for this project, allowing for bi-directional exchange of Technical Data Packages (TDPs). A high-level checklist of activities was developed to create tool-agnostic workflows, designed to accommodate the specific needs of all parties involved, ensuring that the processes align with the tools and methodologies used in the project. Clear definitions of model boundaries were established to facilitate understanding among all parties regarding the development and exchange of models, introducing white, grey, and black box concepts to delineate the levels of transparency and protection required for different model components. Various tools and methods for IP protection were assessed, including obfuscation techniques that allow for controlled access to sensitive model information, which was crucial in ensuring that proprietary information remained secure during the collaboration process. A standard TDP was created to facilitate the sharing of model data in neutral formats, including requirements, architecture, and behavioral data, along with model entity metadata essential for effective model management and exchange. The TDP manifest describes the contents of data within the TDP with an example shown in Fig. 10. To save time and cost, no software tools were developed for NASA in CLINs 004 & 005, instead Boeing-internal tools were used to demonstrate the well-defined processes with Collins as the sharing organization.

The collaborative efforts between Boeing, Collins, and NASA resulted in several significant outcomes. A comprehensive general workflow was developed that integrates the various elements of model sharing, including the creation of model manifests and metadata (Fig. 10). It is a guideline of suggested activities which may be applicable to enable sharing between two organizations depending on the scope of the project. This workflow was highlighted through practical applications and sharing demonstrations with Collins, showcasing its effectiveness in facilitating collaboration. New TDP manifests were developed based on open standards where possible and specific to MBSA&E use-cases including 3-D geometry files, engineering analysis scripts, Simulink files, Functional Mockup Units (FMU), and Cameo MBSE model files. Examples for each manifest were created and shared with NASA (Fig. 11). These manifests could then be used to create the metadata necessary to fully describe the models to-be-shared and create the fully defined TDP that was then transmitted.

The Environmental Control System (ECS) was selected as a use case model for sharing, allowing the teams to demonstrate this process on a real-work-like example. This use case provided valuable insights into the practical

application of the developed workflows to NASA. The ECS example consisted of a Matlab Simulink FMU analysis and a system engineering model of the system architecture with and without obfuscation so as to evaluate both MBSA and an MBSE-based process in the testing.

A data exchange step-by-step guide was developed and delivered to NASA which documents and describes each step of the general workflow for comprehensive, narrow sharing as well as sharing specific types of information. Finally, a lessons learned document was also provided to reflect on the collaborative journey, emphasizing key insights and best practices that emerged during execution.

In conclusion this project brought forth an opportunity to expand on a set of concepts and best practices that had been implemented between Boeing and its supplier partners to accommodate NASA's early design MBSA&E use-cases. The developed frameworks and workflows are designed to accommodate a variety of scenarios, ensuring that all parties can engage effectively while protecting their IP and providing the information necessary to fully describe what is being shared. The project successfully integrated various standards into the model sharing process, enhancing the overall efficiency and effectiveness of the collaboration, including the use of model identity cards and editors to manage metadata and facilitate model exchanges.

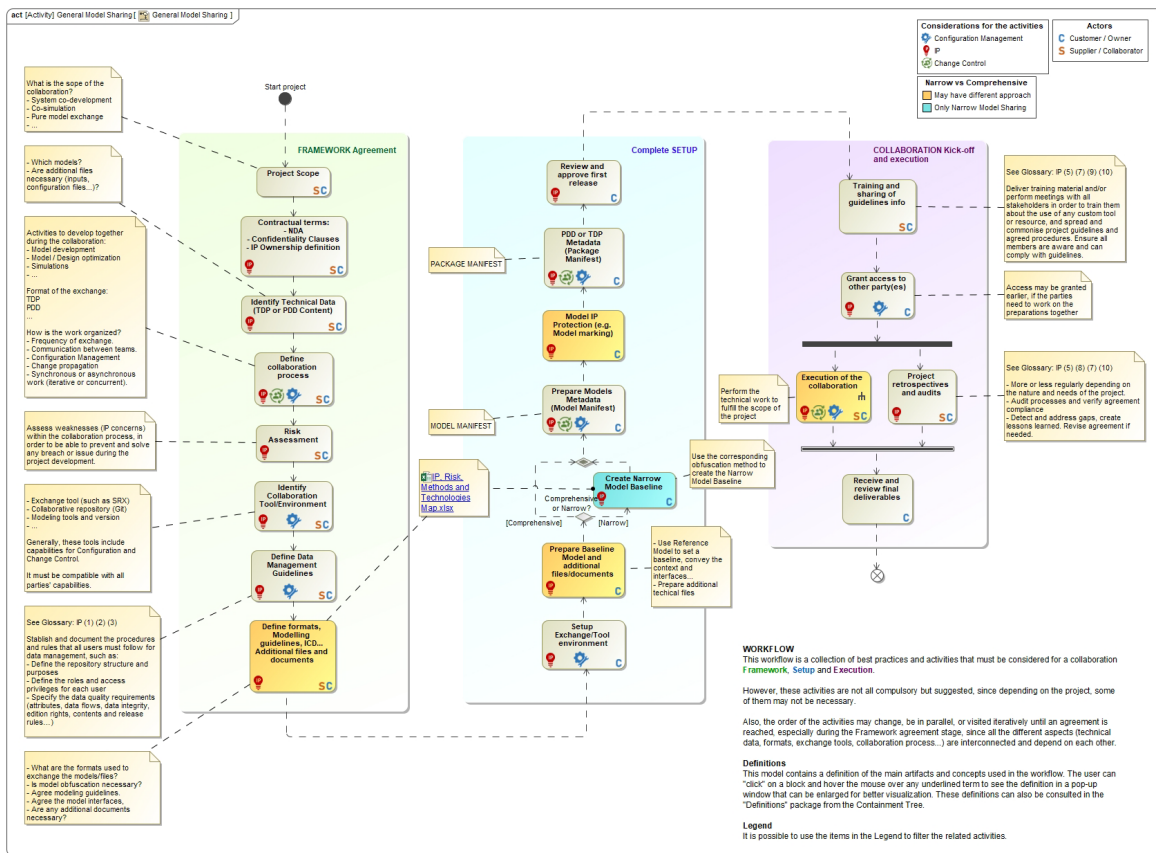


Fig. 10: General Model Sharing Workflow

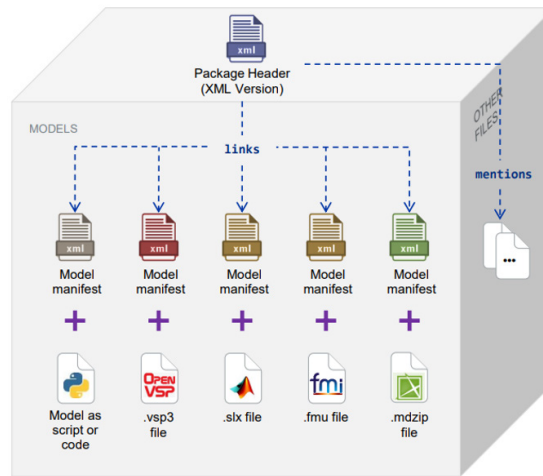


Fig. 11: Package Manifest Example Structure

### MBSA&E Model Benchmark (CLIN 006)

The CLIN 006 Aircraft Benchmarking activity aimed at developing an open commercial transport model that integrates various engineering analyses to support system-level performance assessments. The benchmarking activity focused on creating a model that could be openly distributed across government, industry, and academia, thereby serving as a reference for the MDAO community and eventually become part of a potential stable of aircraft hosted by NASA.

The primary objective of the CLIN 006 activity was to evaluate a commercial transport aircraft using existing NASA MBSA&E tools. The project sought to deliver a model with unlimited rights, allowing for broad distribution and use as a reference for future analysis and optimization efforts. By leveraging the MBSA&E toolset, the project aimed to match the model's performance with industry evaluations, providing a reliable benchmark for assessing the capabilities of the MBSA&E framework.

To achieve these objectives, the project involved collaboration between Boeing and General Electric (GE), with GE providing an open engine model based on the TF01 turbofan engine cycle established by the Numerical Propulsion Simulation System (NPSS) Consortium. The aircraft model was provided by Boeing and based on a conventional transport configuration similar to a Boeing 737, modified from a NASA-Boeing Subsonic Ultra-Green Aircraft Research (SUGAR) study.

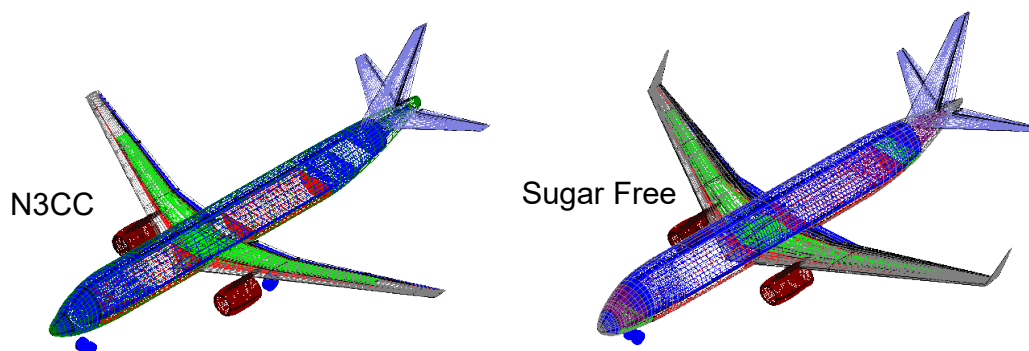


Fig. 12: Sugar Free geometry generated from N3CC using OpenVSP.

The methodology for the CLIN 006 activity involved several steps. The project began with the adaptation of an existing NASA model of a commercial transport aircraft, known as the N3CC model, which was designed for the third next generation technology timeframe (N+3). Boeing modified this model to create the Sugar Free configuration, representing a conventional aircraft design with current technology levels. The geometry of the Sugar Free model was developed using the Open Vehicle Sketch Pad (OpenVSP) tool, with adjustments made

to match the dimensions and features of the original design. The aerodynamic characteristics were analyzed using both VSPAero and Aviary aero models. While VSPAero provided higher fidelity aerodynamic data, it proved computationally expensive for sizing optimization, leading to the use of Aviary aero for its efficiency, with calibration performed to align its results with Boeing's estimates. The GE TF01 engine model was integrated into the Sugar Free aircraft model, designed to be non-proprietary and packaged to run without requiring a local NPSS installation. The engine's performance data, including thrust and fuel consumption, were incorporated into the MBSA&E toolset for comprehensive performance evaluations. The weight of the modified Sugar Free configuration was analyzed using the WATE++ tool, indicating that the operational empty weight was slightly higher than previous studies, primarily due to the larger engine size required for the desired thrust performance. The performance of the Sugar Free model was evaluated through mission profiles that included climb, cruise, and descent segments, demonstrating its capability to accurately represent the aircraft's operational characteristics using Aviary's wrapping of Dymos.

*Table 1: Results of modified Sugar Free evaluated in MBSA&E compared with prior study evaluated by Boeing models*

<b>Description</b>	<b>SUGAR [17]</b>	<b>MBSA&amp;E (Boeing)</b>	<b>MBSA&amp;E</b>
Takeoff Weight (lb)	184,800	186,432	186,061
Operational Empty Weight (lb)	96,000	99,335	98,964
Payload (lb)	30,800	30,800	30,800
Total Fuel (lb)	58,000	56,297	56,297
Engine Thrust	28,200	32,600	32,600

The results of the CLIN 006 activity highlighted the effectiveness of the MBSA&E toolset in modeling and analyzing aircraft performance. The Sugar Free model was successfully calibrated to match Boeing's internal analysis results, providing confidence in its accuracy and reliability. The results of the MBSA&E analyzed SUGAR geometry, and the updated Boeing SUGAR vehicle analysis are included in Table 1.

The sizing optimization conducted using the MBSA&E toolset resulted in a reduction of both engine size and wing area, leading to a lower takeoff weight compared to the baseline configuration. The mission profiles demonstrated that the Sugar Free model could achieve the desired climb and cruise performance, validating the integration of propulsion and aerodynamic data. These results are show in the extended paper.

This project allowed Boeing to explore the MBSA&E toolset, revealing several observations about its capabilities and workflow. OpenVSP effectively modeled most geometry features, though spar locations were approximated due to limitations in the tool. Initial analysis failures arose from component overlaps, necessitating geometry modifications. The setup process was complicated by inputs being spread across multiple files, making it challenging to determine which parameters were active. Additionally, gaps in analysis methods for compressibility drag and buffet were identified. Future enhancements could include optimizing wing area using VSPAero with surrogate models to avoid longer run times and expanding aero data tables for better performance analysis. For a detailed discussion, refer to the full CLIN 006 report.

This activity has implications for the future of aircraft design and analysis within the aerospace community. The development of the Sugar Free model, along with its successful calibration and performance evaluation, underscores the potential of MBSA&E to enhance the design and optimization of future aircraft. The insights gained from this project will inform future developments in the MBSA&E framework, particularly in areas such as compressibility drag analysis and the optimization of aircraft geometry. By delivering an openly distributable model, the project provides a valuable resource for researchers and engineers in the MDAO community, enabling them to benchmark their own analyses against a reliable reference. Continued collaboration and refinement of the MBSA&E tools will further strengthen MBSA&E's utility in addressing the challenges of modern aerospace engineering.

## Future Work

Continued progress of the technical solutions developed under the MBSA&E program is critical for ensuring their lasting impact. The funding provided under MBSA&E enabled the identification and development of these solutions and their application to the MBSA&E use-case, but further development is needed to refine and expand these solutions and the documentation needed to increase their readiness levels and bring them to a wider audience with a larger set of use-cases.

Steps have been taken to publicize findings, encourage adoption, and capture additional funding, while also making the current software available for collaborative efforts. For those who want to contribute to the current solutions, three key projects have been hosted on public GitHub—the ADH, the Standard Evaluator, and the MBSE-ADH connector—each equipped with documentation, demonstrations, and tests to facilitate user engagement and understanding. Some of these developments have plans to be integrated into Boeing's internal processes. In one example, the Standard Evaluator will be implemented as the main interface to external applications in Boeing Design Explorer's codebase, in another it will be incorporated into an application within Boeing Commercial Aircraft (BCA). Additionally, the model sharing processes developed under CLINs 004 and 005 have been brought back into BCA and are expanding the use cases and underpinning methodology of BCA's pathfinder with suppliers like Collins. Looking ahead, there are plans to present six Boeing papers at the SCITECH 2026 conference, helping to disseminate knowledge and insights gained from the project to the wider public. Ongoing discussions, both internally and externally with organizations such as the Air Force Research Laboratory (AFRL), will continue to drive innovation and improvement in the MBSA&E framework and its Phase 1 support contract development to continue to push for industry-wide impact.

Contributions and additional ideas from NASA and the wider community are always welcome to enhance these efforts to continue all or portions of this work.

## Conclusion

The MBSA&E technology areas encapsulate the challenges encountered by users of MBSA and MBSE across industry, academia, and government. By incorporating a wider focus point, the MBSA&E technology development areas have evolved to addressing industry-wide needs while still focusing on the near-term NASA requirement to support MBSA&E development and usage.

The project has successfully delivered several key software outputs, including the ADH, the Standard Evaluator, and the MBSE-ADH connector, all of which are available on public GitHub with documentation, demonstrations, and tests. Additionally, SysML models of the MBSA&E system have been developed, along with a comprehensive and narrow data sharing process that facilitates effective collaboration and information exchange between organizations. The modeling of a conventional commercial aircraft within the MBSA&E framework was developed and compared against Boeing models of the same aircraft to show confidence in the MBSA&E models and approach. The aircraft model used in this study is now available as a reference model for future MBSA&E benchmarking.

As the project continues to evolve, ongoing development and collaboration will create a lasting impact on NASA and potentially the aerospace industry, enhancing the efficiency and effectiveness of aircraft design and analysis processes. The commitment to addressing the needs of a diverse range of stakeholders ensures that the MBSA&E framework will remain relevant and valuable to NASA and others in the years to come.

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