Transforming Systems Engineering through Model-Centric Engineering

A013 Final Technical Report SERC-2020-TR-009

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Executive Summary

This is the final technical report of the Systems Engineering Research Center (SERC) research task WRT-1008. This research task (RT) addresses research needs extending prior efforts under RT-48/118/141/157/170/195 that informed us that Model-Centric Engineering (MCE) is in use and adoption seems to be accelerating. The expected capability of MCE and more broadly Digital Engineering (DE) can enable mission and system-based analysis and engineering that reduces the typical time by at least 25 percent from what is achieved today for large-scale air vehicle systems. The overarching time line from the start of the research until today is:

- 2013-2015: Global scan of most holistic approaches to MCE/DE
- 2015: NAVAIR leadership decides to move quickly to keep pace with other organizations that have adopted MCE by Transforming, not simply evolving, in order to perform effective oversight of primes that are using modern modeling methods for mission and system engineering
- 2016: NAVAIR leadership decides to accelerate the Systems Engineering Transformation (SET) based on a SET Framework concept
- 2017: Systematic planning develops six (6) Functional Areas, including SERC Research
- 2018: Phase 1 of Surrogate Pilot experiments complete with mission, systems and a model for the Request for Proposal (RFP) Response from Surrogate Contractor for Surrogate Pilot experiments resulting in:
    - Characterized SET Framework concept and approach to Model-based Acquisition
    - Provides an implementation and usages for an Authoritative Source of Truth (AST)
    - Demonstrated art-of-the-possible doing “everything” in models using new operational paradigm between government and industry in a Collaborative AST
    - Surrogate contractor RFP response refines mission and system models with detailed design and analysis information using multi-physics and discipline-specific models
    - Digital Signoffs for source selection evaluation directly in RFP response model
    - Phase 1 results and models provide evidence/examples of unclassified models being used to develop workforce development and training
- 2019: Phase 2 objectives to align surrogate pilot experiments with SET priorities:
    - Align Mission and System models with NAVAIR Systems Engineering Method (NAVSEM)
    - Outreach to industry to participate in Phase 2 experiments for other mission and system scenarios using an AST for government and industry collaboration
    - Investigations to transform Contract Data Requirements Lists (CDRLs) and Data Item Descriptions (DIDs) using Digital Signoffs in AST
    - Created Capability Based Test & Evaluation and Model-Based Testing Engineering modeling methods for Mission and System models
    - Refine Model-Centric SOW language
    - Investigate how to perform Airworthiness modeling for deep-dive in Surrogate Design (including competency-specific criteria)
    - Phase 2 results and models provide more evidence/examples of unclassified models being used to develop workforce development and training

We also supported additional efforts that evolved in 2019 and 2020, such as:

- Support for the Cyber Ontology Pilot and potentially broader roll-out of the cyber ontology for other programs
- Support for the Cross SYSCOM Mission Engineering Schemas
- Support the role of the Surrogate Contractor
- Support based on standardization of View and Viewpoints for the Naval Style Guide
- Investigating how Digital Signoffs can contribute to a new form of baselines
- Analysis correlating Digital Engineering Success Measure (DESM) Categories with lessons learned benefits observed during the NAVAIR Surrogate Pilot
- Investigating developing Cost Model for surrogate experimental system called Skyzer
- Developed Model Curation example for Skyzer

The SET team continued roll-out aligned with six Functional Areas represented in Figure 1:

- SET Research (conducted by the SERC, and discussed in this report)
- Workforce & Culture
- Integrated Modeling Environment
- Process & Methods
- Policy, Contracts and Legal
- SET Enterprise Deployment (and Surrogate Pilot Experiments)

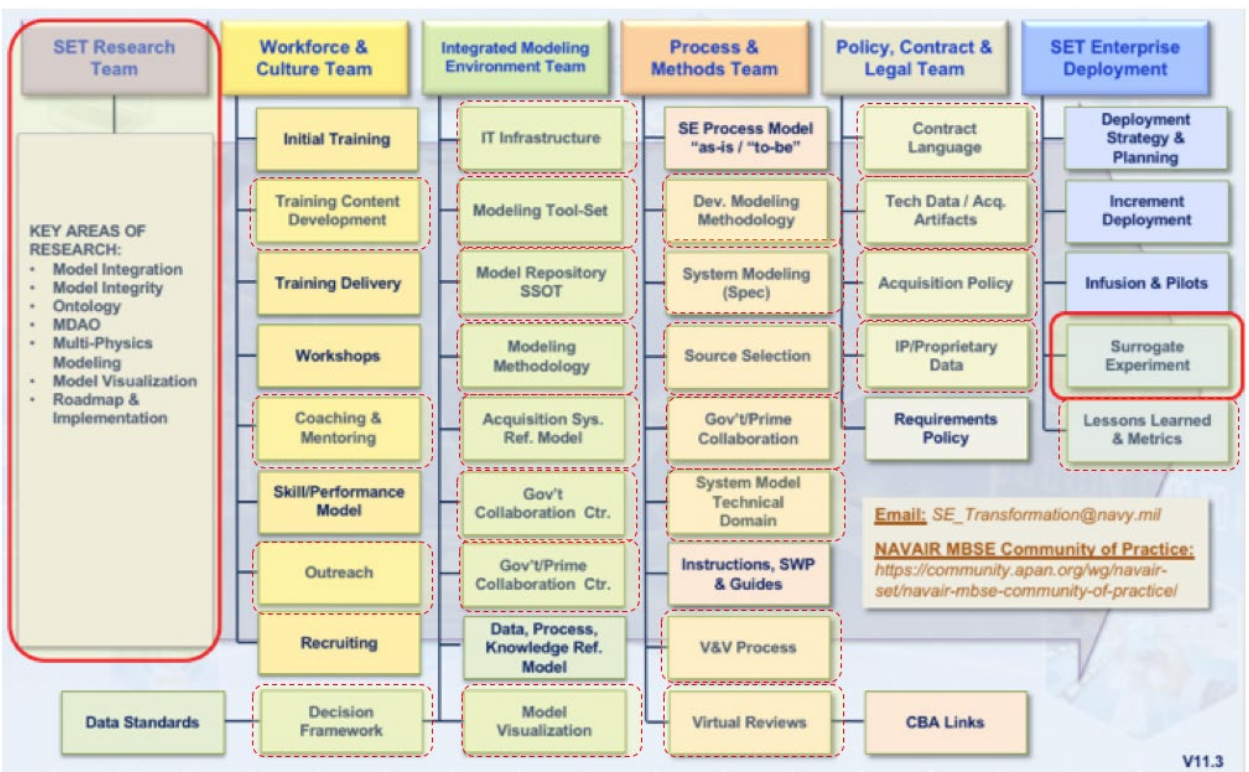

Figure 1. SET Functional Areas with Impacts on SET Research and Surrogate Pilot[1]

[1] This is not the most up-to-date SET Functional Area image, but this image has a NAVAIR Public Release 2018-194. Distribution Statement A – "Approved for public release; distribution is unlimited."

NAVAIR leadership decided to conduct multi-phase surrogate pilot experiments using evolving set of use cases to simulate the execution of the new SET Framework, shown in Figure 2 as part of the SET Enterprise Deployment. The broader impacts of this research to the other sub functions of SET is also reflected by the dash boxes shown in Figure 1. This research provides analyses into NAVAIR enterprise capability and builds on efforts for cross-domain model integration, model integrity, ontologies, semantic web technologies, multi-physics modeling, and model visualization that extend RT-157/RT-170/RT-195 research addressing evolving needs and priorities of SET.

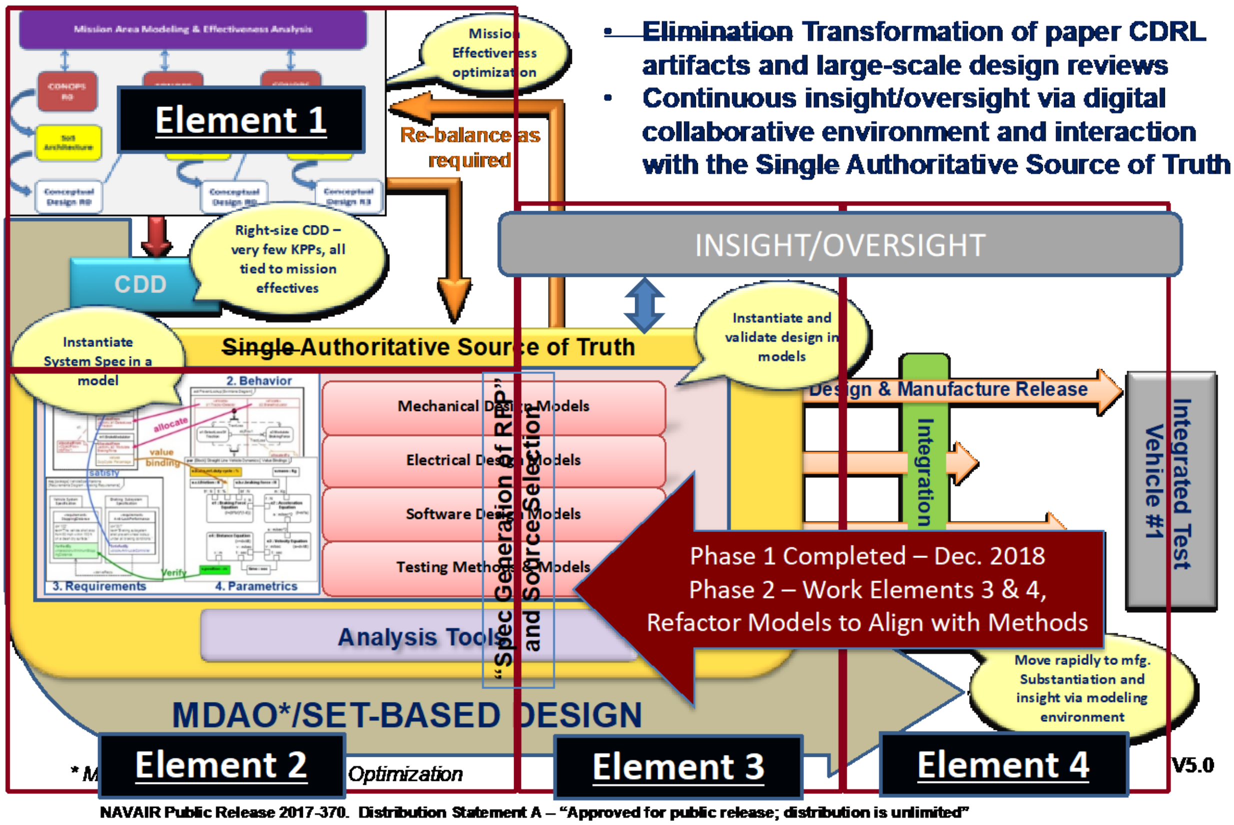

Figure 2. NAVAIR Systems Engineering Transformation Framework[2]

The Surrogate Pilot Experiments discussed in the RT-195 final technical report and this report provide examples demonstrating the art-of-the-possible for many of the cross-cutting objectives of DE; this includes integrating different model types with simulations, surrogates, systems and components at different levels of abstraction and fidelity and provide an enduring AST across disciplines throughout the lifecycle. The integrated perspectives provide cross-domain views for rapid system level analysis allowing engineers from various disciplines using dynamic models and surrogates to support continuous and often virtual verification and validation for trade space decisions in the face of changing mission needs.

[2] NAVAIR Public Release 2017-370. Distribution Statement A – "Approved for public release; distribution is unlimited"

The surrogate experiments have "modeled everything" in order to show that the concept was possible. The team has demonstrated the feasibility of using modeling methods at the mission, systems, and even using models for the request for proposal (RFP), statement of work, and source selection technical evaluation. The Phase 1 and Phase 2 surrogate contractor RFP response models link to the government mission and system models. The surrogate contractor RFP response models includes multi-physics analyses and early design models that illustrate the potential to have deep insight into the design of a proposed air vehicle system prior to contract award. The use of digital signoff directly in the model provides evidence of a new approach for transforming traditional Contract Data Requirement Lists (CDRLs), by documenting and linking digital signoffs with the evidence provided directly in the models.

The latest new model includes a Systems Engineering Technical and Management (SETM) plan model, which provides information beyond Gantt charts or an integrated master schedule and more importantly can link directly to the other mission and systems models in the AST.

The efforts are updating an experimental UAV system called Skyzer, from Phase 1, for a deep dive on search and rescue mission operational scenarios and extending the mission to include a Launch and Recovery, ship-based capability to support experiments for Capability-Based Test and Evaluation (CBT&E). The Skyzer system model is being extended with a landing gear deep dive to bring in Airworthiness use cases. This report blends progress and lessons learned during Phase 1 with knowledge gained during Phase 2 (not yet complete) of these surrogate pilot experiments, where the surrogate team developed:

- Surrogate Project/Planning Model that characterizes the objectives for the surrogate pilot and research
- Systems Engineering Technical and Management Plan model (new)
- Surrogate Mission Model for Skyzer updated to include Launch and Recovery system aligning now with the Integrated Capability Framework schemas
- Surrogate System Model for Skyzer now aligning with latest updates to NAVSEM
- Surrogate Acquisition Model for Skyzer to support Source Selection Evaluation and Estimation
- Surrogate Contractor System RFP model for Skyzer now to be updated by SERC research team and NAVAIR subject matter experts
- Surrogate Contractor Design models for Skyzer now to be updated by SERC research team and NAVAIR subject matter experts
  - Design models address aspects of multi-physics analysis and design
  - Links disciplines-specific design back to Surrogate Contractor system, which traces back to Government Skyzer System and Mission models
- View and Viewpoints for DocGen and other Libraries
  - Used in conjunction with DocGen to generate the specifications from the models based on stakeholder views
- Collaboration Environment for the Authoritative Source of Truth

The focus has been on learning about a new operational paradigm between government and industry in the execution the SET Framework, not necessarily on an air vehicle design. Many of the detailed facets from the surrogate pilot experiments are discussed in this report and are shared on the All Partners Network (APAN) to socialize these new operational concepts, and to solicit feedback from industry, government and academia. This includes more than 60 products that include: models, presentation, reports, videos, and links to the surrogate pilot autogenerated models at the SERC Integrated Modeling Environment hosted on amazon web service (AWS) (https://ime.sercuarc.org/alfresco/mmsapp/mms.html).

In April 2018, the three Navy system commands (SYSCOM) NAVAIR, NAVSEA and SPAWAR initiated a plan to build Navy and DoD interoperable ontologies. This effort is also jointly led by our RT-195 team and NAVAIR sponsors. The initial effort focused on using ontology architecture to scope the identified need, enforce interoperability, creating common terminology across domains, and be an enabler for MCE/DE. A second effort involves a Cyber Ontology Pilot, where our SERC team supported this effort developing a demonstration (video on APAN) for an approach to doing a Round Trip from a SysML model of a computer architecture to a representation that aligns with a Cyber Vulnerability ontology using our ontology platform called the Interoperability and Integration Framework (IoIF). Within IoIF we do some semantic reasoning which associates potential vulnerability with elements of the modeled computer architecture and sends the information back in SysML associating the vulnerability with the elements of the system model architecture. This research supports additional facets of the SET Transformation, which are discussed in this report.

These research results are continually shared with both government and industry in order to share results on the art-of-the-possible and provide industry with the opportunity to make constructive comments on representation and content that will likely be provided as "System Model(s)" as Government Furnished Information (GF)I as part of future solicitations such as Request for Information (RFI) or Request for Proposals (RFPs).

The strategic plans of SET are forging ahead for focus on implementation. WRT-1008 has support from research collaborators from Georgia Institute of Technology, Massachusetts Institute of Technologies, University of Maryland and Georgetown. This report blends RT-195-related accomplishments into this report to document the ongoing progress in support of the NAVAIR SET. We are also working collaboratively with US Army Combat Capabilities Development Command Armaments Center (CCDC-AC) in Picatinny, NJ under RT-168 and the follow-on SERC research task ART-002, and some of the results are from synergies derived from that research such as IoIF.

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PART I: RESEARCH TASK OVERVIEW

Part I of this report provides a historical context and an overview of this evolving research task, including the surrogate pilot experiments and cyber security ontology pilot research. This report sets the context for the needed research as defined and evolved by our sponsor, as well as the objectives, scope and organization of this report. Part I also provides a summary of the current set of research use cases, our Phase 1 & 2 surrogate pilot efforts, status, events, demonstrations, deliverables, models, prototype tools and recommendations based on our increased understanding of the research objectives. Part II of this report contains sections providing additional details for each of the research use cases.

1 INTRODUCTION

In 2013, the Naval Air Systems Command (NAVAIR) at the Naval Air Station, Patuxent River, Maryland initiated research into a Vision held by NAVAIR's leadership to assess the technical feasibility of a radical transformation through a more holistic model-centric system engineering (MCSE) approach. The expected capability of such an approach would enable mission-based analysis and engineering that reduces the typical time by at least 25 percent from what was achieved at that time for large-scale air vehicle systems using a traditional document-centric approach. The research need included the evaluation of emerging system design through computer (i.e., digital) models, which has been extended to factor in mission engineering to consider ever evolving threats.

Through Systems Engineering Research Center (SERC) research tasks (RT-48, 118, 141, 157, 170, 195) starting in August 2013 there was considerable emphasis on understanding the state-of-the-art through discussions with industry, government and academia [25] [27] [34] [41]. The team, comprised of both NAVAIR and SERC researchers, initially conducted over 30 discussions, including 21 on site, as well as several follow-up discussions on some of the identified challenge areas and approaches for a new operational paradigm between government and industry.

In 2015, the NAVAIR leadership concluded that they must move quickly to keep pace with the other organizations that have adopted MCE as the pace of evolution is accelerating enabled by rapidly evolving technologies. NAVAIR made the decision to press forward with a Systems Engineering Transformation (SET). In March of 2016, there was a Change of Command at AIR 4.0 (Research and Engineering) and NAVAIR leadership decided to accelerate the SET. Our research sponsor, Mr. David Cohen proposed a new operational paradigm referred to as the SE Transformation Framework that has evolved into the concept depicted by Figure 2. The research efforts starting in 2017 under RT-170/195 developed a surrogate pilot concept to assess and refine the execution of the SET Framework through a series of experiments conducted as evolving pilot projects. The emphasis was on a new operational paradigm to mission and systems engineering, analysis and model-based acquisition, which would be led by NAVAIR with collaborative design efforts led by industry. We participated with our sponsors in more industry meetings to assist in communicating and clarifying these concepts for a new type of collaboration, and to assess the impacts on the NAVAIR enterprise, from both a technical and socio-technical perspective. Many objectives for assessment and refinement of the SET

Framework are characterized as objectives and captured as part of a Surrogate Pilot Project plan and model that is being traced to experiment models, demonstrations, results and lessons learned documented in the RT-195 final technical report [25].

1.1 Systems Engineering Transformation Framework

As articulated by our sponsor, the concept of the new SET Framework for transforming from a document-centric process with monolithic reviews to an event-driven model-centric approach involves, but is not limited to:

- A concept for collaborative involvement between Government and Industry to assess mission and System of Systems (SoS) capability analyses, where NAVAIR has the lead to:
    - Involve industry in SoS capabilities assessments during mission-level analysis (to the degree possible)
    - Iteratively perform trade space analyses of the mission capabilities using approaches such as Multidisciplinary Design, Analysis and Optimization (MDAO) as means to develop and verify a model-based specification
    - Synthesize an engineering concept system model characterized as a model-centric specification and associated contractual mechanism based on models or associated formalism
- At the contractual boundaries, industry will lead a process to satisfy the conceptual model addressing the Key Performance Parameters (KPPs), with particular focus on Performance, Availability, Affordability, and Airworthiness to create an Initial Balanced Design
    - Industry too applies MDAO at the system and subsystem level
    - There is a potential need to iterate back to re-balance the needs if the trade space analyses of the solution/system for the program of record (POR) cannot achieve mission-level objectives
    - All requirements are tradeable if they do not add value to the mission-level KPPs
    - These are asynchronous activities in creating an Initial Balanced Design
    - Government and Industry must work together to assess “digital evidence” and “production feasibility”

Another SET objective for this new operational paradigm is to replace large-scale document-centric reviews such as Systems Requirements Review (SRR), System Functional Review (SFR), Preliminary Design Review (PDR), etc. with continual event-driven reviews using objective or subjective evaluation based on model-centric information. Some initial surrogate pilot demonstrations illustrated a potential approach to replace large-scale document-centric reviews with continual event-driven reviews directly within the model using objective and subjective evaluation based on model-centric information and digital signoffs, where a digital signoff is linked to the model evidence satisfying some criteria typically required at a formal review or as defined in a CDRL. A collaborative AST is being used in the surrogate pilot and is playing a key role with the continuous asynchronous reviews. NAVAIR needs some type of decision framework to assess evolving design maturity with considerations of value to the KPPs, risk and uncertainty. These surrogate pilot experiments factor in these and other types of evolving objectives.

Early in 2017, the SET team developed the plan for rolling-out SET to NAVAIR, which defined six major Functional Areas as represented in Figure 1 that includes:

- SET Research (conducted by the SERC, and discussed in this report)
- Workforce & Culture
- Integrated Modeling Environment
- Process & Methods
- Policy, Contracts and Legal
- SET Enterprise Deployment (and Surrogate Pilot Experiments, also discussed in this report)

These Functional Areas have other sub functions as part of the overall effort, as shown in Figure 1. The Surrogate Experiments are being conducted using multi-phase Surrogate Pilot use cases that are part of the SET Enterprise Deployment. The SET Research is being performed in the context of the surrogate experiments. The broader impacts of this research to the other sub functions of SET is also reflected by the dash boxes. Some research such as the cyber security ontology pilot aligns with the research use cases.

1.2 Surrogate Pilot Case Study

The SET Surrogate Experiments are elaborating mission and system analyses and requirements using a hypothetical system called Skyzer. Skyzer has a Concept of Operations (CONOPs) for an UAV that provides humanitarian maritime support for search and rescue use cases as reflected in Figure 3. This use case has been extended in Phase 2 to include a ship-based Launch and Recovery system in order to create another capability, where we can research methods for Capability-Based Test and Evaluation (CBT&E), based on a NAVAIR modeling approach for Mission-Based Test Design (MBTD). This particular case study will also include a deep dive related to the landing gear in order to examine some scenarios for modeling information related to Airworthiness. Phase 1 had a very narrow scope in order to focus on the execution through the SET Framework Elements (1-4) as quickly as possible. The scope of the UAV design as requested by our sponsor included multi-physics design considerations that are based on Computational Fluid Dynamics (CFD), topology optimization, structural analysis, weight and vehicle packaging. The surrogate pilot team officially released the RFP in the form of models concluding the Phase 1 efforts. Performance constraints such as speed of 170 knots forced the design to be something other than a traditional helicopter and ultimately a design similar to the Bell Eagle Eye was proposed in the surrogate contractor RFP response models, which was evaluated in a surrogate source selection by the government team. The efforts moving forward are to align efforts with the SET priorities the Phase 2 use cases, which are summarized in this report.

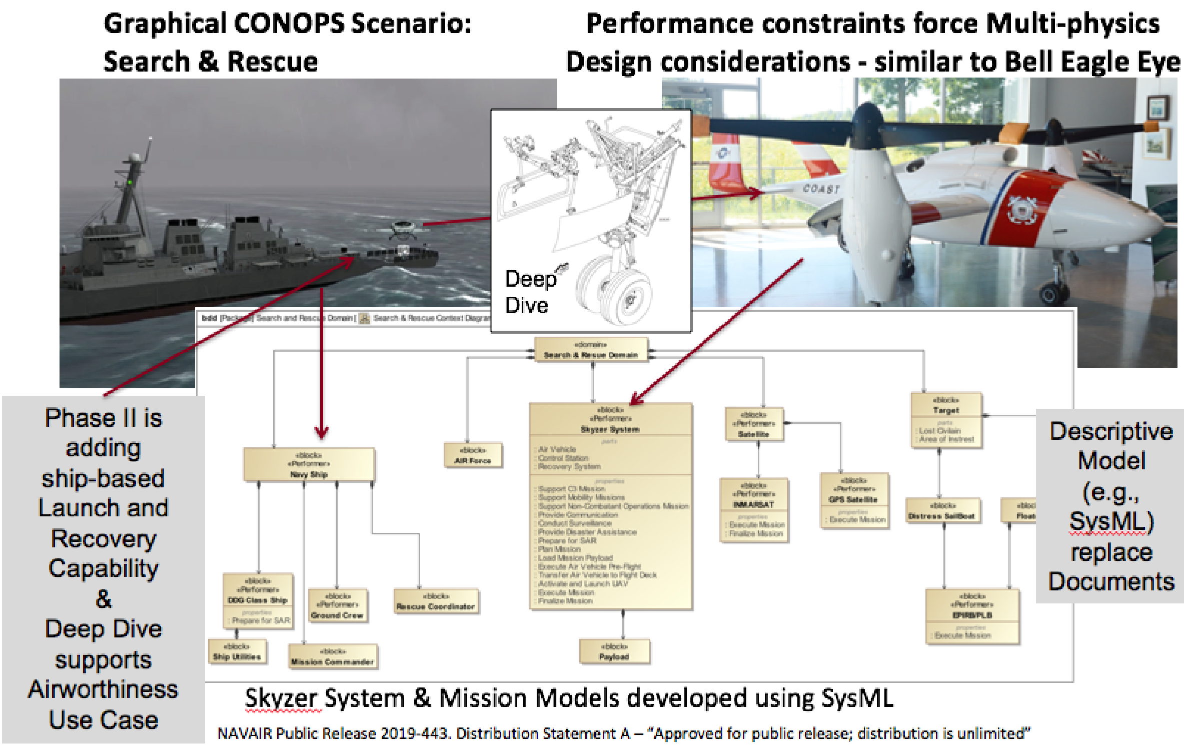

Figure 3. Graphical CONOPS for Skyzer UAV[3]

NAVAIR has been reaching out to industry to engage in discussions about this new operational paradigm to acquisition based on the SET Framework since 2015. Industry has responded favorably about this change of direction. We continually reach out and present at conferences [24], workshops, and using virtual meetings [24] [117][119]. For example, at the two-day Model-based Ecosystem breakout session at INCOSE in January 2019, we briefed details about our surrogate experiments and use of OpenMBEE [152] as a foundational element of our AST and found out that Boeing has 40 programs and over 200 users using OpenMBEE, and Lockheed Martin also has many programs but plans to be part of the open-source community to advance OpenMBEE by developing the next version of the Model Management System (MMS) component of OpenMBEE. Both Boeing and Lockheed Martin consider OpenMBEE as an essential part of their MBSE Ecosystem, and reflecting on that topic Lockheed Martin is leading the next version of MMS.

Much of the weekly details associated with the Surrogate Pilot experiments, models, generated specifications, results, and lessons learned are shared with industry and government on the All Partners Network (APAN.org). APAN was setup and is managed by Defense Information Services Agency (DISA). DoD organizations can request their own groups, and NAVAIR has several groups for the SET. Some are internal for NAVAIR people and their contractors, but the Surrogate Pilot Group (https://community.apan.org/wg/navair-set/set-surrogate-pilot/) is open to the public with the proper registration in APAN. The Surrogate Pilot group captures weekly progress for the SET Surrogate Pilot in the Discussion threads, often with videos. We are sharing this with Industry

[3] NAVAIR Public Release 2019-443. Distribution Statement A – "Approved for public release; distribution is unlimited"

and Government to solicit feedback and recommendations on the way we are proceeding in this pilot. Many of the lessons learned from this surrogate pilot are reflected in this report. Other results related to the research and some Phase 2 results are uploaded to the APAN NAVAIR Research Group (https://community.apan.org/wg/navair-set/research/), which has more limited access to government personnel and government contractors. The SERC team has produced over 60 products such as: SERC reports, models, generated specification, view editor reports, videos and demonstrations, which can be found on APAN.

1.3 Objectives

The objectives for the research factor in NAVAIR's evolving needs and priorities and look at the cross-cutting relationships associated with the research needs, as shown in Figure 4. We have been successful at the initial use and evolving deployments of OpenMBEE as the experimental integrated modeling environment (IME) (or better characterized as the Digital Engineering Environment [DEE]) for an AST, which provide some unique capabilities such as DocGen and the View Editor, which allowed non-SysML Subject Matter Experts (SMEs) to interact and modify model information from the View Editor (e.g., Digital Signoffs). The research needs expand on the prior research and include specific focus on technological aspects to address the prior research gaps in the context of the SET Framework. We summarize and organize in a manner used on RT-168/170/195 and ART-002 as use cases (UC) that cut across the evolving case studies as it relates to Figure 4.

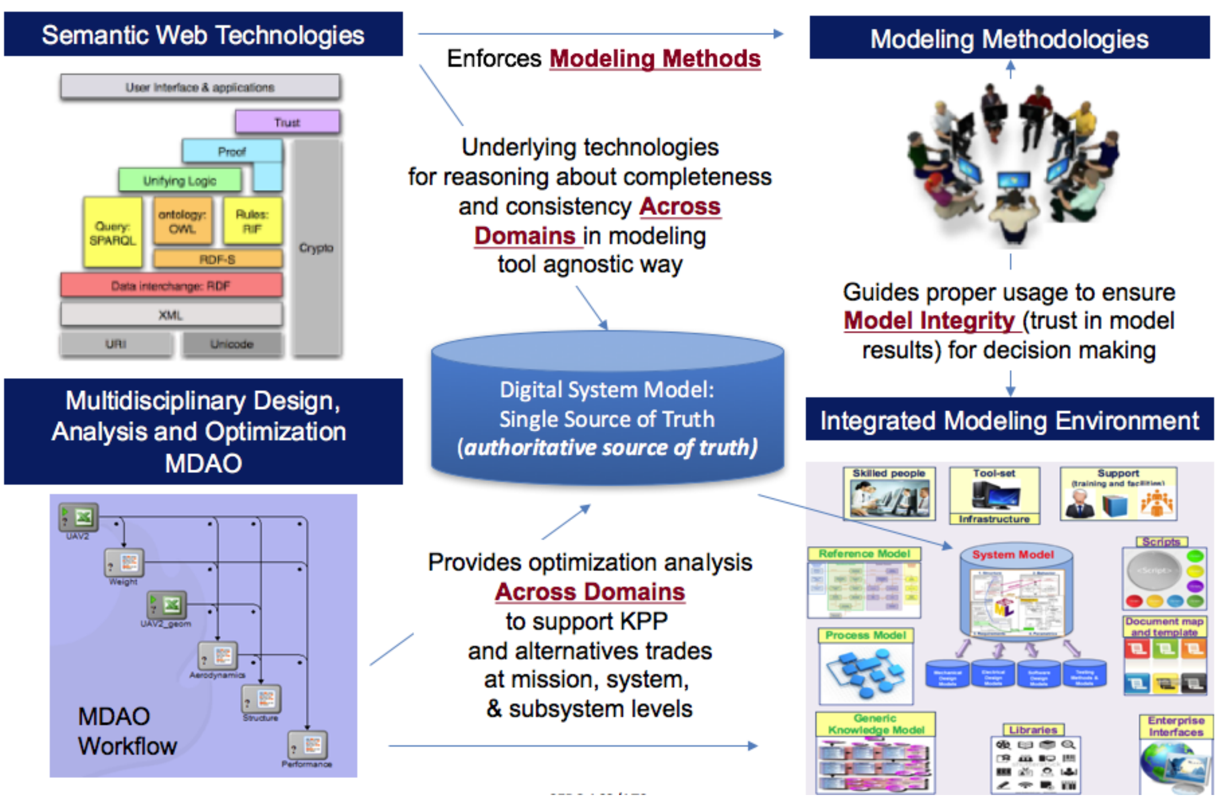

Figure 4. Cross-cutting Relationships of Research Needs

The use cases are discussed in more detail in Part II of this report, and include, but are not limited to:

- UC00: Ontologies and semantic web technologies for reasoning about completeness and consistency across cross-domain model to achieve the notion of model integration through interoperability are enablers for an authoritative source of truth, tool-agnostic approaches to methodology enforcement and conformance that also support model integrity
  - With our CCDC-AC sponsors, we have demonstrated the use of ontologies for Army relevant domains such as munitions and armament, as well as tool and application ontologies for linking cross-domain information from multi-physics tools
  - We have developed an integration with Multidisciplinary Design, Analysis and Optimization tools with a Decision Ontology [76]
  - We have leveraged our Interoperability and Integration Framework (IoIF), which is a platform to integrate ontologies and analyses with descriptive models as demonstration by the cyber security ontology pilot (video on APAN in Research Group)
  - Development of an architectural construct related to the Navy and DoD Ontology Suite (see Appendix); this was developed as a result of a Navy and DoD Ontology Workshop
  - Demonstration using Knowledge Representation with Ontologies and Semantic Web Technologies to Promote Augmented and Artificial Intelligence in Systems Engineering [94]
- UC01: Multidisciplinary Design, Analysis and Optimization (MDAO) at the mission, system and subsystem levels, which provides a means for continual assessment of trades (i.e., analysis of alternatives) to support Key Performance Parameter (KPP) assessment; this also relates to representations within system models
  - Applied to the Surrogate Pilot for Phase 1 and 2, for more elaborate uses of MDAO see CCDC efforts that are relevant to NAVAIR [30]
- UC02: Integrated Modeling Environment (IME) in the context of the workflows, which has implications on both technologies and workforce development
  - We are using an instantiation of NASA/JPL OpenMBEE as the experimental integrated modeling environment (also referred to as the Digital Engineering Environment [DEE]) formalization of the AST, in the context of NAVAIR, but also in the context of one or more industry contractors
  - Model visualization from multiple perspectives including, but not limited to enabling different views relevant to different stakeholder (or due to particular access), reducing complexity, and analytical analysis
  - Methods for model modularization to ensure separation of concerns, classification, acquisition
  - Methods for creating and organizing Enterprise, Process, and Reference models
  - Understanding the operational paradigm between industry and government in the context of the SET Framework through MCE

  - Workflow analysis and representation relative to a program instantiation of tool suites from the IME
- UC03: Methodology for all of these technologies in the context of the IME workflows, such as:
  - Methods for system model supporting the NAVAIR Systems Engineering Method (NAVSEM)
  - Methods for mission model levering Mission Engineering schemas associated with the Navy Integrated Capability Framework
  - Methods for MDAO modeling
  - Methods for modularizing models to support constraints needed for developing an authoritative source of truth, which relates to many other use cases
  - Methods for model management
  - Methods for representing and organizing reference models, process models, discipline-specific models
  - Methods for developing and tracing capabilities measure to KPPs
  - Alternative approaches to improve modeling methods, which is fundamental to ensuring model integrity (strong relationships to UC02)
- UC04: Multi-physics modeling, which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty
- UC05: Representation to formalize research under RT-176 in models to support requirement verification and validation [87] (this research task has completed)
- UC06: Experimentation and learning all prior defined research topics in the execution of the SET through unclassified pilot programs; this includes alignment with the SET Tasking and other research use cases with evolving pilot case studies (as described below)
  - A significant part of the summary for the experiments is provided in Section 2 rather than in Part II of this report, which discusses alignment with NAVSEM and the use of Digital Signoffs
- UC07: Research into Enterprise Transformation to support governance and workforce development
  - Applying Model Curation Criteria to the Skyzer Surrogate Pilot use case

All of these use cases investigate continuing synergistic research to the extent possible with the US Army CCDC-AC, Semantic Technologies for Systems Engineering, and other potential SERC research that is aligned with the principles and concepts for the Systems Engineering Transformation as well as the ODASD(SE) Digital Engineering Strategy with increased focus on DE implementation examples. This includes WRT-1001 Digital Engineering Metrics, WRT-1006 Digital Engineering Competencies, and a DoD effort on Digital Engineering Policy.

1.4 Scope

The scope for the research aligns the objectives as characterized by the use cases in Section 1.3. As reflected in Figure 1, the scope of these research task areas has expanded and continues to realign to the evolving prioritizes of the SET in the context of the surrogate pilot experiments, which have produced models, demonstrations and videos for NAVAIR-relevant examples that can help inform the workforce and other stakeholders. The objectives of the surrogate pilot involve understanding the methods, models, tools, collaboration technologies and process to execute, assess and refine the SET Framework in order to more fully characterize the Elements of SET. All models have been automatically generated from the source SysML model content (e.g., "document") and can be found and viewed on the SERC IME hosted by Amazon Web Services (AWS) server. There are two perspectives as reflected by Figure 5:

1. Use cases about the objectives for the Skyzer experiments and associated environments:
    - Surrogate Pilot Use Cases characterize objectives for understanding the execution of the SET Framework, and for FY20 the transition from Element 1 & 2, to Element 3 & 4 (see RT-195 Final Technical Report [25])
    - Collaboration in an AST Use Cases
        - The government side of the AST is being developed using the NASA/JPL OpenMBEE [152] and commercial modeling tools that is hosted on AWS server
        - The surrogate contractor side of the AST must be "integrated" with the government side of the AST
2. Use cases for the Skyzer Experimental System using AST, which involves the development of evolving models for (OpenMBEE DocGen are viewable on AWS for all models):
    - Surrogate Project/Planning Model
        - Characterizes the objectives for the surrogate pilot and research – stopped after Phase 1
    - Project Planning Model for Skyzer
        - New for Phase 2
        - This new model is inspired by our research with CCDC-AC where we formalized the Systems Engineering Technical and Management (SETM) Plan in a model which includes:
            - Project Overview
            - Personnel
            - Organizations
            - Assignments
            - SET Priorities
            - Deliverables
            - Skyzer Case Study
            - Resources
            - Abbreviations
            - Project Metrics
    - Mission Model for Search and Rescue scenarios
        - Update to investigate formalization based on the Integrated Capability Framework Mission Engineering schema
        - Parts of mission model provided as GFI
        - Primarily associated with Element 1 of SET Framework

- System Model for Skyzer
  - Update to be characterized in NAVSEM Process Steps 3 & 4
  - Parts of system model provided as GFI
  - Primarily associated with Element 2 of the SET Framework, but has been extended for a landing gear deep dive as a case study for Element 3
  - RFP release of Views generated using OpenMBEE DocGen are viewable on AWS
- System Model for the Launch and Recovery
- Acquisition Model Skyzer
  - Primarily associated with boundary between Element 2 and Element 3 of the SET Framework
  - Models for the Statement of Work (SOW)
  - Provide criteria for source selection evaluation as model and provided to surrogate contractor as GFI
  - Source selection technical evaluation criteria
  - RFP release of Views generated using OpenMBEE DocGen are viewable on AWS
- Surrogate Contractor System model for Skyzer
  - Provided as a SysML model as the RFP response
  - Aligned with NAVSEM Process Step 5
  - Model objectives provided hyperlinks to multi-physics models and analyses for discipline-specific tools (e.g., computation fluid dynamics)
  - Surrogate contractor to assess, refine and extend GFI system model
  - Primarily associated with Element 3 of the SET Framework
- Surrogate Contractor Design models for Skyzer
  - Design models addresses aspects of multi-physics
  - Primarily associated with Element 3 and Element 4 of the SET Framework, which were not started during Phase 1
  - Phase 2 providing deep dive associated with Landing Gear and use of ModelCenter for MDAO tradespace analysis
- Capability-Based Test & Evaluation/Mission-Based Test Design Model
- View and Viewpoints for DocGen and other Libraries

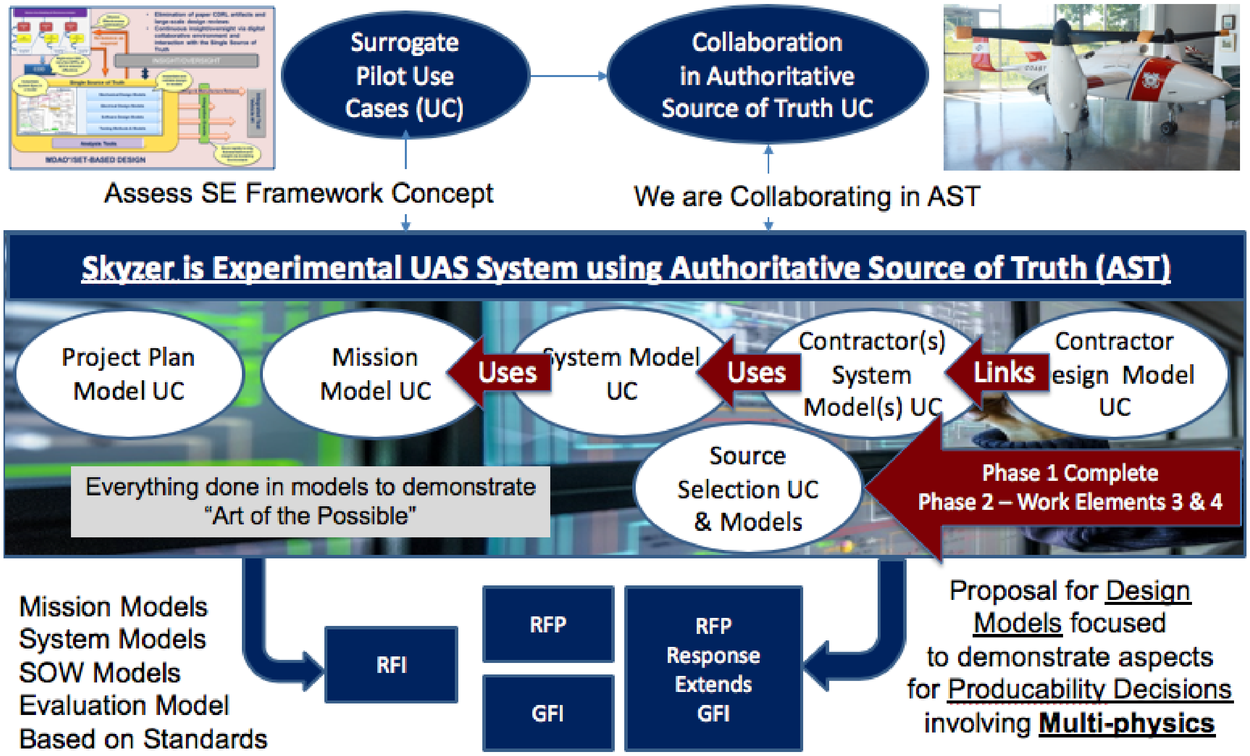

Figure 5. Use Cases for Surrogate Pilot and Experimental System (Skyzer)[4]

As discussed in the lessons learned of the RT-195 Final Technical Report [25] the surrogate pilot experiment did not make much progress until we deployed our DEE (aka IME by NAVAIR) for the government elements that are part of a broader AST as shown in Figure 6. The capabilities support modeling, the AST, model management, collaboration through web-based browser to view the information generated from the model. This is an important capability and it is one of the six SET Functional Areas as shown in Figure 1. For NAVAIR programs this is more difficult due to the needs for managing security and access to potentially classified information. For the surrogate pilot, we wanted to use an environment to demonstrate the art-of-the-possible, and therefore we selected OpenMBEE. Our research team developed several Docker configurations for script-based deployment of OpenMBEE that enables the use of the Model Development Kit/DocGen in conjunction with the Model Management System (MMS) and View Editor. The IME for the AST as shown below includes:

- Docker mechanism for easy deployment of OpenMBEE
  - Docker provides a mechanism to install OpenMBEE with a single script, and this has allowed us to deploy OpenMBEE on AWS, at Stevens, at Georgia Tech, and at the Surrogate Contractor site; this approach allows us to not only provide models at GFI, but also provide the exact environment that we used to construct the GFI
  - Deployed mission models, system model, SOW, and evaluation model views to the AWS OpenMBEE MMS

[4] NAVAIR Public Release 2018-194. Distribution Statement A – "Approved for public release; distribution is unlimited"

    - Expected to be upgraded using Kubernetes in 2020
- Developed the information for the Request for Proposal (RFP), including:
    - Skyzer Mission model
    - Skyzer Capability-Based Test and Evaluation (CBT&E)/Mission-Based Test Design (MBTD) model
    - Skyzer System model
    - Skyzer Mission views created by OpenMBEE Model Development Kit (MDK)/DocGen
    - Skyzer System views created by DocGen
    - Skyzer Statement of Work (SOW)
    - Source Selection evaluation model
    - Source Selection estimation model
    - Source Selection evaluation views created by DocGen
    - Surrogate Contractor created models for the RFP response, which provided links to other type of discipline-specific models (e.g., Computational Fluid Dynamics [CFD])
    - Matlab/Simulink/ModelCenter models for the landing gear tradespace analysis
- All models stored in the Teamwork Cloud, which is synchronized with MMS
- Produce analysis comparing the Cameo Collaborator with the View Editor in producing DocGen auto-generated documents from View and Viewpoints
    - Cameo Collaborator does support the concept of View and Viewpoints, but they have to be re-created
    - Cameo Collaborator does support key feature of Digital Signoff
    - Cameo Collaborator does NOT support printing of a generated specification, which is still needed from a contracts point-of-view
- Any NoMagic Client (e.g., MagicDraw or Cameo System Modeler) can access the models if the user has the appropriate access rights

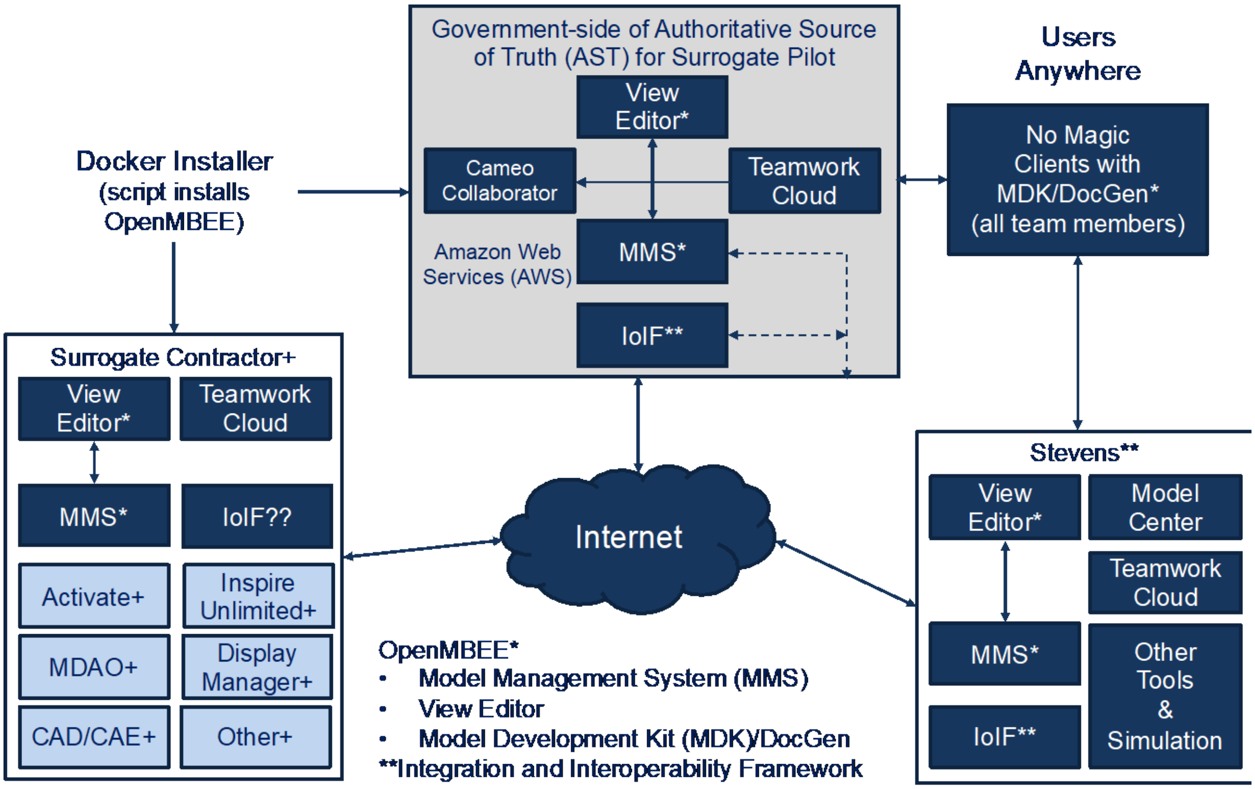

Figure 6. Digital Engineering Environment (DEE) Elements of Authoritative Source of Truth[5]

As shown in Figure 7, we developed operational models and user capabilities, which are primarily defined in the Skyzer Mission Model. The mission model(s) provides inputs that are captured in an "Initial System Model" that characterizes the "requirements" in the Skyzer System Model. The Phase 1 & 2 Skyzer System Model was developed by our Georgia Tech collaborator, in conjunction with subject matter experts from NAVAIR. These Skyzer Mission and System models provide the basis for the RFP that was refined and elaborated by the surrogate contractors during source selection into a "Final System Model" for Phase 1. The SERC research team developed the contractor model during Phase 2 due to a short of resources. We are simulating this concept during the pilots. Notionally, Figure 7 shows the related alignment to the four Elements 1, 2, 3, & 4 with the focus of formalizing the use of models. OpenMBEE DocGen also generated stakeholder-relevant views [69] of the Skyzer SETM, Mission, System, SOW, CBT&E/MBTD and Technical Evaluation criteria and have been synchronized to the OpenMBEE environment on an AWS server that is shared with the entire team, and is also viewable to the public using a guest account.

[5] NAVAIR Public Release 2019-443. Distribution Statement A – "Approved for public release; distribution is unlimited"

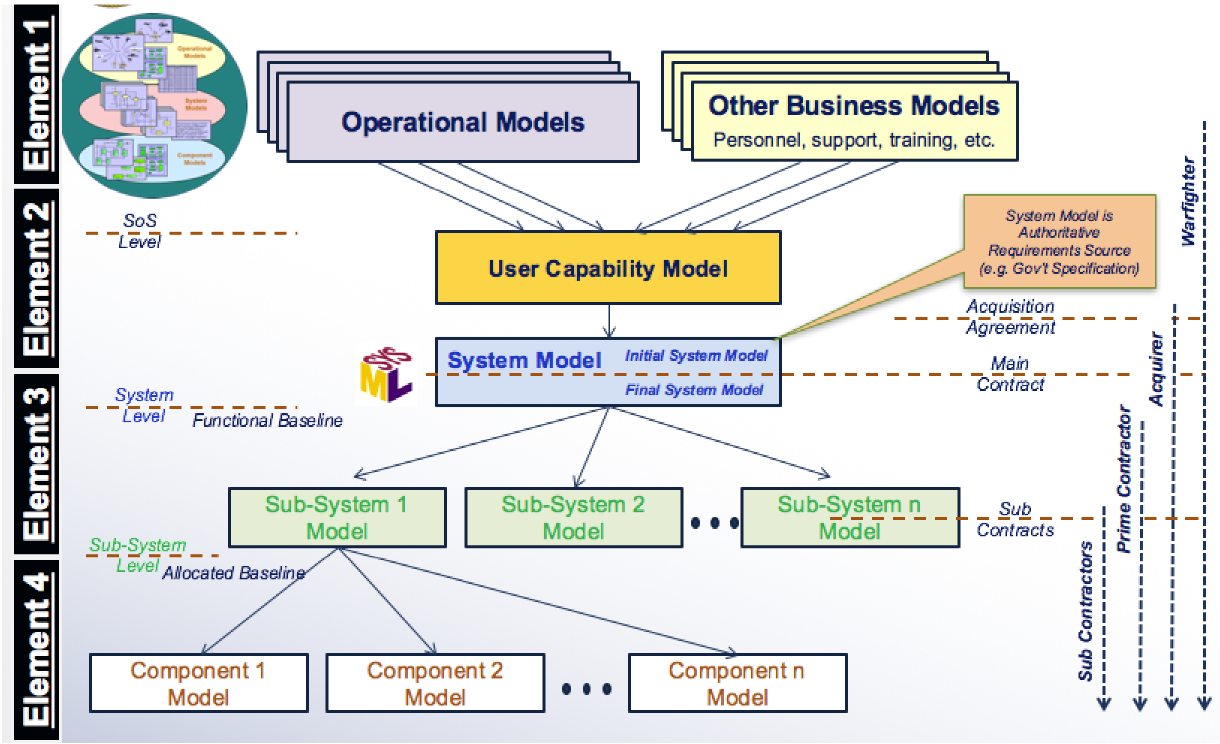

Figure 7. Characterizes the Boundary of Models between Government and Industry[6]

An emphasis of the research is to use deep-dive experiment of threads in evolving pilot project scenarios to create reference models as examples to exemplify best practice methods that can then be used for train material for workforce development; this is already underway. We demonstrated concepts that have never been attempted by NAVAIR. In the Phase 1 we tried to model everything primarily to show it could be done, to provide examples, and to explain the benefits, issues or challenges associated with the development of such models, and continue that during Phase 2. We found the development of the Technical Evaluation Criteria (normally Section L of the SOW) to be extremely valuable, because it eliminated many typical document-based requirements about form, and instead focused on functional information that is captured directly in models that should be provided by responders to the RFP as models. This also allowed us to use DocGen, which also demonstrated how valuable it is to have a web-based editable version of the model for reviews and commentary by subject matter experts not versed in a SysML authoring tool.

There are many questions that surfaced related to the execution of the SET Framework in Phase 1 and this continues in Phase 2. Some of the early challenges were related to incompletenesses in the definition of the modeling methods work products (i.e., artifacts) for the NAVSEM process steps. We have developed an initial set of mission, system, and contractor RFP models that align with the NAVSEM Process Steps 1, 2, 3, 4 & 5. The following is a high-level list of objectives, with some information on status, and additional needs for Phase 2, which continue to be realigned based on changes in the planning and resources at NAVAIR. The highest priority objectives

[6] NAVAIR Public Release 2017-892. Distribution Statement A – "Approved for public release; distribution is unlimited"

involve aligning with the evolving SET Priorities for Phase 2 (FY19 and FY20), which include but are not limited to objectives such as:

- Lead surrogate pilot experiments including formulating use cases to continue assessment and refinement of SET Framework, which are currently focused on:
  - Aircraft landing on ship
  - Aircraft grabbed by L&R
- Transform CDRLs and Data Item Descriptions (DIDs) and use Digital Signoffs in AST
- Align Mission model with NAVSEM Process Steps 1 & 2, but are looking at the ICF and Mission Engineering schemas
- Align System models with NAVSEM (method)
  - This involves formalizing the work products to be produced by the NAVSEM Process Steps 3 & 4
  - Created the View and Viewpoint hierarchy for the formalized work products and added Digital Signoffs using different types of templates for using one or more approvers (e.g., Chief Engineering vs. Subject Matter Expert)
- Align contractor System model for the RFP and beyond using NAVSEM Process Step 5
- Demonstrate MDAO using contractor design model for landing gear deep dive, currently modeled in Matlab/Simulink with MDAO using ModelCenter to provide for tradespace analysis example
- Demonstrate methods for modularizing model using Project Usage mechanism, and corresponding Views that are used by DocGen to “generate specification” and for sharing digital models while addressing access needs such as security
- Leverage created models that comply with modeling methods to provide unclassified examples and to support training and workforce development
- Created a CBT&E/MBTD model associated with some of the deep dive elements of the landing gear as it relates to capability of the UAV landing gear and the ship-based Launch and Recovery system
  - Bring in V&V criteria, which is likely to align with needed analyses, and hopefully include the CBT&E and MBTD models; we may be able to leverage Launch and Recovery as another capability
- Investigate how to perform Airworthiness modeling for deep-dive in Surrogate Design (including competency-specific criteria) related to the UAV landing gear and ship-based launch and recovery system
- Focus on analyses needed for decision making to mature a design for Elements 3 & 4
- Simulating “Execution” of Oversight / Insight in AST per SET Framework and capturing abstractions of recommended or best practice processes in potentially heterogeneous environments (Elements 3 & 4)
  - Ongoing after simulation of contract award following Source Selection
  - Created digital signoff model element as part of the source selection technical evaluation criteria, which is embedded within the surrogate contractor RFP response
- Developing and assessing the use of objective measures for evaluating evolving design maturity, while assessing the reduction of risk and uncertainty

- Created digital signoff for System Engineering Technical Review criteria as means to provide a transformation from Contract Data Requirements Lists (CDRLs), which are embedded in the contractor models for later milestone events such as Critical Design Review (CDR)
- Investigate the use of digital signoffs as a way to align with traditional "baselines"
- Ongoing after simulation of contract award following Source Selection

There have been other objectives that have been started, but due to lack of SME resources at NAVAIR, some remain on the secondary list of objectives, and include, but are not limited to:

- Refine Model-Centric SOW language and contract language that would be useful for programs requesting to start applying this type of DE approach to new programs
- Revisit early research concerns for formalizing Risk and Uncertainty measures
- Continue the model started on Reliability and Maintainability (R&M); this is a reference model, and we can show a specific instantiation for some elements in this model
- Simulating feedback back to mission engineering caused by specified objectives for unachievable KPP
- Simulating source selection and investigating if it is possible to use dynamic simulations and V&V as part of the source selection process and evaluation criteria
  - Developed an Evaluation Model that is GFI as a supplement to Section L of the SOW, which calculates using the Cameo Simulation Tool kit margins for the KPPs specified in the mission model
- Working with contracts/legal to get agreement on what a "specification" would or can be, while helping to understand potential needs to change acquisition policy
  - Developed example models for SOW and Technical Evaluation Criteria
  - Provide examples for model-based contracting and digital approaches to traditional concept of CDLRs prior to contract award
- Assessing how or if we can use automated means such as an ontological representation of the Systems Engineering Technical Review (SETR) guide and checklist that NAVAIR uses? And, how will we make recommendations for its evolution in the context of MCE
  - Part of Element 3 in Phase 1 briefly shows a few examples for how models can subsume SETR criteria using Digital Signoffs
- Use of Multidisciplinary Design, Analysis and Optimization (MDAO) on the Government side to apply MDAO early as part of Mission Needs analysis
- Include cost as part of digital signoff and "baseline" decision making

1.5 Collaborative Research Synergies

NAVAIR is also involved in synergistic collaborative efforts with CCDC-AC and the Digital Engineering (DE) Working Group led by the Office of Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE)). We are working to demonstrate implementation examples that align with the five DE Transformation goals [73] [216] that include:

- G1. Formalize the development, integration and use of models to inform enterprise and program decision making.

- G2. Provide an enduring authoritative source of truth.
- G3. Incorporate technological innovation to link digital models of the actual system with the physical system in the real world.
- G4. Establish a supporting infrastructure and environment to perform activities, collaborate and communicate across stakeholders.
- G5. Transform a culture and workforce that adopts and supports Digital Engineering (DE) across the lifecycle.

We are also fostering bi-directional sharing of research interests and results with our US Army CCDC-AC sponsors. We are collaborating in several MCE-related efforts to provide the opportunity to leverage and share with the Open Collaboration Group for MBSE and OpenMBEE [152], Semantic Technologies for Systems Engineering (ST4SE) initiative, which is now part of the INCOSE MBSE Patterns Working Group, DoD Digital Engineering Strategy, the Aerospace Industry Association (AIA) on Concept of Operations (CONOPS) for Government and Industry collaboration through MBSE [3], the National Defense Industry Association (NDIA) Modeling and Simulation & NDIA System Architecture groups and INCOSE who are coordinating working groups to investigate approaches for using Digital Models for competitive down select.

We have provided research updates to other organizations that reached out to us who are investigating similar MBSE-based transformations such as US Army Aberdeen, US Air Force research labs, and US Air Force Space and Missile System Center. We are also collaborating with SAIC who developed an ontology for the process aspects of the International Standards Organization (ISO) 15288 standard on systems engineering. This effort also created a collaboration with SBE Vision who has been funded by SAIC to develop a Semantic Data Broker technology that uses underlying ontologies to integrate data sources from different tools and technologies; it is similar to the IoIF, and is more complete for some different tools. We have a relationship with SBE Vision and plan to do further investigation later in 2020.

1.5.1 Summary Status of Accomplishments

A summary of the contributions includes:

- See spreadsheet of more than 60 products on APAN Research Group
- All updates on reports, presentations, models, generated model reports (DocGen) and Videos on APAN
- Attended NAVSEM Method Review
- Supported the Cross SYSCOM Mission Engineering Schema Summit
- Refactored the Skyzer Mission Model for the NAVSEM Process steps 1.0 and 2.0 that align with Element 2 (Government Mission Model) in order to be able to generate the specification
- Developed View and Viewpoint hierarchy for the NAVSEM Process steps 3.0 and 4.0 that align with Element 2 (Government System Model) in order to be able to generate the specification
    - Added Digital Signoffs to models for Process steps 3.0 and 4.0
    - Created a video for performing Digital Signoffs (on APAN)

- Developed View and Viewpoint hierarchy for the NAVSEM Process step 5.0 that align with Element 3 (Contractor refinement of the Skyzer System Model) in order to be able to generate the specification
    - Creating an example multi-physics tradespace for the Skyzer landing gear
- Developed View and Viewpoint hierarchy for the Capability-Based Test and Evaluation/Mission-Based Test Design concept
- Cyber Ontology Pilot
- Aligning Skyzer System Model with NAVSEM – defining artifacts that align with the process steps
- Created View and Viewpoint for Launch and Recovery (L&R) System and used DocGen to generate the document, which resides and is visible using the View Editor in the Surrogate Pilot organization on Amazon Web Service (ASW)
    - This provides a characterization for the interaction from the Skyzer UAV to the ship L&R
    - It also demonstrates the use of some requirement profiles created by NAVAIR
- Created report on *Digital Engineering Measures Correlated to Digital Engineering Lessons Learn from Systems Engineering Transformation Pilot*
- Performed an assessment and comparison of the Cameo Collaborator in comparison to OpenMBEE/DocGen with need to support Digital Signoffs
    - Potentially more stable environment, easier setup and non-open source
    - Existing MDK viewpoints need to be recreated and adapted
        - Need for further investigation (e.g. custom tables) with simplified viewpoints
    - Existing view hierarchies might need adaption (changed top-level views)
    - Less editing capabilities than with View Editor
        - Potential editing of elements besides names, documentations and tag values
    - Signoff mechanism needs adaption, but can function similarly
        - Stereotype assigned to signed off element instead of stereotyped dependency
        - Different tracking of changes without MMS database (No IoIF integration)
    - Improved (and graphical) commenting and resolving of comments
    - No generation of conventional document (e.g. adding text)
- Surrogate Pilot weekly meetings discuss use cases to realign Surrogate Pilot to NAVAIR SET priorities
    - Videos and presentations from sessions uploaded to APAN Research Group
    - Focus on Element 3 & 4 use cases, with plan to extend Skyzer and may be landing gear/system and nearing completion of models that align with NAVSEM process steps 1.0, 2.0, 3.0, 4.0 & 5.0
    - Identify new capability for Launch and Recovery System
    - Transformation needs focus on Decision Framework for needed Analysis vice Data in CDRLs/DiDs

    - SME should leverage Analyses performed by Contractor-side of AST
    - Investigating application of the Model Maturity measures to Surrogate Pilot
    - Created example for use of CBT&E/MBTD for Launch and Recovery (R&L) Capability

- Defined new Mission Use Cases for interaction between Skyzer UAV and L&R system, with specific focus on Landing Gear and L&R interaction during landing use cases, which will factor in Airworthiness
    - Aircraft landing on ship
    - Aircraft grabbed by L&R
    - Aircraft has to land "hard" due to environment/weight conditions (impacts on availability)
    - Aircraft aborts because L&R misaligned - to support Airworthiness
    - Add CBT&E thread
    - Create a representative from Mission, L&R, UAV System models, Digital Signoff for the traditional review points
    - Show us your collaborative environment permits our SME to navigate through the based on the specified criteria that should be embedded in the model for digital signoff
    - Investigating use of Digital Signoffs for characterizing new baselines for SET

- Creation of a new Systems Engineering and Technical Management (SEMT) plan model for the Surrogate Pilot
    - This concept was developed for our Army sponsor under ART-002
    - The model can be viewed on Amazon Web Service using the OpenMBEE View Editor
    - Used information from Project Object, Actions and Milestones (POA&M) in Gantt chart form

1.6 Organization of Document

<u>Part I provides an overview of the research task.</u>

Section 1 provides an overview of the context for the needed research, objectives, expanded and evolving scope of needs and organization of this report.

Section 2 provides a summary of the most recent research results, surrogate pilot experiments and lessons learned, research-related events, and deliverables.

<u>Part II describes the details for each research Use Case (UC) and other collaborative research efforts.</u>

Section 3 describes use case UC00 including challenges of cross-domain model integration where we are investigating the use of ontologies and semantic web technologies approach for interoperability.

Section 4 describes use case UC01 and the examples, demonstrations and methods for Multidisciplinary Design, Analysis and Optimization.

Section 5 describes use case UC02 that discusses our approach for a Digital Engineering Environment (DEE), which NAVAIR refers to as an Integrated Modeling Environment (IME) using OpenMBEE with specific focus on creating and collaborating in an Authoritative Source of Truth (AST) for the surrogate pilot experiments. Much of this information was introduced in Section 1 and covered in Section 2.

Section 6 describes use case UC03 that discusses developments and demonstrations for focused around methods that align with technologies in the context of the DEE workflows, for mission, system, MDAO, and model modularization.

Section 7 discusses use case UC04 that investigates model-physics modeling, MDAO and model integrity which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty.

Section 8 summarizes use case UC05 that investigates the development of SysML representations to formalize the Monterey Phoenix (MP) research under RT-176 to support requirement verification and validation, and one example of applying MP to a surrogate pilot mission scenario, however the RT-176 [87] effort has completed.

Section 9 discusses use case UC06 for experimentation and learning in the context of surrogate pilot focused on the execution, assessment and refinement of the SET Framework, which is introduced in Section 1 and discussed in more detail in Section 2.

Section 10 discusses use case UC07, which is the research into Enterprise Transformation to support governance, approaches to model curation, model-centric contracting and language, and workforce development.

Section 11 discusses some preliminary analysis to investigate facets of an approach to develop an artificial intelligence (AI)-based assistant to augment human systems engineers.

Section 12 discusses other SERC research synergies with organizations like the US Army CCDC-AC, Semantic Technologies for Systems Engineering, OpenMBEE and Open Collaboration Group for MBSE, Aerospace Industry Association, National Defense Industry Association Modeling and Simulation, and International Council on Systems Engineering (INCOSE) model-based ecosystem.

Section 13 provides conclusions with a brief summary of the planned next steps.

<u>Part III provides references material from completed or related research tasks.</u>

Appendix A includes some references material from completed or related research tasks.

2 RESEARCH SUMMARY, EVENTS AND DELIVERABLES SUMMARY

This section provides a summary of the research results, lessons learned, research-related events, deliverables and ongoing priorities. We only minimally discuss historical perspectives of prior research in this report. We have shifted focus to the recent developments addressed through the surrogate pilot research results and the lessons learned. The technical reports RT-141 [27] and RT-157 [28] provide a comprehensive summary and historical perspectives leading up to the SET of the two first phases of the research: 1) global scan of state-of-the-art in MCE, and 2) initiating the NAVAIR SE Transformation (SET).

Additional details are in Part II of this report, which includes a summary of each research use case of the cross-cutting research. Appendix A provides links to information from RT-170 [31] and RT-195 [24], such as: SET Framework Surrogate Project model using OpenMBEE DocGen, which provides details on the surrogate pilot plan and objectives. In addition, Part II describes research synergies leveraged from the ARDEC research under RT-168 [30] that are still relevant to SET (e.g., MDAO, Decision Framework, IME), the surrogate pilot, and a demonstration of the IoIF on the Cyber Ontology Pilot under ART-002.

2.1 Cyber Ontology Pilot

The Cyber Ontology Pilot aligns with research use case UC00 demonstrating an example of cross-domain model integration using ontologies and semantic web technologies (SWT) approach for interoperability, in conjunction with descriptive SysML models. We provided support for the development of capabilities within IoIF to conduct the cyber security ontology pilot. In a demonstration conducted on December 16, 2019, IoIF was used to round trip from a SysML model, into a SWT triple store, and then using ontologies and SWT to associate vulnerabilities with model elements in Resource Description Framework (RDR) (i.e., RDF is a standard model for data interchange, and in this case of ontology compliant data), which are then propagated back into MMS and finally back into the SysML model with updates derived from the semantic processing. The demonstration shows how to use a cyber ontology and SWT to associate potential vulnerabilities to elements of a modeled system.

We supported NAVAIR and contractor CUBRC to demonstrate the following scenario, as shown in Figure 8:

- CUBRC provided a simple computer architecture SysML model that had a number of components (these types of models would be developed by the Navy, for example to represent a potential or existing computer and network configuration on a ship)
- CUBRC gave our team an ontology with a few vulnerabilities (fictitious) that could apply to those components (these types of vulnerabilities would be in an RDF triple store/database)
- Our team updated the model and attached stereotypes to the different types of elements of the model which had place holders (properties) for whether there was or was NOT a vulnerability (initially NO vulnerability)
- Import the SysML model through OpenMBEE/MMS into the IoIF
- Run SWT reasoner and SPARQL queries (using OWL and RDF) and it determined the vulnerabilities that could be associated with modeled components in the SysML in IoIF
- The results from the Reasoner and/or SPARQL generated new RDF elements to attach vulnerabilities to components (originally in the SysML model)
- Exported the results from IoIF (OWL/RDF) back into the OpenMBEE/MMS
- Synchronized the MMS back into the SysML model, which updated the vulnerability properties associated with each component in the SysML model

- DocGen to generate the entire demonstration so that you could in real-time see that in a web browser (View Editor)

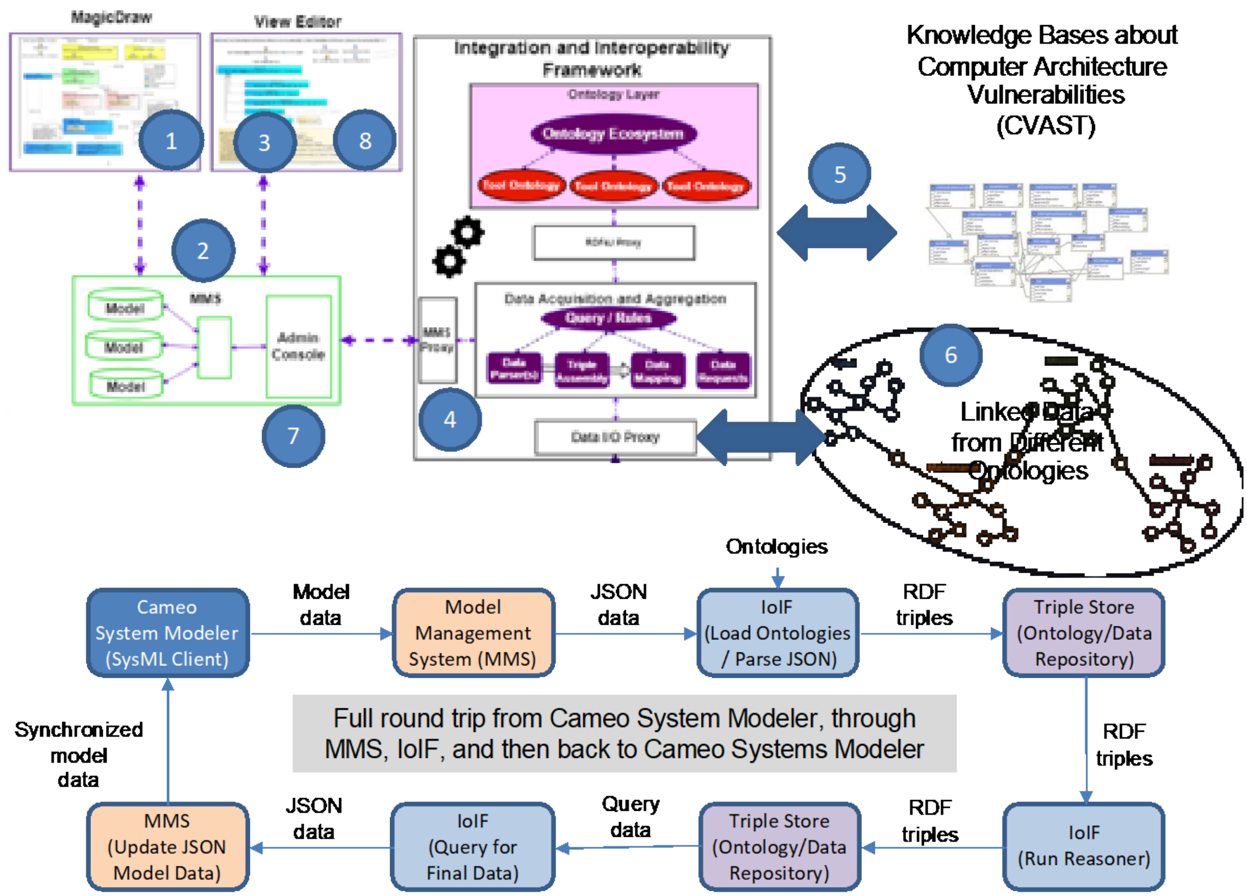

Figure 8. Round trip from Cameo System Modeler (SysML), through MMS, IoIF, and back to Cameo Systems Modeler

There is a video on APAN captured during a session where we demonstrated how to use the IoIF with SysML and OpenMBEE to analyze a SysML model. The video and discussion were led by Dr. Tom Hagedorn and Dr. Benjamin Kruse.

2.2 Surrogate Pilot Experiments Results Overview

This section provides details on key results of performing the surrogate pilot experiments under Phase 1 with updates related to Phase 2. The reason for characterizing these results as key comes from sponsor responses to the results and knowledge gained from our presentations of this information at working sessions, conferences with industry, webinar and to the Navy system commands (SYSCOMs); key results summarized in this section include, but are not limited to:

- Example of an implementation of an AST as shown in Figure 6 comprised of multiple modeling environments

- Understanding of View and Viewpoints used by DocGen to produce stakeholder-relevant views of models that are editable in the OpenMBEE View Editor (aka Digital Engineering Environment)
- Project Usages model linking capabilities that provides a foundation for an AST to link Mission, System, and Contractor descriptive SysML models
- How the contractor RFP response links SysML models to discipline-specific design and multi-physics analysis models
- Digital signoff using editable model objects in the View Editor as a means for transforming CDRLs and performing source selection technical evaluation
- Significant detail on the contractor design and analyses provided as part of the RFP response using discipline-specific models for multi-physics analysis and design
- Case study updates for Phase 2 to create method compliant models for unclassified examples to support workforce development

This section provides the most coverage for the research use cases ***UC02: Integrated Modeling Environment (IME)***, **UC03: Methodology for all of these technologies in the context of the IME workflows*, UC06: Experimentation and Learning for Research Topics in the Execution of SET, and UC04: on how Multi-physic modeling is being planned for incorporation into the Surrogate Pilot for Phase 2***; this information has been moved to Part I of this report to provide early focuses on the surrogate pilot experiments and results. Much of this information is a refinement from information that is captured in the Surrogate Pilot Group of APAN (APAN.org @ https://community.apan.org/wg/navair-set/set-surrogate-pilot/). For much of Phase 2, some of the material has not been marked for public distribution and therefore this material is in the NAVAIR Research Group of APAN (https://community.apan.org/wg/navair-set/research/). The APAN groups and discussion threads provide a project journal with videos, which help in constructing a lessons-learned summary.

Phase 1 of the surrogate pilot focused on moving through the SET Framework concepts Elements 1 through Element 4 as quickly as possible, shown in Figure 1. We defined only three mission scenarios to form the basis for the Skyzer Mission model associated with Element 1 of SET Framework. We further reduced the scope to one mission scenario, maritime search and rescue, for the refinement of the mission requirements that are captured in a Skyzer System model for Element 2. These two models provide the basis for the deep dive that includes multi-physics designs concepts for the RFP response and Element 3. An unexpected benefit in this process was that we formalized, in models, much of the process associated with SOW, RFI, RFP and source selection, which is effectively at the boundary between Elements 2 and 3.

For Phase 2 we extended the mission and system analyses and requirements for Search and Rescue (SAR) use case as reflected in Figure 3. This use case adds a ship-based Launch and Recovery (L&R) system in order to create another capability, where we can research methods for Capability-Based Test and Evaluation (CBT&E), based on a model for Mission-Based Test Design (MBTD). This particular case study includes a deep dive related to the landing gear in order to examine some scenarios for modeling information related to Airworthiness. We updated the models and refactored based on the NAVSEM method for the Skyzer Mission, System, and Contractor RFP model. We extended the Surrogate Contractor descriptive model in SysML and look at multi-physics analysis and perform an MDAO tradespace analysis for the landing gear design looking at tradeoffs between a hydraulic vs. electric landing gear. We demonstrated techniques for modularizing these models while linking them to demonstrate an implementation of an AST.

2.2.1 "Full Stack" of Models Compliant to Modeling Method Standards

In Phase 1 we had a surrogate contractor who refined the government system model into an RFP response; they also did multi-physics analyses that linked to the RFP response. Due to resources constraints, in Phase 2 our research team along with NAVAIR staff and contractors played the role of contractor in completing the updates to the contractor models, with specific focus on landing gear deep dive. These included an RFP response extending the GFI for the mission and system models in a descriptive SysML model as reflected in Figure 5; we have referred to this as the "full stack" of models in Figure 9. The contractor SysML model links to discipline-specific models that characterize multi-physics analyses and a preliminary air vehicle design as shown in Figure 10. This level of detail is generally not provided to NAVAIR prior to contract award. The surrogate experiment demonstrated that models requested as part of an RFP response provide evidence that SMEs from NAVAIR would be substantially more well informed about analyses and system design prior to contract award. The approach demonstrated on the surrogate pilot provides more design information earlier, which should be able to reduce time to the initial test vehicle or system; this is a key desire and objective of the NAVAIR sponsors.

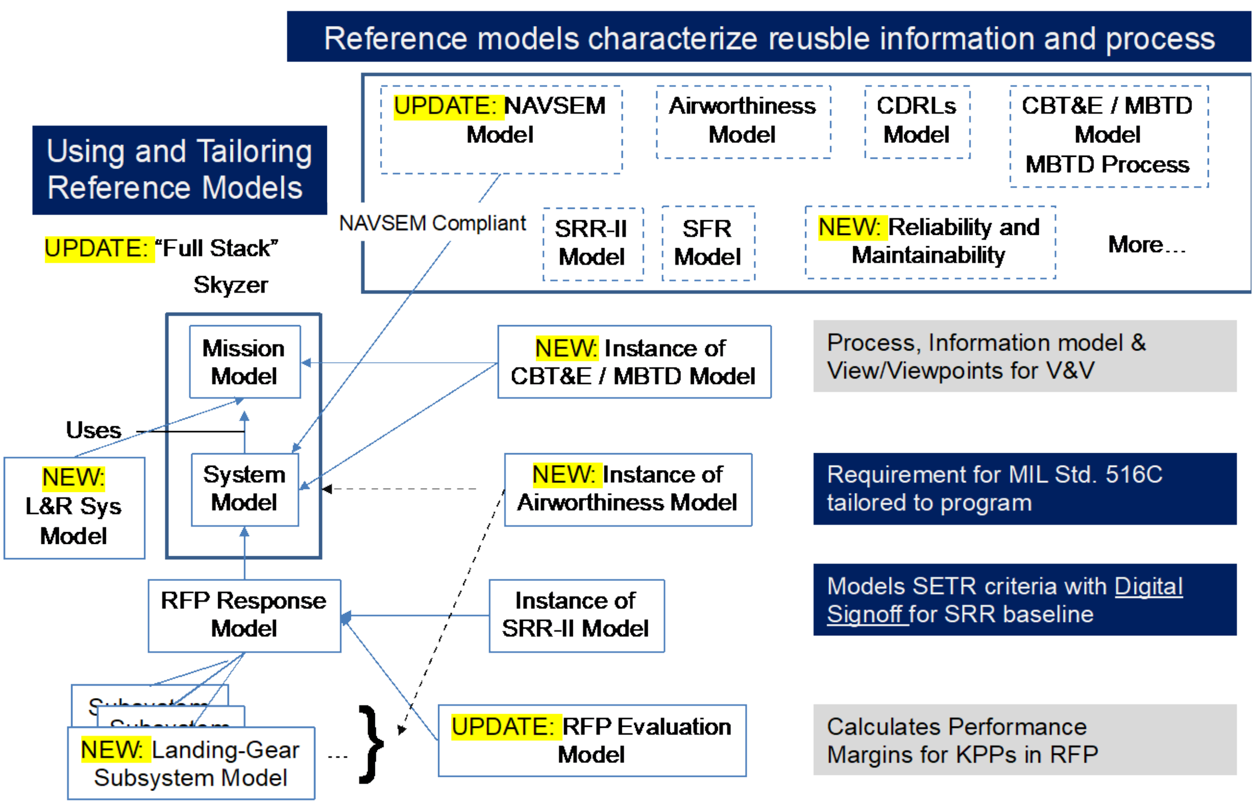

Figure 9. "Full Stack" of Modularized Models

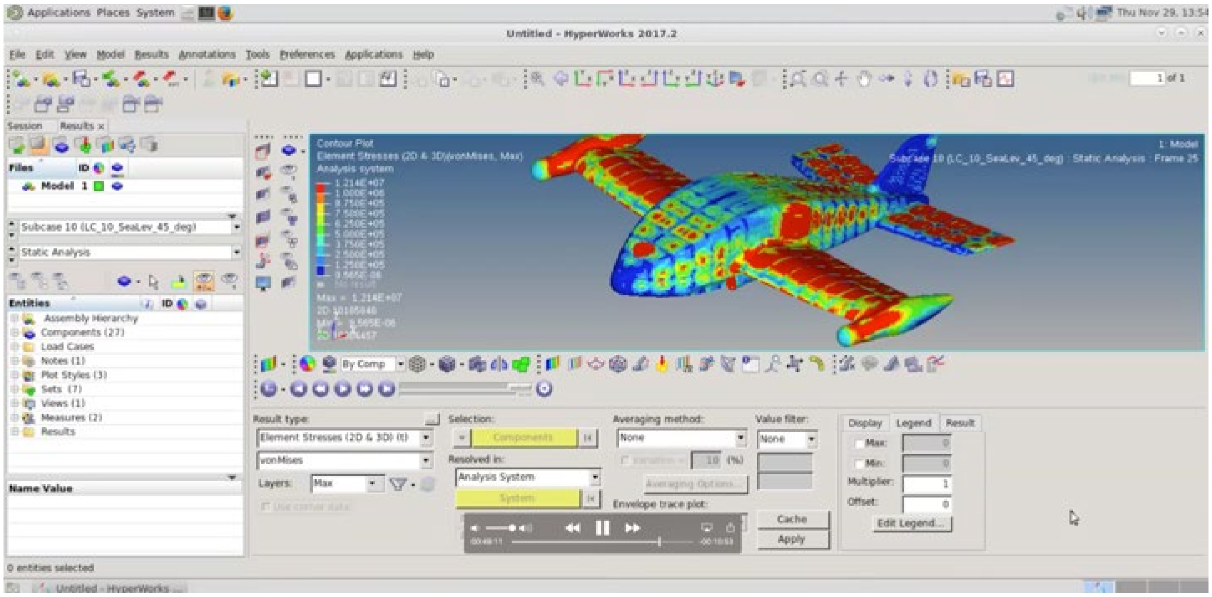

Figure 10. Multi-physics Analysis and Design Provided in Request for Proposal Response[7]

2.2.2 Aligning the DocGen Views and Viewpoints with the NAVSEM Method Artifacts

At the NAVSEM review in January 2020, the NAVAIR methods teams presented their progress on defining the process model for NAVAIR Systems Engineering Method (NAVSEM). The gap identified in January was that there was not much detail on the model-based artifacts, also referred to as work products (e.g., SysML Structural, Behavioral, Parametrics and Requirements elements and diagrams) that should be produced for each of the NAVSEM process steps. We have since addressed some of the gaps and moved forward to use our best judgement to create artifacts that align with the process steps as reflected in Figure 11. We developed the model artifacts for NAVSEM process steps 3.0 and 4.0 for the Skyzer System model and included digital signoffs. We also refactored the Skyzer Mission Model to align to the NAVSEM process steps 1.0 and 2.0. We created the surrogate contractor Candidate Physical Architecture models to align with NAVSEM process steps 5.0 as the contractor refinement of the system model as shown in Figure 14. We also created a CBT&E/MBTD model.

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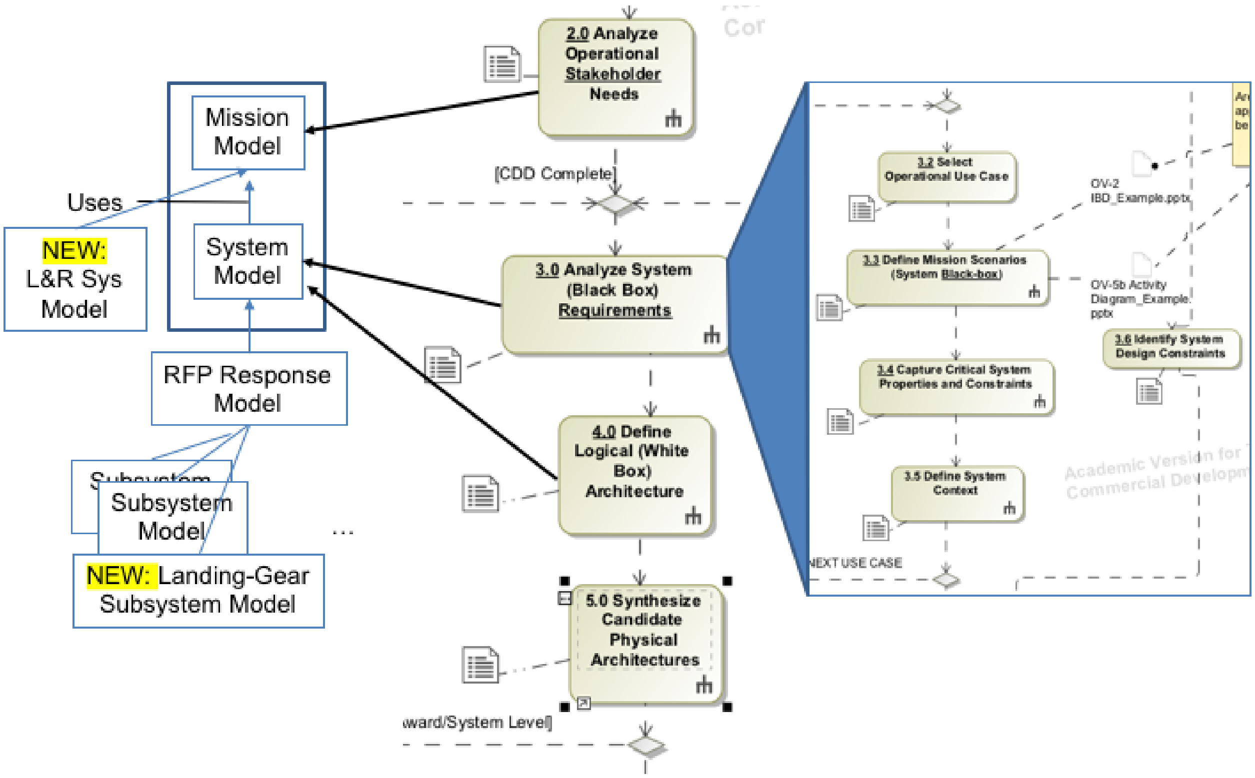

Figure 11. Models Need to Produce Artifacts/Work Products for NAVSEM Method[8]

Figure 12 shows the generated View in the View Editor for the Skyzer System Model that reflects on mapping the Views to the process steps of NAVSEM. The current efforts produced model elements that comply with the process steps. We tried to confirm the validity of the model content through our weekly meetings (videos on APAN) with NAVAIR subject matter experts. We are still working through the details to ensure that model content aligns with the thoughts of the NAVAIR NAVSEM team. We plan to use a dual approval digital signoff as shown in Figure 13 with both the subject matter experts from the methodology team as well as some leader such as a chief engineering as a means to confirm the information structure and content.[9]

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[9] This requires the support of NAVAIR subject matter experts and this may not be possible before the end of the period of performance for this research task.

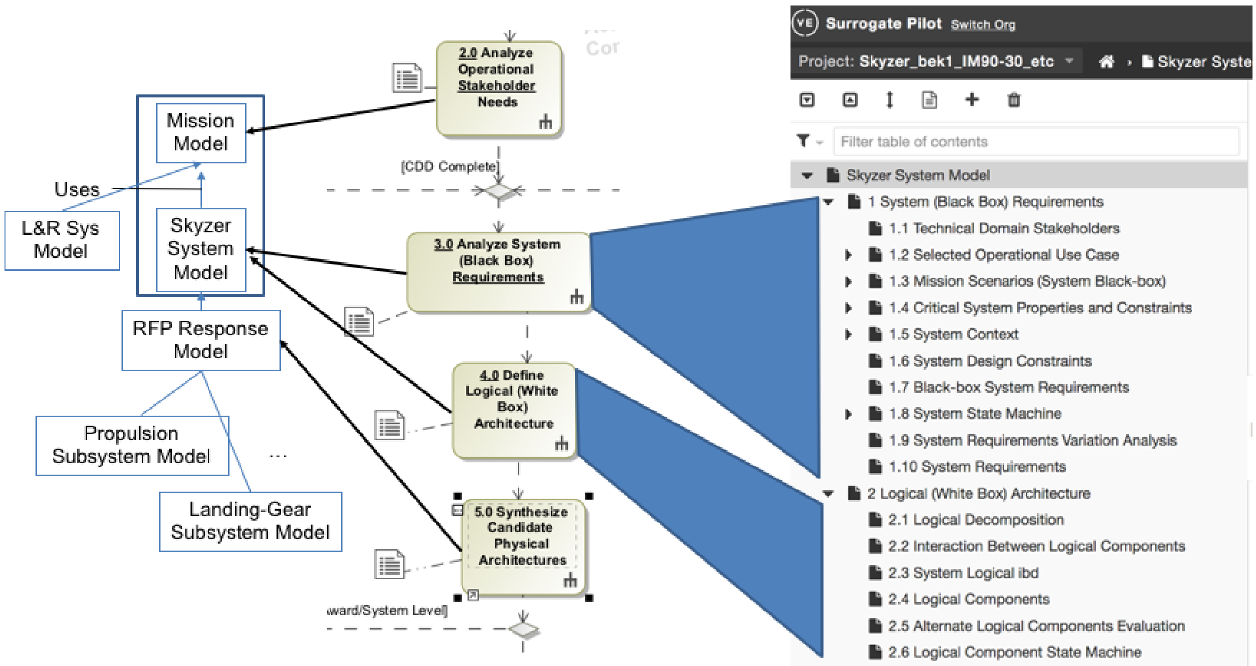

Figure 12. Update View and Viewpoint for Skyzer System Model[10]

1.1 Technical Domain Stakeholders Signoff

EXPORT CSV FILTER TABLE

Table 2. Technical Domain Stakeholders Signoff

Approved Elements	Approval Status	Approved By (SME)	Approved By (Chief-Engineer)	Completeness	Comment
Technical Domain Stakeholders	undefined	-	-	0	-

Figure 13. Dual Approval Digital Signoff

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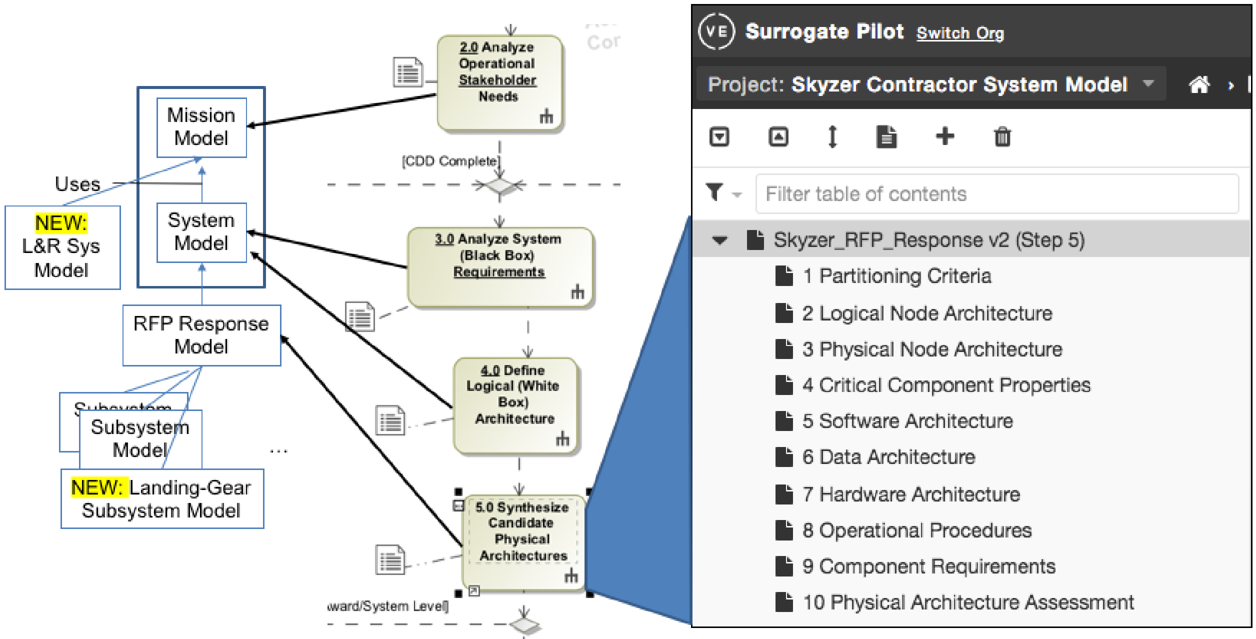

Figure 14. View and Viewpoint for Skyzer Contractor Model to Comply with NAVSEM Step 5.0

2.2.3 Digital Signoff for Transforming Contract Data Requirement List (CDRLs)

During Phase 1 of the surrogate pilot, we formalized the RFP source selection process as a model and performed the Technical Evaluation directly in the View Editor using Digital Signoffs. These digital signoffs are model objects that can be edited and saved in the View Editor, and then they get synchronized back into model as part of the AST. Use cases also demonstrated how to embed digital signoffs in a model, where the signoff can occur in the View Editor (i.e., web browser). The digital signoff is associated with criteria that is typically required at a formal review such as System Requirement Review (SRR); this demonstration provides an approach for eliminating Contract Data Requirement List (CDRLs), which define documents to be delivered. Instead the digital signoffs are directly associated with evidence (e.g., structural or behavioral models, traceability matrices) in the surrogate contractor model[11]. An example of a digital signoff is shown Figure 15; this is an image of the View Editor that provides a View (see section 2.3) of information generated from the model. A SME could enable edits, add a risk and then add approval status. The digital signoff is template-based, which means that digital signoffs can have different columns, such as multiple signoffs as shown in Figure 13.

[11] See Video: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/252732

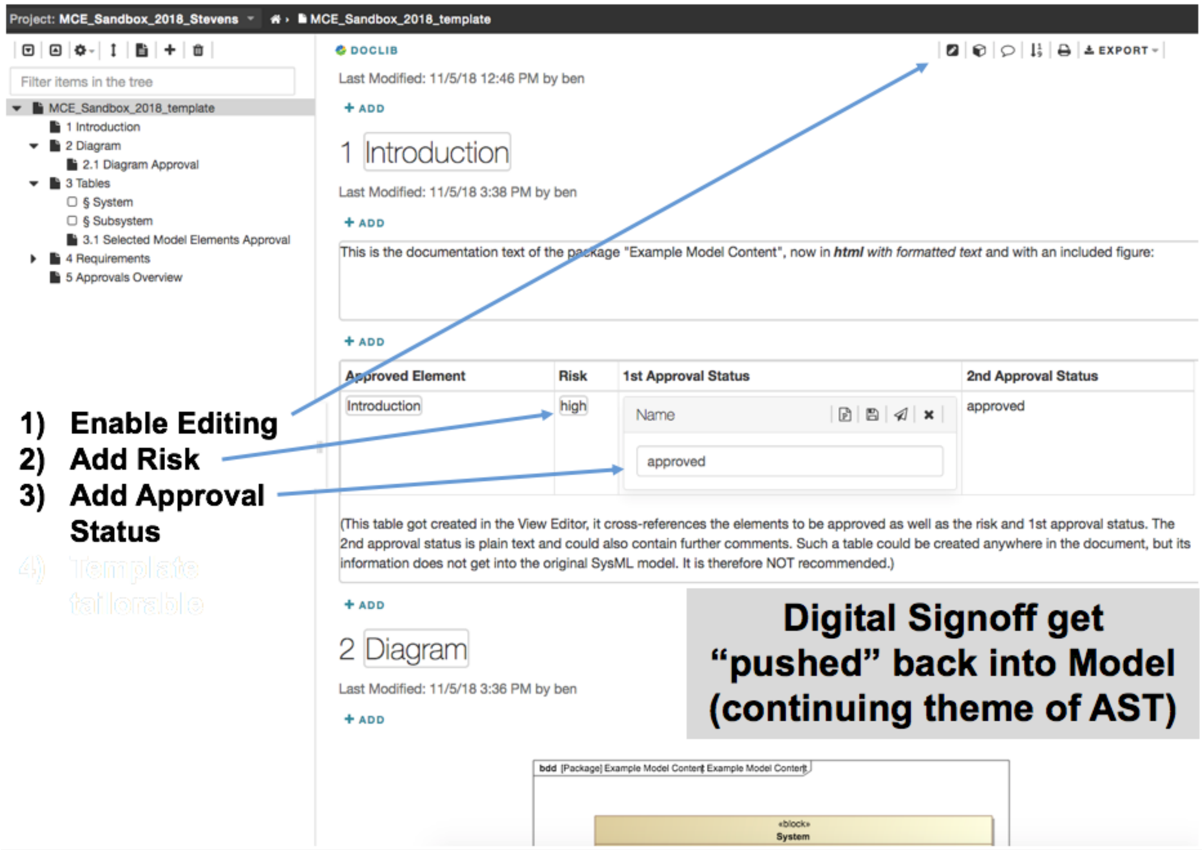

Figure 15. Transform CDRLs and DIDS using Digital Signoff in Model Through View Editor[12]

As shown in Figure 16 digital signoffs are elements within the generated view, as reflected in the View Editor folder structure. The digital signoffs are associated with model objects as reflected in Figure 17; this particular signoff is used to determine the completeness of the Operational Use Case included in the System Model. We had provided different examples as shown in Figure 17 to associate a Risk value associated with the expectation about the completeness of the model artifact. We started discussions with the NAVAIR subject matter experts about these types of risk association that can be used in the cumulative set of digital signoff metrics, which are shown in Figure 18.

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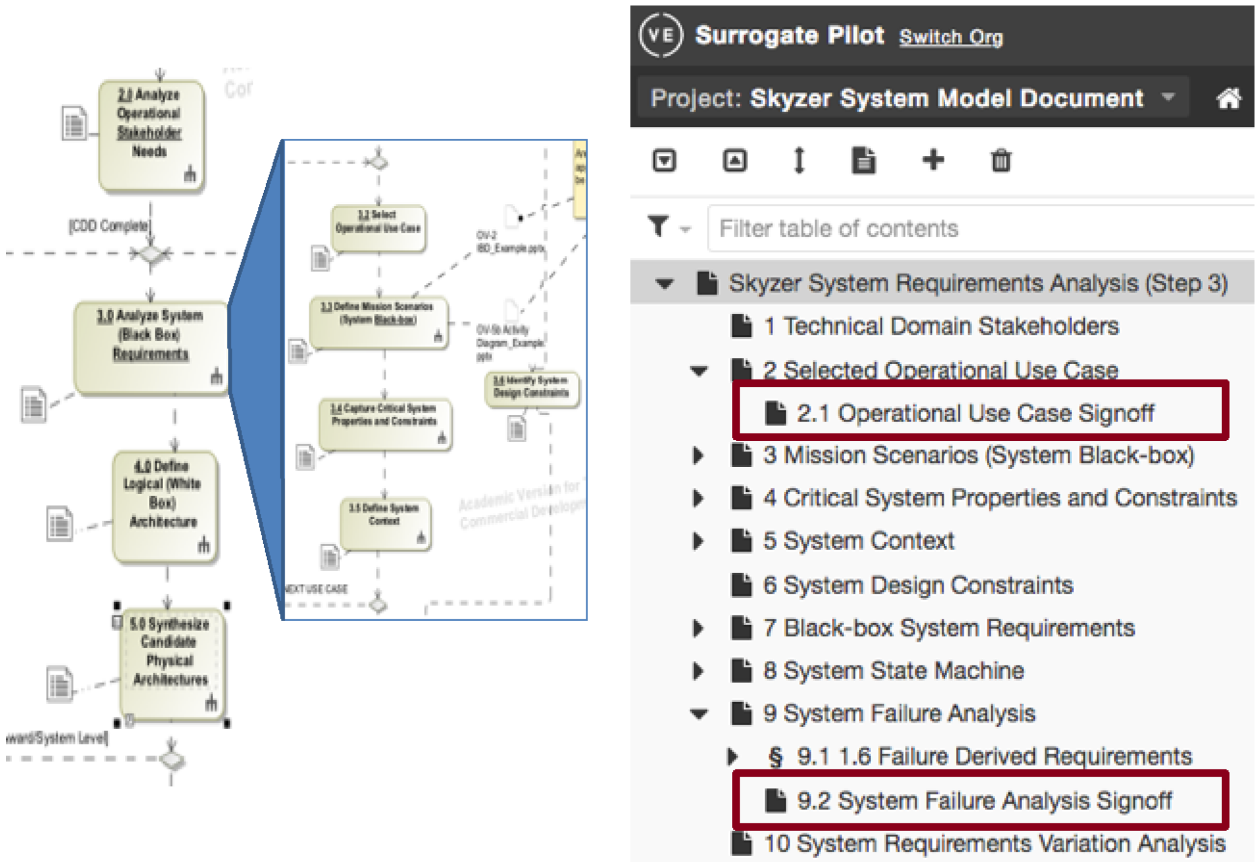

Figure 16. DocGen Generated View for Skyzer System Model with Digital Signoffs

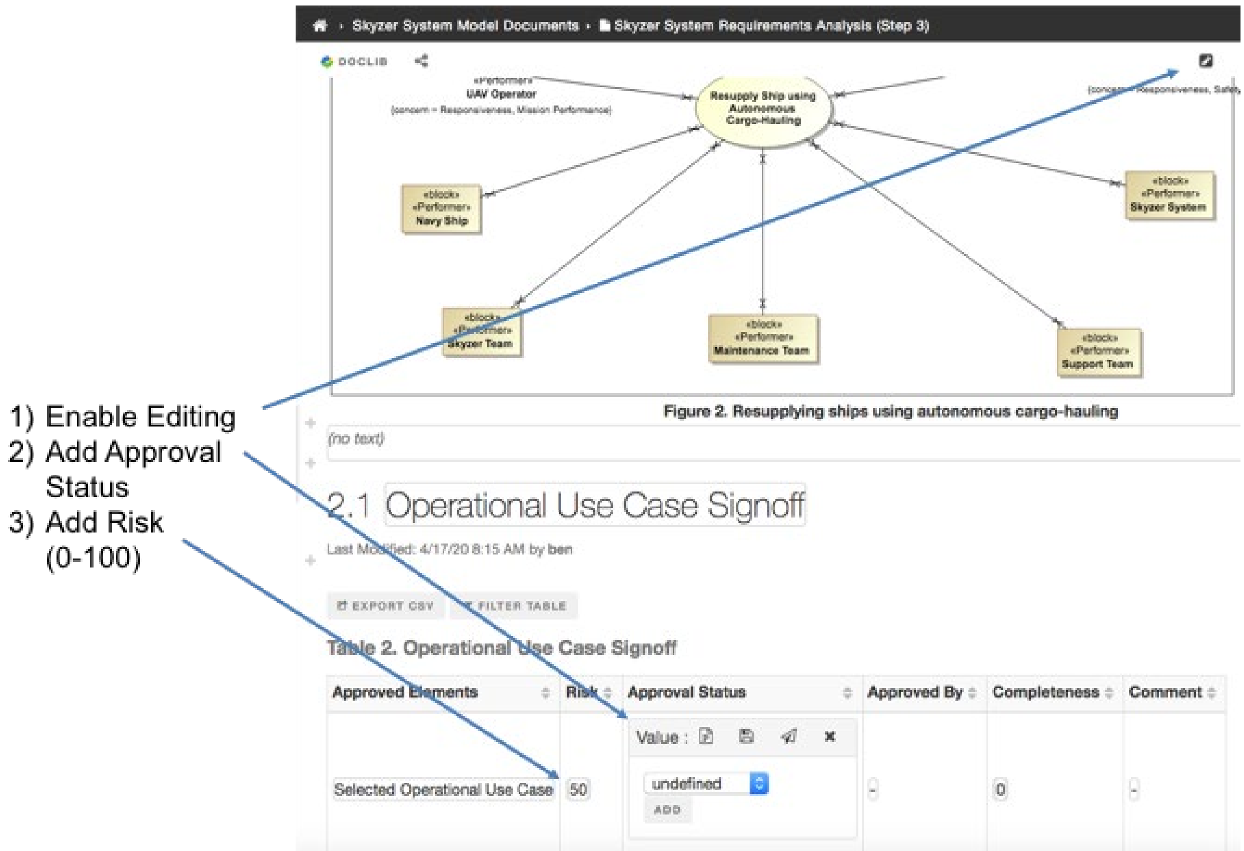

Figure 17. Digital Signoff for Operational Scenario Applicable to System

Digital Signoff metrics are another item that has been introduced, but there is a need for discussions with the NAVAIR subject matter experts on all of these Digital Signoff topics (e.g., multiple signoffs, risks, measures, metrics, baselines). These measures and metrics are automatically calculated in the SysML tool. Finally, we will likely move to a more traditional approach for risk as reflected in Figure 19, where the risk values are associated with the Likelihood or Consequence values from the traditional Risk Matrix. This particular example provides a good example for discussing a digital signoff for a hazard/failure analysis that is modeled using a fault tree.

2 Signoff Metrics

#	Date	Number Of Sign Offs	Number Of High Risk Sign Offs	Ratio Of Approved Sign Offs	Ratio Of Rejected Sign Offs	Average Risk
1	2020.04.17 13.44	5	1	0	0	55
2	2020.04.29 16.54	5	1	0.6	0.2	40

Figure 6. Signoff Metrics

Figure 18. Digital Signoff Metric Example

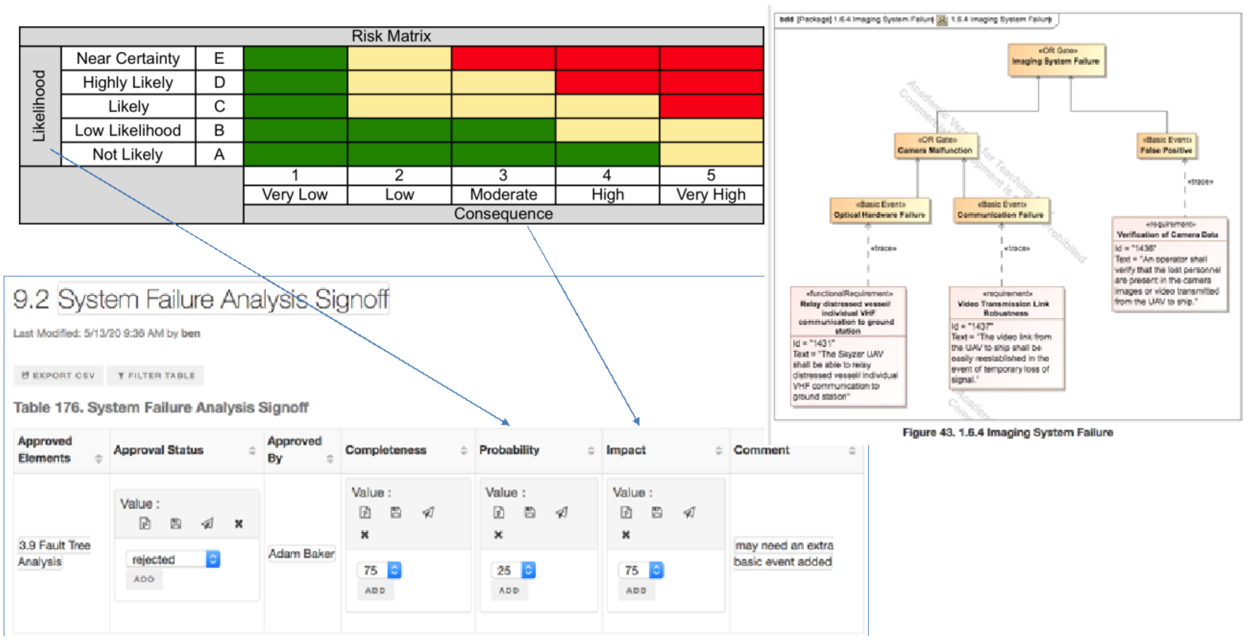

Figure 19. Digital Signoff In View Editor for Subject Matter Experts

In Phase 2 we extended the contractor SysML model with subsystem models for the landing gear deep dive based on NAVSEM process step 5.0. We want to include high-level airworthiness models as reflected in Figure 9 that are based on the Mil. 516C and map detailed analysis and design criteria that is associated with satisfying the airworthiness criteria in the lower-level subsystems back up to the airworthiness criteria in the contractor descriptive models. This is normally accomplished using CDRLs. Our objective is to characterize criteria as digital signoffs that link directly to model artifacts. More details about digital signoffs are provided in Section 6.

The surrogate pilot did demonstrate how the government and surrogate contractor could collaborate in an implementation of an AST, which is reflected in Figure 6. We demonstrated how to create linkages between system models to discipline-specific models such as Computational Fluid Dynamics (CFD), shown in Figure 10. The surrogate contractor did provide one example for Multidisciplinary Design, Analysis and Optimization (MDAO), which was an extension from information provided in Government System Model. The surrogate contractor model also used an Evaluation Model provided as part of the RFP to calculate margins for the KPPs for the requirements from the Skyzer Mission Model.

2.3 View and Viewpoints Used by DocGen to Produce Stakeholder-Relevant Views of Models That Are Editable in the OpenMBEE View Editor

The concept of View and Viewpoints has been around for more than a decade, but the specific implementation embodied in the NASA/JPL implementation of the Model Development Kit (MDK) and DocGen provide a concrete mechanism for people to better understand how DocGen can produce stakeholder-relevant views of models that are editable in the OpenMBEE View Editor (i.e., web browser). This capability also provides the basis to support Digital Signoffs. The following scenario illustrates that working examples are important for understanding new technologies.

The approach for developing the mission model views for Phase 1 was based on a Navy Integrated Capability Framework standard. We have aligned it with the artifacts of NAVSEM process steps 1.0 and 2.0 in Phase 2. This approach demonstrates that modeling can be used to align modeling produce artifacts with existing standards that traditionally have been document-based. We have a View and Viewpoint hierarchy that extracts information from all of the Skyzer models to "generate specifications" that can be viewed in the View Editor, transformed to other document types (e.g., .pdf, .docx, .html) or also printed. A portion of the mission model View and Viewpoint hierarchy shows the basic elements, as shown in Figure 20 that can be included within an overarching document, which includes:

- Document – the overarching model element
  - Document can include other documents, which also provides another level of modularization and support for reuse
- View (there can be one or more views in a document – these map to headings in a document)
- A View uses the Exposes relationship to associate the View with some element in a SysML model (e.g., Package, Diagram, etc.)
- View conforms to a Viewpoint
- Viewpoint in MDK is a special language created out of a profiled activity diagram that can collect, filter, sort, and then produce a document through a DocBook standard

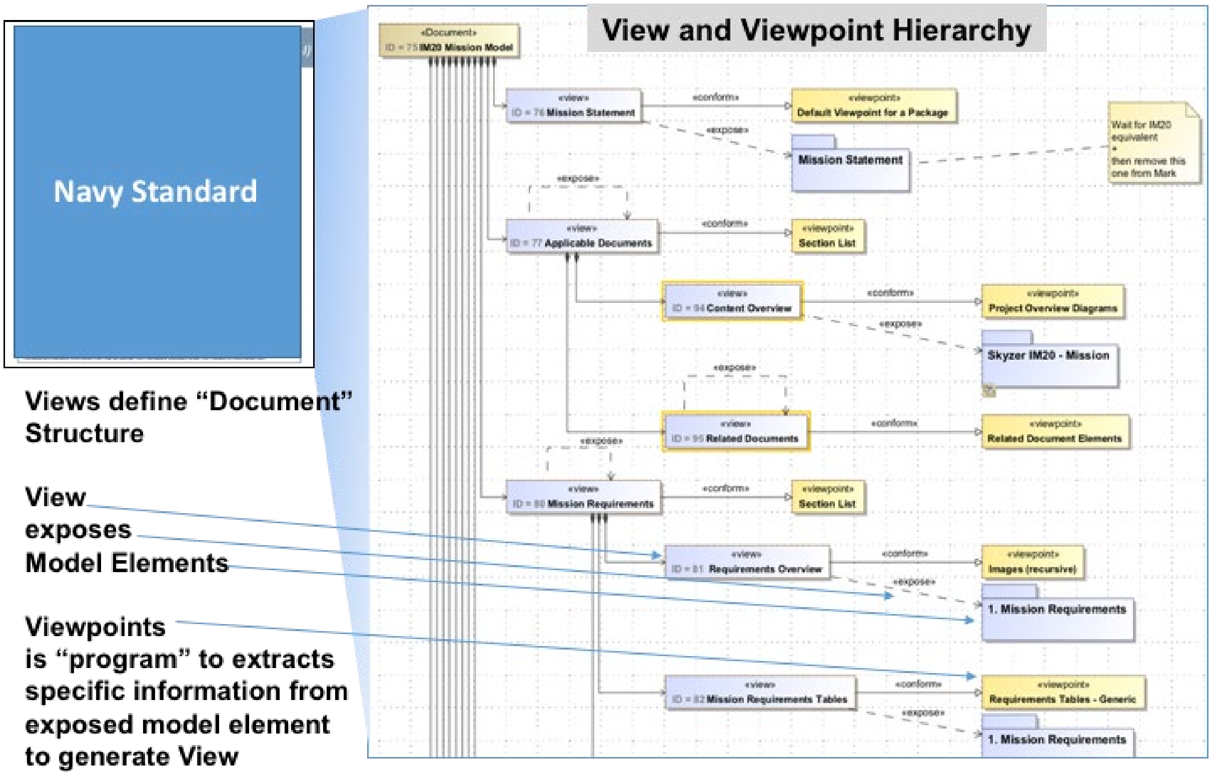

Figure 20. View and Viewpoints for Mission Model[13]

A document assembled from a number of Documents or Views can be generated into DocBook, which can then be transformed into PDF, Word, HTML, and other formats. These Views can also be synchronized into the OpenMBEE Model Management System (MMS). The View Editor can then be used to view the generated specification as shown in Figure 21. The View Editor also allows for editing and updating a generated view that can also be pushed back into the MMS, as well as back into the model (for certain types of model elements). NASA/JPL open-sourced the OpenMBEE capabilities in an attempt to encourage companies to incorporate the capabilities into their offerings. Version 19 of the NoMagic tools provides DocGen capabilities with Cameo Collaborator, and we conducted a comparison of the capabilities between the View Editor and Cameo Collaborator. Briefly to provide a summary Cameo Collaborator comparison to View Editor, therefore Cameo Collaborator:

- Does not provide editing of property values
    - Un-editable parts of documents only update through publishing
- Does not have element history comparison
- No addition of further presentation elements (e.g. figures, videos or text added in View Editor)
- No print or generation as static document
- No specific branching and tags of documents
- Is potentially more stable environment, easier setup and not open source

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- Existing MDK viewpoints need to be recreated and adapted for Cameo Collaborator
  - Need for further investigation (e.g. custom tables) with simplified viewpoints
- Existing view hierarchies might need adaption (changed top-level views)
- Less editing capabilities than with View Editor
- Digital Signoff mechanism needs adaption, but can function similarly
  - Stereotype assigned to signed off element instead of stereotyped dependency
  - Different tracking of changes without MMS database (No IoIF integration)
- Improved (and graphical) commenting and resolving of comments

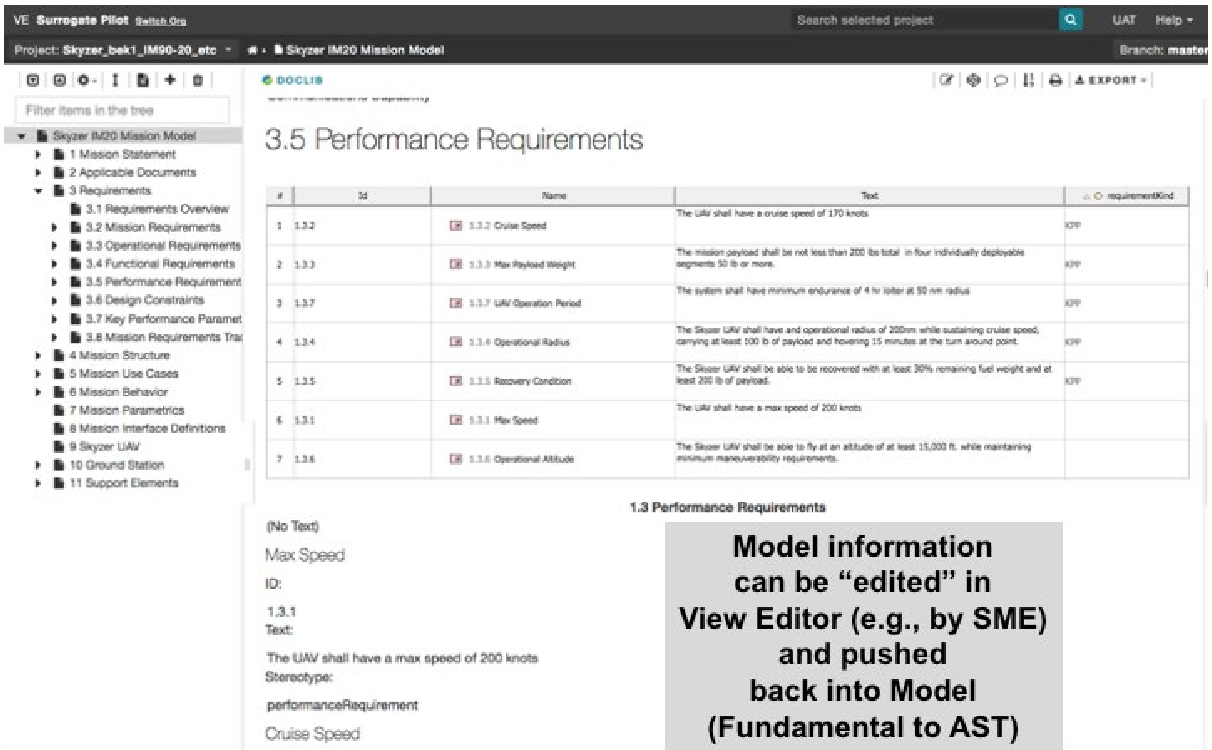

Figure 21. Example: View Editor shows Skyzer Mission Model View[14]

2.4 Integrated Modeling Environment and Elements of the Authoritative Source of Truth

Figure 6 reflects that the AST is actually comprised of one or more nodes. For example:

- Government-side of the AST holds the Skyzer Mission, System, and SOW models and views on an AWS server with OpenMBEE and Teamwork Cloud
- Surrogate Contractor AST node holds the refinement of the Skyzer System models, but includes OpenMBEE, Teamwork Cloud and other design-specific modeling tools
- Stevens AST node provides another example of part of the AST; this is notionally similar to another contractor that might be involved in a program, but be contracted to support different mission requirements

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- Any contractor may also have linkages to any of their subcontractors, which would extend the AST as a type of graph

We are currently working to formalize the linkages and access mechanism from descriptive models such as SysML to discipline-specific analyses such as CFD and topology optimization as reflected in Figure 22. We want to demonstrate the use cases for linking these types of analyses back to the Government Skyzer System and Mission requirements. This is part of the Phase 2 effort needed for Element 3, where we will look at these types of analysis for the landing gear deep dive.

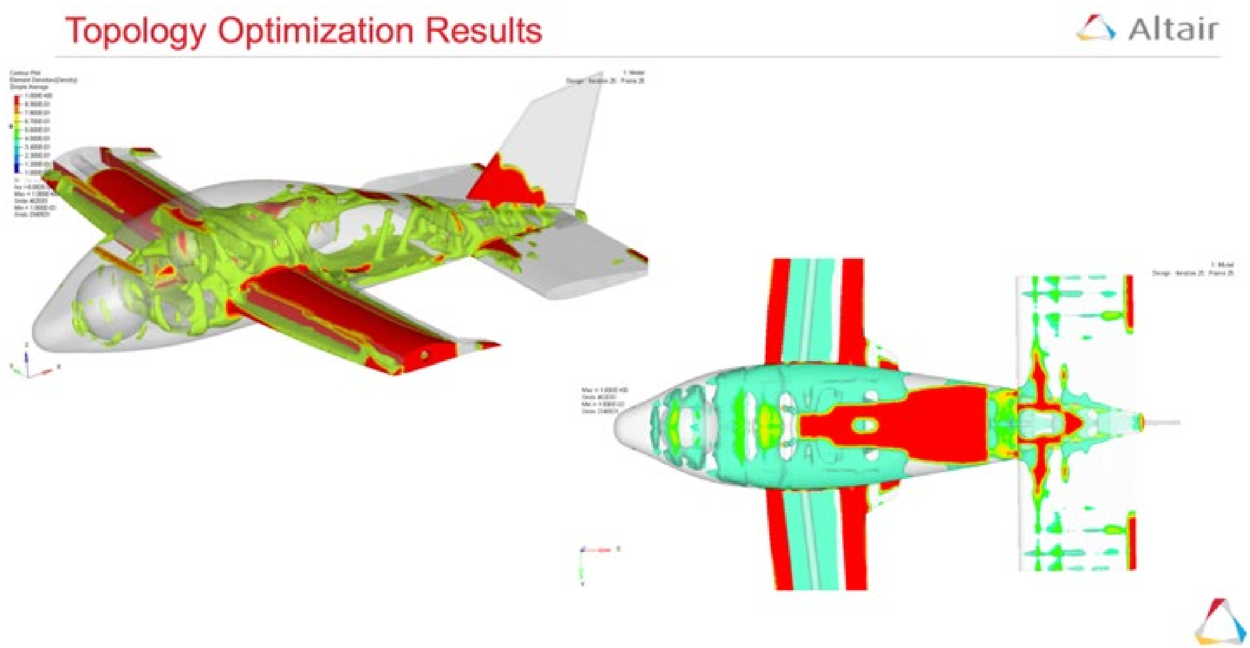

Figure 22. Surrogate Contractor Topology Optimization Analysis[15]

2.5 PROJECT USAGES FOR MODEL MODULATION METHOD

Project Usages is an approach and mechanism for modularizing and reusing different models, and is fundamental to establishing the AST. Project Usages are similar to "include" mechanisms for software languages like "import" for the languages Python. Project Usages allows a model to be included into other models as shown in Figure 23. Figure 9 also reflects on the Project Usage relationships. The creator of the used model can restrict visibility to Packages within that model when it is included in another model, and it can have different restrictions such as Read-only or Read-write permission applied to the model.

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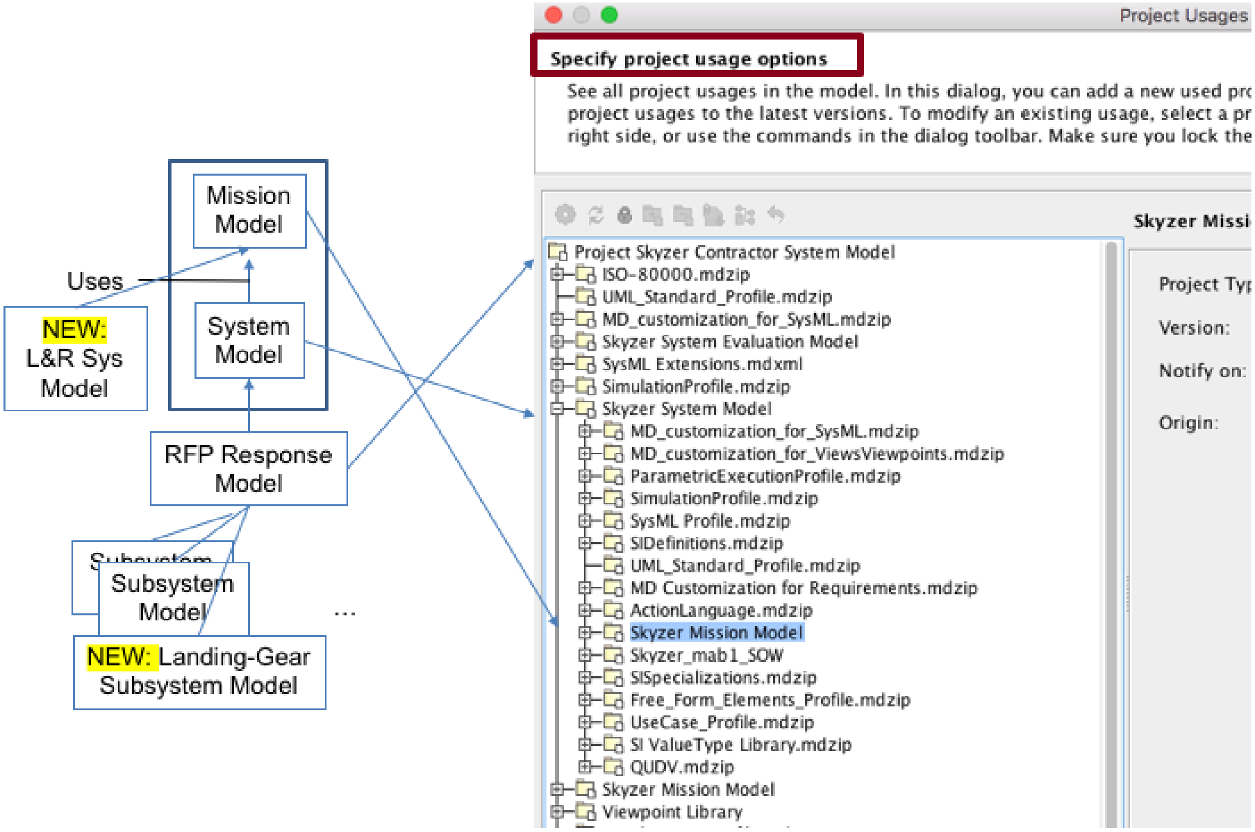

Figure 23. Project Usages for Skyzer Mission, System and Contractor System Model[16]

The following enumerates a few use cases for Project Usages:

- Project Usage of the Surrogate Contractor System Model uses the Skyzer System Model, which uses the Skyzer Mission Model
- Project Usages of Skyzer Mission Model in the Skyzer System Model supports tracing mission requirements to system requirements
  - Figure 23 shows that the Skyzer System Model has several Project Usages, such as the Project Usage of the Mission Model. This allows the System model to create traceability linkages from system information (e.g., behavior in state machine and activity diagrams) in the Skyzer System model (columns) to the Skyzer Mission requirements (rows) as shown in Figure 24. This requirements table is automatically generated. The rows of the table show the mission requirements that are visible inside the system model through project usage, and the columns show the system requirements.
  - This provides significantly more rationale through analysis for requirements. Some of the behaviors have simulations that allow reviewers to understand the broader implications through these dynamic views of a simulated model.

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    - If Mission requirements are updated, this will be immediately visible in the System model, which may then need to be modified to address those changes in the mission model.
- Reuse Model Libraries of DocGen Viewpoints
    - We have collected and developed a number of Viewpoints (mechanism for extracting information from models to produce documents) in Viewpoint Model. Our team is standardizing on Viewpoints, which adds uniformity to the generated specification. In addition, this means that very few modelers need to create or know how to create viewpoints.
    - As part of the OpenMBEE, NASA/JPL developed an implementation for View and Viewpoints are part of the MDK/DocGen [69], which is extensively used to generate stakeholder-relevant views from all of the models used in the surrogate pilot
- Project Usages of Evaluation Model and Estimation Model
    - Our team is also working on an Evaluation Model to be used for Source Selection (see Section 2.6 for more details)

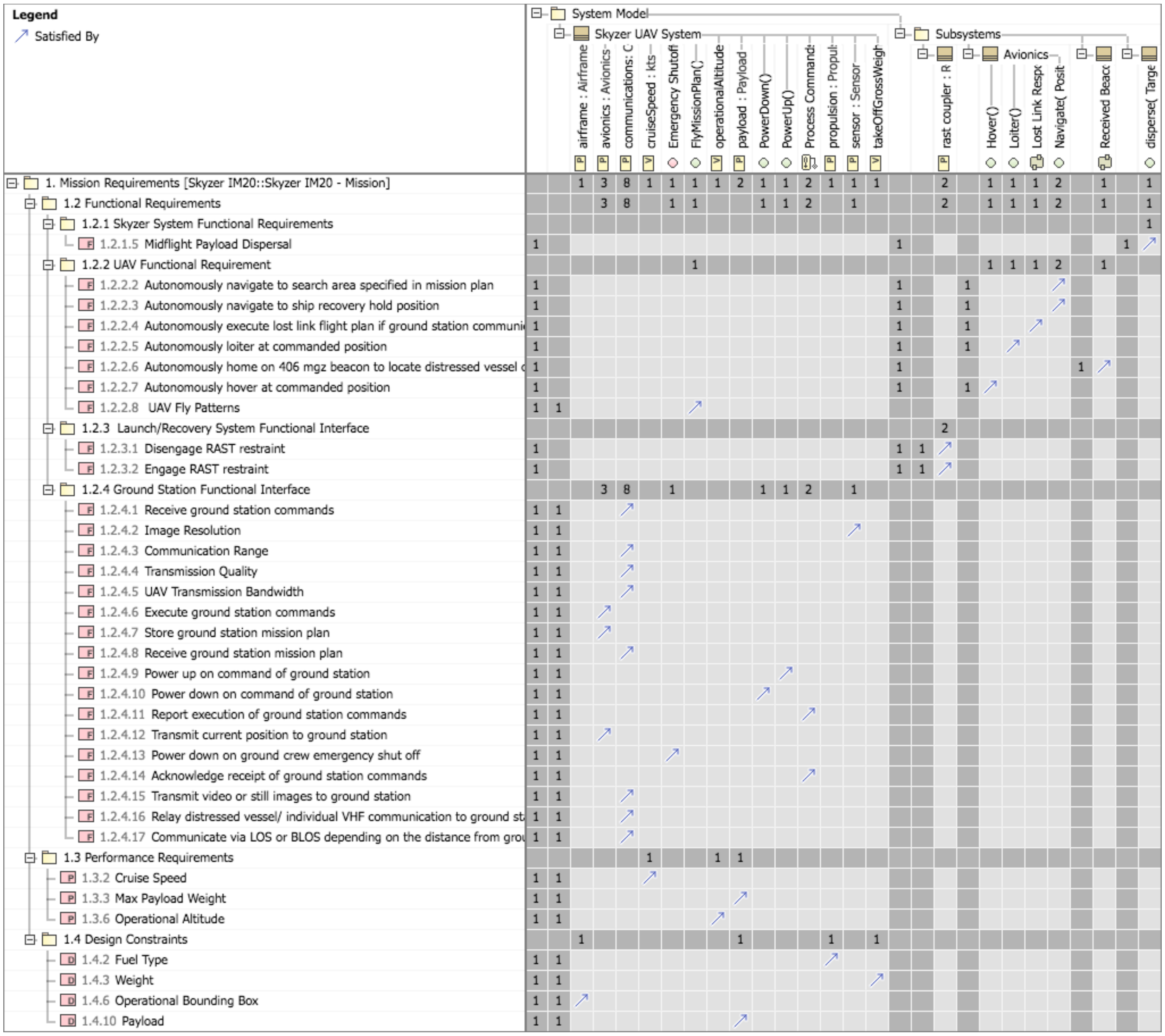

Figure 24. Requirements Traceability from Mission Requirements to System Requirements[17]

2.6 Source Selection Evaluation and Estimation Models

There is a video[18] that can be downloaded from the APAN Surrogate Pilot Group that captures both an explanation about the evaluation model and demonstration for how the Source Selection Evaluation and Estimation Models can be used by a government evaluation team to have a means for rationalizing some of the source selection responses. Briefly, this video describes:

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[18] Demonstration of Evaluation Model for Source Selection https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/241801

- Approach to use an Evaluation model for the Key Performance Parameters/requirements in Source Selection Evaluation; this formalizes Section L, which is part of the SOW
- Approach to create an Estimation model for anticipating performance estimates to be provided in a Source Selection response
- Realization of important use cases for Project Usages mechanisms, for example:
  - We can separate almost anything we need, but combine them through Project Usages (e.g., Skyzer System Model *Project Usages* Mission Model to trace system requirement and analyses to mission requirements). This way we know that if anything changes in Mission Model, Skyzer System Model will see that change and need to be updated appropriately.
  - How to use Project Usages to separate Estimation model from the Evaluation model. The Evaluation model can be provided to the contractor, so that we know it would work correctly when they provide their model at Source Selection. We do not give the Estimation model, but we (the government) uses both at Source Selection.
  - The Surrogate Contractor is using the Project Usages mechanism to include System Model, which again includes Mission Model.

The video discusses three different scenarios using the Skyzer System model to calculate margins for the required KPPs using SysML parametrics and equations. Two scenarios were discussed and demonstrated using an example in SysML:

- Evaluation Model: provides a template-based set of blocks to characterize the Evaluation Context for the system that can be looked at in terms of Minimum or Maximum Margin. The response to a performance requirement includes that specified by the government and that claimed in the proposal response/submission, which allows an equation to characterize the margin - if acceptable, then the response for the KPPs would be acceptable to the government
  - Demonstration showed where the Minimum and Maximum margin equations are defined in parametric blocks
  - How they are used in the Evaluation Context that maps the KPP of the System Model (linked to the Mission Model) to associated margins
  - One or more responses (submission from proposers) could be Project Usage into this Evaluation model used during Source Selection, where the simulations are run to generate the margins and tabularize the responses for comparison using Cameo Simulation Toolkit
  - The demonstration showed how the responses can be traced to the requirements and if the result is acceptable it could be labeled with the verify stereo type
- Estimation Model: the estimation model is similar in concept to the Evaluation Model, but would be developed so that a government evaluator has some type of “ball park” estimate for an expected value of each of the KPPs defined in the Evaluation Context; this model would not be given as part of the RFP.

As part of the Section L supplement to the SOW, an Evaluation Model was provided as GFI as part of the RFP to the surrogate contractor. The responders to the RFPs would be able to use Project Usages from their model to the Evaluation model in order run the evaluation constraints that are formalized as parametrics. As a caveat, there are limitations to what can be characterized in parametrics, and the Phase 2 use of Matlab and Simulink provide a demonstration for the landing gear deep dive estimates. An MDAO workflow that combines one or more solvers related to KPPs (e.g., endurance) could also provide a richer way to deal with more expressive computationally involved performance constraints as discussed in Section 4.

2.7 Request for Proposal and Government Furnished Information

The RFP included a government furnished model that had to interface with contractor models as part of the RFI response. In an actual program the government would need to provide a pre-RFP release step where the government would make available a practice version of the GFI model for the sole purpose of exercising the offerors model interfaces. All offerors would have the chance to exercise their interfaces to the "practice GFI" and send comments to the government if they have problems interfacing to the Evaluation Model. Based on comments received, the government would decide whether the GFI needed to be modified or the offeror would need to fix the interface of their interfacing model. Once the RFP was released, if any contractor could not get the model to work because they did not take advantage of the practice model, there would be no issue on the government.

An issue with this approach is that the GFI interfacing approach might not work with all of the commercial tools. We know that NAVAIR's first choice is the NoMagic tools. While most companies use several different SysML modeling tools, not everyone may use NoMagic. There are possible work arounds including the use of OpenMBEE MMS as is discussed more in the context of our Interoperability and Integration Framework in Section 3.5. Our research using IoIF also demonstrates an approach for using interoperability through an ontology, which is similar to the SBE Vision Semantic Data Broker approach discussed in Section 1.

2.8 Lessons Learned Summary

As shown in Table 1, we are providing a non-exhaustive list of categorized observations and lessons learned topics from our Phase 1 & 2 efforts, with cross-reference links to other sections to explain some of the details and implications. Another perspective on these lessons learned is presented in Section 2.9, which correlates these lessons learned with some DE metrics that reflect on the benefits of DE.

Table 1. Lesson Learned Summary from Surrogate Pilot Experiments

Category	Explanation/Examples
Identify objectives for each phase of the pilot (see Appendix A)	• We developed objectives using the NASA/JPL ontology in a model to capture high-level stakeholder-related concerns our questions about the SET Framework concept • Objectives were mapped into use cases that could cut across one or more objectives • We added new objectives as they were identified

	• In Phase 2 we developed a Systems Engineering Technical and Management (SETM) plan model
Manage Versions for Tools Used to Support Migration to New Toolsets	• We adopted new tool versions more slowly while we waited for knowledge gained from other organizations to avoid problems experienced by the early adopters • Commercial organizations discussed at INCOSE 2019 IW a systematic approach for bringing in new tool versions • Be aware that automated updates in some commercial tools can make the model authoring tool out of sync with the model management tools (e.g., Cameo System Modeler may update to SP3 and the Teamwork Cloud is still using SP2) • Containerization mechanisms such as Docker and now Kubernetes provide a way to integrate many tools and technologies prior to deployment • We provided back to the community a Docker build mechanism that has been used and evolved by a number of organizations, including other commercial organizations using OpenMBEE • Commercial organization are using containerization to manage tool upgrades
Establish infrastructures for IME tools and AST as early as possible (see Section 2.4)	• This is a critical need, because one cannot exercise an MCE or MBSE project without sufficient tooling and methods • OpenMBEE and associated modeling tools provided key capabilities such as model management, DocGen, and View Editor (visualizing stakeholder-relevant views in a web browser) • Example AST provides understanding for AST versus Single Source of Truth • OpenMBEE is extensible to allow for research to integrate ontologies, semantic web technologies, and cross-domain linking of other models to demonstrate the art-of-the possible • OpenMBEE allowed surrogate contractor to have similar environment, which was useful for non-SysML subject matter experts to view, edit, and comment on models in View Editor; NOTE, editing in the View Editor must be performed on objects in order for the edits to be synchronized back to model, including MMS and Teamwork Cloud • Expertise is required for: 1) setting up OpenMBEE, 2) Teamwork Cloud (or SysML repository), 3) account management for OpenMBEE and Teamwork Cloud • Containerization supports infrastructure upgrades and has feature for dealing with security

<table>
<tr><td>Technically feasible to develop everything as a model</td><td>While one may argue about the value of doing everything in a model, the pilot demonstrated that it is possible to develop everything in model (see Section 2.4 for the list of models), even for example the SOW
Key benefits of models:
Focus on needed information and artifacts (not the form, form is embedded in model)
Every model element can be check for uniqueness (there should only be one element for any type of instance, class, or relation)
Every model element has its own unique identifier
Every model element has its own history
Establishing precise SOW language that should be more reusable in the future, and is moving away from a review-based perspective to focus on criteria about models reflecting maturing design</td></tr>
<tr><td>Establish model management practices early</td><td>We identified the lack of model management in Phase 1 as an issue, but established better practices at end of Phase 1 and start of Phase 2
We did model management with both OpenMBEE and the Teamwork Cloud, but need to develop better practices for branching analyses and then merging back into the trunk, which represents the AST
Model management is different from configuration management of software or documents
We asked NASA/JPL and other members of the OpenMBEE Collaboration group for documented practices, but found there are not many documented
We are using concepts of Gitflow for Phase 2 efforts; Gitflow Workflow is an established practice used for “agile” software development practices
Model management needs to factor tooling capabilities</td></tr>
<tr><td>Project Usages for Model Modularization (see Section 2.5)</td><td>Project Usages is a capability provided in the NoMagic tools we are using in conjunction with OpenMBEE that provides a means for modularization of models in a manner analogous to concepts that has been around in software for including and reusing different software modules and libraries
Model modularization allows for links and reuse of many types of models, including mission, system, contractor, source selection evaluation
Modularization has potential for an approach to isolate classified information
Provides access controls at finer level of granularity</td></tr>
</table>

	• Helps modularize to reduce complexity
Create View and Viewpoints to provide stakeholder relevant views and leverage Viewpoint libraries	• View and Viewpoints provide the means for generating document-like views directly from model content, which provide stakeholder relevant information that can be viewed in web-browser or can produce a document in Word or PDF • Views provide a means for associating Digital Signoff with model views • View and Viewpoint provide as templates provide a way to represent the Work Products (i.e., model artifacts) that should be created for a modeling method; demonstrated as a means for ensuring model method compliance for NAVSEM • Students dating back to 2018 have used DocGen and View and Viewpoint to automatically generate their entire final project directly from their SysML model for a Stevens course SYS673
Use Digital Signoffs as a means for evolving from CDRLs	• Digital signoffs have provided an example for how to transform CDLRs and DIDs in Authoritative Source of Truth • Digital signoffs link criteria that is often required at different program review points to be linked to model evidence directly in the model • Digital signoffs are model objects that can be updated in the View Editor, but get synchronized back into the model • Established a basis for metrics that can be automatically calculated in from a View and Viewpoint hierarchy
Generated Views/Specs	• Standardize on DocGen Viewpoints to makes Views look consistent ▪ We have/use a library of Viewpoints • Use SME Stakeholders to define relevant Views ▪ Views align with the artifacts associated with NAVSEM ▪ Provides a means from transitioning from Doc-based to Model-based ▪ Use standards to define the Views; for example, we used the Navy standard to define mission model View ▪ Views provides a means to use an artifact-driven approach to enforce modeling methods ▪ Program leadership will make an approval decision based on model generated stakeholder-relevant reports ▪ Only modeler will likely know/understand what is in entire model; Views are tailored to specific stakeholder interests/concerns
Requirement management can be done directly in models	• Provides means for characterizing requirement directly with other structural and behavior analyses within the model

	• Leveraging Project Usage provides means for performing traceability from various related models (e.g., Mission, System, Contractor, etc.) directly in the models
Modeling provided a means to simplify SOW with emphasis in providing tool agnostic modeling information	• SOW and Evaluation Criteria focus strictly on the needed information • Focus on function of the information needed for source selection vs. form (e.g., in a Word Document) • Determine if SOW language characterizes minimal acceptable criteria for information that needs to be in the models or exposed model views, including for future baselines; this should probably be associated with Digital Signoffs or digitized criteria such as Section L • Creates new needs to develop some type of criteria to characterize what needs to be captured in a model, which can be associated with a digital signoff
MDAO being applied by Surrogate Contractor	• Methods for ensuring that Government System Model is properly structured was required to use MBSEPak and ModelCenter; further demonstrates importance of model methods • MDAO provides a means to link Descriptive System Models and Discipline-specific Multi-physics models at the conceptual and parametric level • See Section 5 for five examples for using MDAO
Establish and align modeling with methods & guidelines	• Understand the difference between a process model and one that also provide methodological guidance that describes the desired work products (artifacts) that should be produced by the process • Defined modeling guidelines for the Surrogate Pilot SysML models for Phase 1 have been evolved for Phase 2 to comply with the NAVSEM method • Models for MDAO using ModelCenter and MBSEPak are necessary and were defined and documented • Methods for tagging KPP in mission models were developed • Methods for tagging objective that might be involved in Airworthiness • Methods for modularizations were developed using Project Usages
Leverage social-media technologies for continuous communication to	• APAN provided the means for journaling the events, results and lessons learned on a continuous basis and provided a means for sharing that information, now in the form of videos too • This approach is effective for documenting weekly progress between team members, but it does take time to document and refine the meeting information

complement modeling in an AST	• This journaling provides substantial input for these lessons learned • Original motivation was to share openly the objectives and results of the surrogate pilot experiments. Many people have joined the group, but the responses are low, and we are not sure if they are only watching and not open to commenting publicly on the Surrogate Pilot efforts • Videos from weekly meetings provide valuable information about evolving pilot, new techniques and approaches (e.g., Evaluation Model for Source Selection), modeling method guidance • There is some curation that is needed to provide some type of information textually for an uploaded video

Surrogate Pilot demonstrated a new operational paradigm for collaboration in AST	• Communicating the proposed approach about a new operation paradigm for collaborative AST during the SET Industry resulted in positive responses from industry RFI responses
	  ▪ This can support continuous and asynchronous insight and oversight by the government
	  ▪ This concept is planned after we simulate contract award for continuing Element 3 in Phase 1 and now Phase 2

Request for Information (RFI) as models useful to test new operational paradigm	• Do not provide mission model as GFI for RFI phase, because it may be too confusing to potential responders • There have been counter arguments to this item • Do use Views of mission model for appropriate context, such as those generated through DocGen for stakeholder-relevant views • Need some type of evaluation criteria for a model-based RFI response
Request for Proposal (RFP) as models is technically feasible	• Simulating Virtual Industry Days as part of pre-RFP process was useful to the pilot • Model (part of Section L) ▪ Can be distributed as GFI for Section L to ensure contractor model characterizes performance for KPPs

Technology enables collaborative capabilities in MCE	• Understanding Project Usage Use Cases for “including” models are important for many reasons:
	  ▪ Skyzer System project uses Skyzer Mission to ensure traceability
	  ▪ Skyzer RFP response project uses Skyzer System and Mission model
	  ▪ Other use cases listed in Section 2.5
	• Linking descriptive models with discipline-specific/domain-specific

	▪ Examples emerging for integration of Descriptive Models are leveraging dynamic simulations from the SysML/UML level with one or more discipline-specific/domain-specific engines • Semantic approaches to tool interoperability gaining attention ▪ See Cyber Ontology Pilot ▪ See NDIA presentation from SAIC and SBE Vision ▪ Ontologies and SWT are enablers for AI – See INCOSE INSIGHT [94] ▪ Interoperability and integration demonstrated for RT-168 using semantic web technologies using IoIF ▪ Navy Cross-SYSCOM ontologies ▪ Other companies: Intercax, NoMagic, AGI, Airbus using or adopting SWT • Use Glossary Capability in modeling clients to fully define terms
Issue tracking necessary	• Categorized issue tracking and notification was necessary especially when we neared the release of the RFP • Used native capabilities in OpenMBEE to allow use of web-based View Editor in order to eliminate need for more user ID and passwords on other tools • OpenMBEE has some advantages, but NAVAIR is using Jira
Releases should tag master branch as AST	• Agreed on using a stereotype (or Tag) for identifying Key Performance Parameters (KPP) • Release included model versions, but also tool versions used to produce the models • Branching and merging are important concepts to understand Authoritative Source of Truth
Competitive and Legal concerns for early collaboration using models	• Iterative interaction with surrogate contractor during RFI and pre-RFP very useful ▪ Is there anything “illegal" with doing this ▪ How would it work in a competition? • Need to address potential of unintentional data leak can enable a protest
Access to AST	• The AWS server is hosted in the public domain, and proved to be very effective for the non-government surrogate pilot team • There are restrictions on accessing the hosted models by the team members using government computers
Model exchange in AST	• Even though government and contractor teams used SysML with the same tool, specific methods need to be more explicitly characterized to support model exchanges, such as using the Source Selection Technical Evaluation Model and the use of proper methods to support use of MBSEPak for Model Center

High Performance Computing	• While storage is becoming inexpensive, the massive storage produces large amount of data, and there is a need for consideration for High Performance Computing (HPC), such as needed for:
	  • MDAO alternative analysis – we can generate hundreds or thousands of alternatives
	  • Use of reasoning such with ontologies, AI and Machine Learning

Workforce skills	• There is a likely need for new types of skills for government subject matter experts in order to navigate the digital information in environments such as, but not limited to:
	  • Views of models in a web browser
	  • Editing and commenting within a View
	  • Digital signoffs
	  • Navigating branches
	  • Model linking
	  • Issue tracking
	  • Navigating and reviewing with industry discipline-specific tools (e.g., Computer Aided Design, Computational Fluid Dynamics, Finite Element Analysis, Failure Models and Effects Analysis), including understanding modeling assumptions and model boundary conditions
	• SERC Digital Engineering Competency Framework research task is defining the needed and related DE competencies and videos have been developed to show how to do Digital Signoffs in a web browser

Other	• Industry MBSE RFI suggested use of parametrics, which has been developed into an Evaluation and Estimation models (see Section 2.6)
	• Team SME with modelers
	  ▪ SME may supply mission scenario and constraints in non-modeling representations
	  ▪ Early mission requirements were provided to lead on mission modeling using a spreadsheet
	• Establish relationships with commercial tool vendors so that research is performed with advanced tools that are often used by industry

2.9 Application of DE Metrics

We performed an analysis on a related SERC effort to correlate DE benefit categories with lessons learned benefits observed during the NAVAIR Surrogate Pilot that applied digital engineering methods and tools using an AST by creating models for everything to demonstrate the art-of-the-possible [125]. The analysis discussed herein performed a correlated rating from 17 lesson learned categories to 22 DE benefit areas grouped into four metrics. The metrics categories include:

- Measure people *adoption*, and enterprise process adoption (**adoption**)
- Analyze breadth of *usability*, and issues with usability (**user experience**)
- Measure *productivity* indicators (**velocity/agility**)
- Generate *new value* to the enterprise (**quality and knowledge transfer**)

We include a narrative of what happened during the pilot efforts that attempted to "model everything" in order to demonstrate the art-of-the-possible. The correlated analysis uses a rating system to correlate the strength of each key lessons learned benefit against the benefit categories. We used the lessons learned in this analysis, because they directly rely on DE practices, methods, models and tools that should enable efficiencies, and contribute to productivity. The DE approach integrated methods and tools with enabling technologies: Collaborative DE Environment (DEE) supporting an AST not just for the Government but also for the contractor. It also required the use of DEE technology features (e.g., Project Usage [model imports], DocGen, View Editor, Digital Signoffs) and methods to accomplish those lessons learned. The efforts demonstrated a means for a new operational paradigm to work directly and continuously in a collaborative DEE to transform, for example, how Contract Data Requirement List (CDRLs) can be subsumed into the modeling process using Digital Signoff directly in the model that is accessed through a collaborative DEE.

2.9.1 Quantitative Analysis

The analysis approach used to correlate lessons learned from the NAVAIR surrogate pilots to the DE/MBSE metrics categories is shown in Figure 25. The rows list 17 categories of lessons learned derived from the projects and the columns list the metrics category and associated grouping categories. We used a scoring/weight of: blank (0), three (3), five (5), and nine (9), where 9 has a strong relationship from underlying aspects of the lesson learned/benefits to the benefits categories. We create a total weighting across the benefits categories (row 2 has score for each measure) and similarly for each lesson learned (final column computes score for each lesson learned by row).

The highest-ranking DE/MBSE benefit areas across the lessons learned are summarized below. The numbers in the parentheses reflect the rankings from Table 1.

- [Knowledge Transfer] Better Communication/Info Sharing (1)
- [Quality] Increased Traceability (2)
- [Velocity/Agility] Improved Consistency (3)
- [Knowledge Transfer] Better Accessibility of Information (7)
- [User Experience] Higher Level of Support for Automation (14)
- [Adoption] Quality and maturity of DE/MBSE Tools (Adoption #1)

These align quite closely with the highest ranked metrics categories in the literature review and survey [125]. As this analysis was developed independently of the literature review and survey results, it provides additional validation of the rankings listed in Table 1. Of note in this example, which is more advanced than a number of other DoD acquisition pilots, is the focus on automation. Reducing workload via automation is a key aspect of User Experience in the DE/MBSE implementation.

	Quality						Velocity/ Agility							User Experience					Knowledge			Other					Total
This analysis is attempting to relate the lessons learned from the Surrogate Pilot to the DE Metrics Categories	Reduce Errors/Defects	Increased Traceability	Improve System Quality	Reduce Risk	Increased Rigor	Reduce Cost	Improved Consistency	Increased Capacity for Reuse	Increased Efficiency	Increased Effectiveness	Comm/Info Sharing	Early V&V	Reduce Time	Support for Automation	Reduce SE Task Burden	Manage Complexity	Increased Productivity	Imp. System Understanding	Better Access. of Info.	Better Knowledge Capture	Imp. System Design	Alignment w/Customer	Support/Commitment	DE/MBSE methods & proc.	DE/MBSE Tools	Workforce Development	
Total	58	108	87	80	95	62	117	77	91	99	111	51	60	111	59	71	91	76	101	90	79	84	62	93	116	77	
Identify objectives for each phase of the pilot				5	5		5	5	5	5	5			5	3	9	5	3	9	9	3	9	9	5	5		109
Manage Versions for Tools Used to Support Migration to New Toolsets	3	3	4		3	3	9	3	5	5	5	3	5	9	3	3	5		3			5	5	5	9	3	101
Establish infrastructures for IME tools and AST as early as possible	3	9	9	5	5	3	9	5	5	5	9	5	5	9	5	5	9	5	9	3	9	5	5	3	9		153
Technically feasible to develop everything as a model	5	9	9	5	9	3	9	5	5	5	9	3	5	9	5	5	5	9	9	5	9	3	3	5	9	3	160
Establish model management practices early	3	5	5	3	5	5	9	5	5	5	3	3	3	3	3	5	5	5	5	3	5	9	5	9	9	5	130
Project Usages for Model Modularization	3	9	5	5	9	3	5	5	5	3	9	3		5		5	5	5	5	5	5	3		5	9	3	119
Create View and Viewpoints to provide stakeholder relevant views and leverage Viewpoint libraries	5	5	5	5	9	3	9	9	5	9	5	3	3	9	3	5	5	5	5	5	5	5	3	9	5	5	144
Use Digital Signoffs as a means for evolving from CDRLs	5	9	3	5	5	9	9	5	9	9	5	5	5	9	5	3	5	3	5	5	3	5	5	5	5	5	146
Requirement management can be done directly in models	5	9	5	5	3	3	5	3	5	5	3	3	5	5	3	1	5	3	5	5	1	5		5	5	3	105
Modeling provided a means to simplify SOW with emphasis in providing tool agnostic modeling information	3	3	3	5	5	5	5	3	5	9	3	5	5	3	5	1	5	1	1	9	5	9	5	5	5	3	116
MDAO being applied by Surrogate Contractor	3	3	3	5	5	3	3	3	3	3	5	1	3	9	3	5	5	5	3	5	5			5	3	5	96
Establish and align modeling with methods & guidelines	5	9	9	5	5	5	9	5	5	9	5	5	5	5	5	3	5	5	5	5	9	5	3	9	5	9	154
Leverage social-media technologies for continuous communication to complement modeling in an AST	3	3	3	3	3	3	3	3	5	3	9	3	5	3	3	3	5	5	5	9	5	5	3	3	9	9	116
Surrogate Pilot demonstrated a new operational paradigm for collaboration in AST	3	9	5	5	9	3	9	3	5	5	9		3	9	3	5	5	9	9	9	5	3	3	6	6	9	149
Request for Information (RFI) as models useful to test new operational paradigm	3	5	5	9	5	5	5	5	5	5	9	3		5		3	3	3	5	5		9	9		5	5	
Request for Proposal (RFP) as models is technically feasible (supported using DocGen and providing model as Government Furnished Information)	3	9	9	5	5	3	5	5	5	5	9	3	5	5	5	5	9	5	9	3	5	3	3	5	9	5	142
Technology enables collaborative capabilities in MCE	3	9	5	5	5	3	9	5	9	9	9	3	3	9	5	5	5	5	9	5	5	1	1	9	9	5	150

Figure 25. Correlation Matrix for Lessons Learned and DE/MBSE Benefit Metrics

Primary lessons learned are:

- It is technically feasible to develop everything as a model
- Must establish and align modeling with methods and guidelines
- Establish infrastructures for IME tools and AST as early as possible

- Technology enables collaborative capabilities in model centric engineering

Both DE/MBSE are tightly coupled to quality of systems engineering methods, processes and workforce capabilities. However, the digital transformation of SE in much more tightly coupled with technology. The quality and maturity of the **DE/MBSE tools**, particularly integration of the Collaboration Environment and the AST is critical. This reflects on the NAVAIR senior leaderships beliefs that we have modeling technologies now as descriptive models (e.g., SysML) that can replace documents and actually provide more information than is typically provided in government document-based specification. We do know that there might be some perception that modeling takes longer, but we also know that the **increased rigor** leads to **reduced errors/defects**, especially cross-domain, or level-to-level (mission to system), because all of the models are linked together (i.e., **increased traceability**) using enabling technologies such as Project Usage/imports. We are also able to render and edits these models in a more, what might often refer to as "cloud-based" way, as well as being able to **improve collaboration** and provide **better access to information** directly in a "cloud-like" way. The models **increase rigor** using formal standardized languages (**MBSE terminology/ontology/libraries**) enabling **higher level support for automation** leading to **increased productivity** and **increased efficiencies**; these should result in **reduced time.** This quantitative analysis is followed by a set of narrative summaries that explain how these benefits relate to the process of a DE/MBSE transformation.

2.9.2 NARRATIVE ANALYSIS

The rating process made it apparent that many of the lessons learned are listed because they do exactly what DE should do - integrate several related DE elements/facets: Collaborative DE Environment supporting and AST, not just for the Government but also for the contractor. It was also enabled by the use of DEE technologies features (e.g., Project Usage/imports, DocGen, View Editor) and modeling methods to accomplish those lessons learned. It also produced unclassified and NAVAIR relevant examples in models for discussing the results and approaches supporting workforce development. The following are narrative summaries of each of the lessons learned.

Model Everything in Authoritative Source of Truth

One of the best early decisions in the surrogate pilot experiments was the attempt to "model everything," not because one would normally do that, but to demonstrate the art-of-the-possible. This made everything accessible in the context of descriptive models using the system modeling language SysML. These descriptive models formalize information about the system structure, behaviors and requirement and can completely replace documents as demonstrated during Phase 1. We used OpenMBEE[19], which provided collaborative access to the government team members as well as industry surrogate contractor. OpenMBEE also provided the DocGen capabilities, which permitted all stakeholders access to the model using a web browser representation of the model. DocGen creates stakeholder-relevant views extracted directly from the modeled information so that some of the SMEs that did not have any SysML model training, nor did they have a SysML authoring tool, were able to easily visualize the information in the

[19] OpenMBEE, http://www.openmbee.org

OpenMBEE View Editor. The View Editor also allows users to edit or comment on information in the model directly from a web browser. Any edits to the model made in the View Editor can be synchronized back into the model repository with appropriate model management controls for tracking all of the changes.

We also used a modeling modularization method (through Project Usages, i.e., model imports), which facilitated an implementation of our DEE demonstrating the concept of an AST. The biggest finding was that modeling everything might eliminate some types of things done in traditional documents. More importantly all models were linked together in the AST, which has the potential to promote **collaboration/info sharing**, **information access, reduce errors/defects**, **improved consistency**, **increased traceability**, and eliminating some type of works for **increased efficiency**, because the work was inherently represented in and subsumed by the collaborative ASOT.

Model using Methods for Needed Purpose

The next critical lesson learned is to establish and align modeling with appropriate methods and guidelines. Methods extend beyond processes and identify the artifacts that should be modeled in order to have sufficient and relevant information to make decisions. For example, descriptive modeling languages should include: structure (decomposition and parts), behavior, interfaces and requirements. A method also defines the types of relationships between the artifacts, which often provides information about cross-domain relationships and dependencies. Technology features that complement methods are the use of View and Viewpoints which are inputs to DocGen. A View and Viewpoint can be used to define the needed model artifacts that are associated with the desired modeling method, which is exactly the approach used on the surrogate pilot. Methods, beyond processes define the required types of artifacts, which again leads to **improved consistency**, **improved system understanding** (better understanding of the system architecture), **increased effectiveness** (standardization), as well as a way to more easily assess completeness (**improved system design**) of the generated "specification."

There are also several types of modeling methods needed for different abstraction levels such as: mission, system, contractor refinement of the system model, subsystem and discipline-specific. There are other types of methods for tradespace analysis such as Multidisciplinary Design Analysis and Optimization (MDAO), as well as model management methods that were demonstrated in the surrogate pilot. We even modeled the Statement of Work (SOW) language and RFP Technical Evaluation criteria for the mission key performance parameters. This is a broad topic that is completely related to **improve system quality** and **improved systems understanding** and needed to **increase traceability**. Standardization of the artifacts as specific types of model elements, properties and reasoning lead to **higher level of support for automation**. We can automate validation rules either in the authoring client or using other approaches such as ontologies and semantic technologies, which permit cross-domain reasoning for **better decision-making**. In addition, our resulting models provide unclassified examples that are method compliant in collaborative environment for workforce development (**training**, **demonstrating benefits/results**).

Model management methods and practices are somewhat different from configuration management of documents, primarily because model management deals with configuration management of objects within a model vs. textual information that can be compared and merged. However, it also relates to some other types of modeling method validation rules, such as: there should only be one object representing a specific element (traced to the design), because we can use that one object in different model views (e.g., diagrams). In addition, if one uses Project Usage (i.e., model imports) that additionally avoids duplicating a representation of some entity in more than one place throughout the models, and fosters **increased capacity for reuse** and **increased traceability**.

Establish Infrastructures for IME Tools and AST Early

General resources for DE/MBSE implementation and maturation of **DE/MBSE Tools** must be committed early. The IME/DEE must be defined and used in a way to establish a collaborative AST. Certain methods, as discussed in the previous narrative are necessary as well as having some tool features (e.g., Project Usages/Import, DocGen). Early efforts during Phase 1 made slow progress, until we had the DEE in place for **better accessibility of information** and **collaboration/info sharing**. However, we want to warn people that tools alone are not enough, one must establish a set of model methods (**DE/MBSE methods and processes**) that defines the artifacts you need to produce, and View and Viewpoint/DocGen can help with this too, as discussed in the previous narrative on modeling using methods for needed purpose.

Technology Enables Collaborative Capabilities in DE

There are evolving technologies that need to be incorporated into the overarching approach. For example, the OpenMBEE approach was an early leader in the creating of DocGen and the Model Management System (MMS); while there are other document generation capabilities in tools, this particular approach seems to be much better than other competitors as reflected by the adoption of tool companies. The DocGen was first created by NASA/JPL to enable non-modeling subject matter experts (SMEs) to interact with the model through generated representations of the models.

Understanding Project Usage, which provide for modeling importing, supporting **increased capacity for reuse**, but also as an enabler for **collaboration/info sharing** in an AST and **increased traceability** within the AST from mission models, to system models, to contractor descriptive models provided as an RFP response that is discipline-specific/domain-specific. Examples are emerging for integration of descriptive models that are leveraging dynamic simulations from the SysML level with one or more discipline-specific/domain-specific engines using semantic technology approaches to tool interoperability [94].

Surrogate Pilot Demonstrated New Operational Paradigm for Collaboration in AST

Phase 1 was able to demonstrate an approach to one of the objectives of the SET Framework concept, which is to affect a new operational paradigm for **collaborative information sharing** in an AST for government and industry to better interact in order to **increase efficiency** during acquisition. We can also confirm that this approach has been socialized with industry a number of times and has resulted in positive responses from industry as well as written in industry-provided RFI responses. The pilot also demonstrated another SET Framework objective to enable asynchronous insight and oversight by the government (**alignment with customer requirements**); this was accomplished in the AST and the use of asynchronous reviews using Digital Signoffs through **better accessibility of information**. In terms of **training** and **demonstrating benefits/results,** the surrogate pilot has been one of the only means for having an open-source and unclassified example where we can talk about all of the things that were accomplished.

Digital Signoffs for Transforming from Contract Data Requirements List (CDRLs)

Another objective of the SET Framework concept was to eliminate Contract Data Requirements List (CDRLs), which we characterized as "transform." Digital signoffs in the AST provided an example for how to transform CDLRs and Data Item Deliverables (DIDs) and support asynchronous reviews enabled by **better communication/information sharing.** Digital signoffs link criteria often required in a CDRL that is used at different program review points to be linked to model evidence. We determined an approach to use OpenMBEE View and Viewpoints as a means for placing a digital signoff directly with model information that provided the needed evidence, a clear example of **reduced time** and **increased effectiveness**. Digital signoffs are model objects that can be updated in the View Editor, with the signoff information (e.g., signoff, risk, approver, comments) added that get pushed back into the model. We also established a basis for automating digital signoff metrics that are automatically calculated in a View and Viewpoint hierarchy.

Digital signoffs for criteria that would normally be requested in CDRL can be placed directly in the model with information that provides evidence supporting the requested criteria. No additional documentation is needed, because it is created in the View and Viewpoint, which means it can also be automatically generated. The Digital Signoffs are templates, and can be tailored to incorporate one or more signoffs, and other information such as Risk of a particular signoff (if it has not been assigned a value) as well as Risk for the value assigned (i.e., certainty into the decision). Finally, if a piece of information associated with the Digital Signoff is changed, the signoff can be automatically transition to a new state.

This capability supports **increased traceability** for digital signoffs from high-level mission requirements to low-level discipline-specific design constraints as demonstrated in the surrogate pilot. This should **reduce cost** by transforming/eliminating CDRLs that take on a new form in the model providing increased **efficiency**, improved **consistency**, support for **automation**, and standardized **DE/MBSE methods and processes**.

View and Viewpoints Provide Stakeholder Relevant Views using Viewpoint Libraries

DocGen using View and Viewpoints is a key enabling capability that provides support for allowing SME to understand the modeled information, without needing to know how to use a model authoring client (**improved system understanding**). Potentially more important is the ability to allow views to explicitly show the needed artifacts (work products) that should be produced through modeling; this can be done independent of the process, but further supports standardization of **DE/MBSE methods and processes** and compliance with the modeling method. It also provides a way to create different views that are relevant to different stakeholders and provides a way of rendering links to imported models to show views of the AST at different abstraction levels (**more stakeholder involvement**). The direct editing in the View Editor again provides an important DE Competencies capability for people that do not have skills (or tool license) for using model authoring tools (increases the number of **people willing to use DE/MBSE tools**).

The capability of View and Viewpoints provide the means for generating document-like views directly from model content (**support for automation**), which provide stakeholder relevant information that can be viewed in web-browser or can be exported into a document in Word or PDF (**improved collaboration**). The views provide a means for associating Digital Signoff with model views. An empty View and Viewpoint template provides a way to represent what modeling artifacts should be created for a modeling method. This is an important technology to **improve consistency** of "specifications," through support for **automation, increased capacity for reuse** of curated Viewpoint libraries, which provides **better accessibility of information** in a web browser for those stakeholders that may not have access to tools, and it is a capability that provides the digital signoff mechanism.

Request for Proposal (RFP) as Models is Technically Feasible (supported using DocGen and providing model as Government Furnished Information)

This is both a technical and policy approach. Technically, we developed an approach to support the concept that the RFP response that becomes part of the AST by linking and **increasing traceability** of the contract RFP response directly to the government mission and system model that was the basis of the RFP. This again supports new concepts such as digital signoffs by government SMEs directly in a Contractor model. We also demonstrated how to represent the technical Source Selection criteria as a Digital Signoff in the RFP response model. The digital signoffs in the ASOT provided an example for how to transform CDLRs and DIDs and support asynchronous reviews enabling **increased collaboration** and **better communication/ information sharing**.

2.10 Model Curation

Under the WRT-1009 project [166], the criteria for placing models under curation is being generated, along with defining what specific information is to be included in the accession record (accepting a model into an enterprise collection) and model pedigree (information about the model origins, assumptions, context etc.). In WRT-1008, the criteria and templates for accession and pedigree information are being applied and tested using the Skyzer System Model. This application to Skyzer serves to identify needed refinements for criteria and curation-related information. The ongoing activity produced a demonstration example based on Skyzer that can be used as a reference for practitioners, as well as for education purposes. See Section 10.2 for details.

2.11 Roadmap Views

The NAVAIR SE Transformation is part of a broader DE Transformation. We believe this will be followed by transformational advances in the discipline of systems engineering using artificial intelligence (AI) and machine learning (ML) technology for automation of many routine engineering tasks. We proposed this theme on enabling SE with AI as part of the SERC five-year technical plan, and in 2019 created a number of roadmaps that align with the DoD Digital Engineering Strategy.

We used a two-dimensional roadmap construct first shown by Airbus' Hartmann at the NASA/JPL MBSE Symposium in 2017 [95]. We adapted this construct on a roadmap that aligns with the five goals of our DoD sponsor's strategy: 1) Model Use for Decision Making; 2) the Authoritative Source of Truth (AST); 3) Technological Innovation; 4) Collaborative Environments; and 5) Workforce and Cultural evolution [73]. The roadmap anticipates the increased need to formalize the underlying information model (e.g., using ontologies and SWT) as we move to the right (i.e., future), which can exploit more computational automation such as (i.e., AI, machine learning, etc.), enabled by high performance computing.

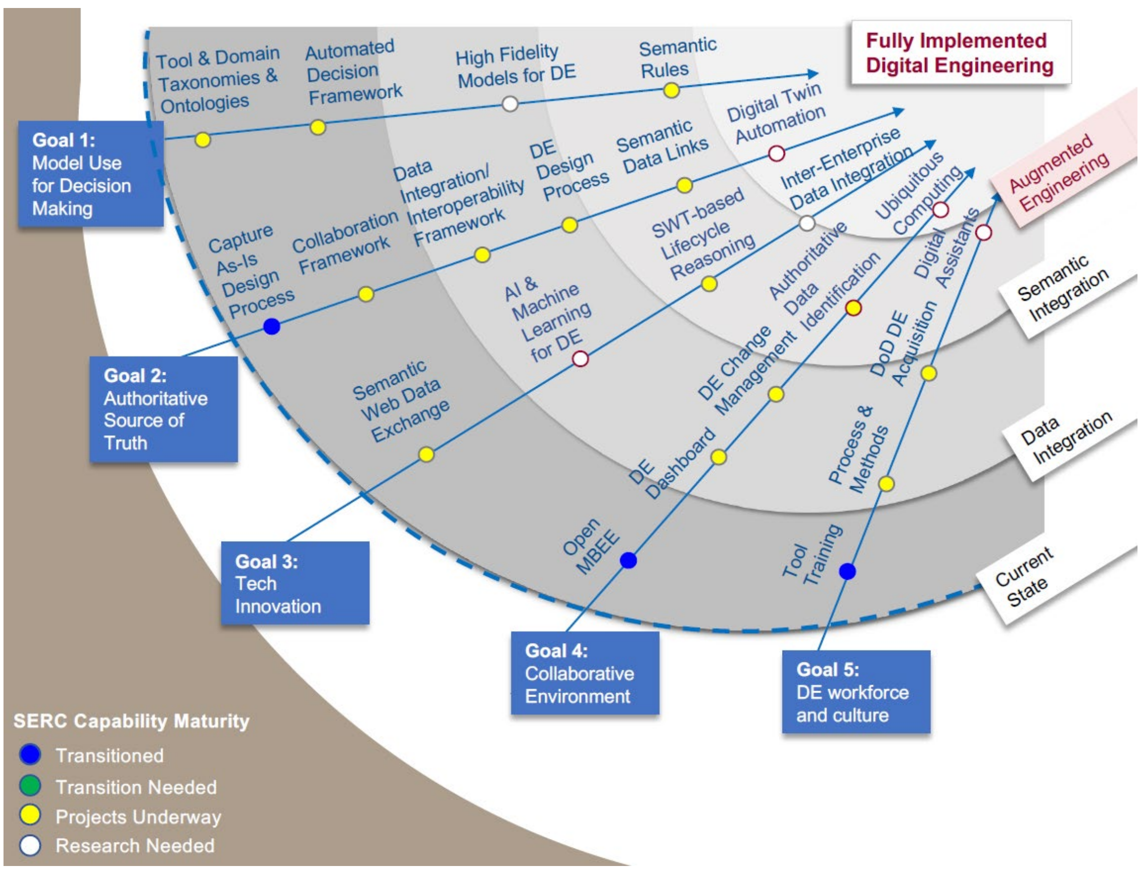


Figure 26. Roadmap for Enabling Technologies for Digital Engineering

2.12 AI-BASED ASSISTANTS TO AUGMENT HUMAN SYSTEMS ENGINEERS

The SERC five-year technical plan documents the plans for leveraging enabling capabilities such as AI. There has been much interest of late in how best to leverage AI and ML to enhance the capabilities of military platforms, other vehicles, and various technology-based processes. Section 11 provides potential guidance on how to use AI-based support to enhance the performance of the engineers that design and develop these platforms, vehicles, and processes.

A brief background on key constructs is first provided using a case study on supporting automotive engineering is then presented in some detail. The conceptual design of a Systems Engineering Advisor (SEA) is presented. This section concludes with consideration of the prospects for developing and deploying SEA.

2.13 WORKING SESSIONS AND SPONSOR-SUPPORTING EVENTS

A component of the research and required deliverables are conducting working sessions that inform the NAVAIR team about progress against the plan. These working sessions, totaling 50 to date) also inform the team about relevant information and feedback to scope the deliverables in the context appropriate for NAVAIR to leverage in SET; this has been especially important given the recent changes under SET and in resources supporting major functional areas such as the Modeling Methods (e.g., NAVSEM). We also use bi-weekly drumbeats to share status and updates. Each working session has a defined agenda and the SERC research is always covered in the context of the surrogate pilot. We keep a normal rhythm with the team using a weekly meeting of the surrogate pilot research team and NAVAIR contributors. The following provides a summary of the working sessions and other events, and a brief description of the contributions to the tasks and deliverables.

- Participates in Functional Leads bi-weekly meeting with SET leadership
- Conducts weekly meetings with the Surrogate Pilot team; meeting note and other relates resources are stored on All Partners Access Network (APAN) Research Group
  - Current team is approximately 32, including nine (9) from SERC, and the rest from NAVAIR or NAVAIR contractors
  - Details provided at APAN.org @ https://community.apan.org/wg/navair-set/set-surrogate-pilot/; group has 300 members
  - Details provided for Phase 2 at APAN.org @ https://community.apan.org/wg/navair-set/research/; group has 94 members (some material not yet marked Distribution A)
- Over 20 videos on APAN for many meetings and presentations on various subjects related to SET and the Surrogate Pilot experiments
- Outreach presentation to US Air Force Space and Missile Systems Center DE Team, June 11, 2020
- Presentation at NAVAIR University Brown Bag, *Modeling Methods for Specification Generation, Digital Signoffs and Cyber Applications,* May 2020 (194 Attendees)
- Outreach presentation to the OpenMBEE Google group discussing the *Digital Engineering for Systems Engineering Roadmap* and the Cyber Ontology Pilot on May 12, 2020

- Outreach providing industry presentation of Skyzer Pilot (INCOSE and Lockheed Martin) April 2020
- Demonstration at the Digital Engineering Environment at Digital Engineering Competency Framework Workshop March 12, 2020
- NAVAIR SE Transformation Working Session #50, February 13, 2020
- Participation at NAVSEM Review on January 14, 2020
- Demonstration of Cyber Ontology Pilot on December 16, 2019
- Presentation at SERC Sponsor Review on November 19, 2019
- NAVAIR SE Transformation Working Session #49, October 17, 2019
- NAVAIR SE Transformation Working Session #48, July 18, 2019
- NAVAIR SE Transformation Working Session #47, May 9, 2019
- Presentation at SERC Sponsor Research Review, November 19, 2019
- Presentation on Digital Engineering Enabled Artificial/Augmented Intelligence at US Army Combat Capabilities Development Command Armaments Center (CCDC AC) and SERC Technical Interchange Meeting, Nov. 14, 2019
- Presentations at National Defense Industry Association, Oct 22-24, 2019
  - Systems Engineering Transformation Surrogate Pilot Experiments: Doing Everything in Models to Demonstrate the Art-of-the-Possible
  - SysML-based, Collaborative Research Project Management
- Presentation at The Technical Cooperation Program (TTCP) Artificial Intelligence Strategic Challenge titled: AI & Model-Based Systems Engineering by Dr. Bill Rouse on August 13, 2019
- Presentation SERC Advisory Board on NAVAIR Surrogate Pilot, July 9, 2019
- Presentation SERC Research Council on MCE and DE Strategy Roadmaps, June 11, 2019
- Presentation SERC Research Council on MCE and DE Strategy Roadmaps, May 2, 2019
- Presentation SERC Research Colloquium on Model Centric Engineering – Enabler for System Security and AI based Solutions, April 15-16, 2019
- Participation in Bi-weekly Drumbeat

Other related NAVAIR/SERC events:

- Weekly participation on research related to System Engineering ontologies in the Semantic Technology for Systems Engineering (ST4SE); Dinesh Verma initiated an effort with the support of Chi Lin, Steve Jenkins and Mark Blackburn to bring a community of people together in an attempt to create and ecosystem on Semantic Web Technologies
  - Core ST4SE team general meets bi-weekly and there have been three face-to-face meetings
  - Effort being moved to INCOSE MBSE Patterns Working Group and the proposed name for the project is: Semantic Patterns for Systems Engineering (SP4SE) Project
- Bi-weekly participation in the Open Collaboration Group for MBSE that is providing support for adopting and contributing to OpenMBEE
  - This was critical to our success in deploying OpenMBEE for the Surrogate Pilot
  - Mark Blackburn is part of the OpenMBEE leadership team
  - Benjamin Kruse is part of the OpenMBEE committers team
- Collaborative Research Under:

- US Army CCDC-AC: Transforming Systems Engineering through Model-Based Systems Engineering (ART-002)
- Digital Engineering Metrics (WRT-1001)
- Digital Engineering Competencies (WRT-1006)
- Digital Engineering Policy model
- Architecting Digital Twins for Model-Centric Engineering (WRT-1025)

2.14 OUTREACH

NAVAIR created the Surrogate Pilot Group on APAN open to government, selected industry, and selected academia individuals as an approach to share the results and to solicit feedback. The group currently has over 300 members, and provides discussion threads about many of the topics discussed in this report such as:

- NAVAIR SET Surrogate Pilot Discussion Thread – main thread summarizing weekly events, discussions and status, with links to models, presentations and videos
- Collaboration Environment for Authoritative Source of Truth
- Model Management Methods and Practices, includes Project Usages
- Source Selection using Models
- Ontologies and Semantic Technologies
- Transformation of CDRL/DIDs through Model Artifacts and Digital Signoff in AST
- OpenMBEE Resources and Models
- Issue Tracking in Surrogate Pilot
- Releases

The APAN Surrogate Pilot and Research Groups also have other information and resources, such as:

- Organized folders with files that contain:
  - Models (e.g., mission, system, etc.)
  - DocGen Generated Views from Models
  - Information on Installing OpenMBEE with Docker
  - Presentations from working session, conferences and other events
  - Videos (e.g., of the weekly meetings and deep dive sessions)
- Wiki with links to resources, such as:
  - Ontologies for Systems Engineering
  - Surrogate Pilot SysML Modeling Guidelines
  - NASA/JPL Systems Engineering Cookbook
  - Views and Viewpoints

The APAN Research Group contains more that 60 products developed throughout this research in the form of reports, models, generated specifications, and videos. Much of the content from Phase 2 of the Surrogate Pilot is in the Research Group, because it has many items that are not yet marked as Distribution A.

2.15 DELIVERABLES

As required by the contract, we produced:

- Technical Management and Work Plan
- Interim Technical Report
- Bi-monthly status reports
- Final Technical Report

We have also produced models, demonstrations, videos, examples and assembled tools for an IME for the surrogate pilot. The following provides a list of models that have been produced and supplied to NAVAIR:

- APAN (apan.org)
  - Tracking progress of the surrogate pilot using Discussion group that is linked to related evolving artifacts
  - Posting documents into both the general NAVAIR SET area as well as the Research area
- Successfully created instantiation of OpenMBEE both at Stevens and on (AWS) to be used in the surrogate pilot
- Demonstration of OpenMBEE Model Development Kit (MDK)/DocGen
- Automated OpenMBEE installation mechanism using Docker [75]
- Surrogate Systems Engineering and Management Technical Plan Model (new)
- Surrogate Mission Model for Skyzer
- Surrogate System Model for Skyzer
- Surrogate Capability-Based Test & Evaluation/Mission-Based Test Design Model
- Skyzer Request for Information package
- Skyzer Statement of Work Model, and associated Section L & M (Technical Evaluation Criteria)
- Skyzer Request for Proposal (RFP) Response by Surrogate Contractor
  - Source Selection Technical Evaluation embedded in RFP Response Model
  - Measures and Metrics Derived from Models leads to measures/metrics
    - How many Digital Signoffs are in the model
    - How many Digital Signoffs are approved, rejected, undefined (no action taken)
    - How many Digital Signoffs have a risk higher than Medium
    - Rate of Approval Signoffs
    - Ratio of Rejected Signoffs (to total)
    - See Video: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/253172
- Use cases, demonstration and video for doing Digital Signoff in the model (View Editor) against example criteria from the System Requirement Review (SRR)
- Briefing on creating SysML Activity Diagram for Monterey Phoenix in support of RT-176
- MDAO demonstrations
- Videos for the operations of OpenMBEE with Teamwork Cloud to be used on surrogate pilot

- RFP Configuration Index for Surrogate Pilot Release:
  - For the RFP (Request For Proposal) there are read-only tags created in the View Editor, capturing the state of the documents.
    - There are RFP tags for Mission Model Views IM90-30, System Model with Views IM90-20, IM20, IM30 spec, IM30 evaluation and SOW.
    - Their documents can be downloaded as pdfs here: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/235974
    - The matching SysML models are available here: https://community.apan.org/wg/navair-set/set-surrogate-pilot/m/documents/235977
  - Their project versions in Teamwork Cloud are:
    - Surrogate Pilot Project Model
    - WRT-1008 Project Model (like SEP)
    - Viewpoint Library
    - Skyzer Mission Model (NAVSEM 1 & 2)
    - Skyzer Mission Model Document
    - Skyzer System Model (NAVSEM 3 & 4)
    - Skyzer System Model Document
    - Skyzer Surrogate Contractor Model
    - Skyzer System Evaluation Model
    - Skyzer System Estimation Model
    - Skyer CBT&E/MBTD
    - Skyzer Statement of Work (SOW) Model
    - 516C-TACC-Airworthiness
    - Cyber Ontology Pilot Model
  - The used tools and their versions are:
    - Magicdraw 18.5 SP3 or Cameo Systems Modeler 18.5 SP3
    - Magicdraw 19.0 SP2 or Cameo Systems Modeler 19.0 SP2 (recent transition)
    - MDK plugin v. 3.3.6 (v. 4.1.3 – recent upgrade)
    - MMS v. 3.2.2
    - View Editor v. 3.2.1
    - Teamwork Cloud 18.5 SP3 and Teamwork Cloud 19.0 SP2 (recent transition)
- Deployment of the Integrated Model Environment for the AST as shown in Figure 6, which include:
  - Docker mechanism for OpenMBEE on Amazon Web Services (AWS)
  - Docker provides a mechanism to install OpenMBEE with a single script, and this has allowed us to deploy OpenMBEE on AWS, at Stevens, at Georgia Tech, and at the Surrogate Contractor site; this approach allows us to not only provide models at Government Furnished Information (GFI), but also provide the environment that we used to construct the GFI

Part II: Task Detail Summary

Part II provides details associated with the research use cases listed in Section 1.3. An extensive amount of material covered in Part II of the RT-141 final report [27] and RT-157 final report [28] is still relevant information to this research, but has not been included in this report. For the convenience of the readers, we list some of the key topics that are relevant and still evolving from those reports and the final technical report of RT-195 [25]:

- Traceability and scope of data collection of state-of-the-art MCE relevant topics collected from global scan of industry, government and academic
- Characterization of canonical reference architecture of an Integrated MCE Environment (aka Digital Engineering Environment [DEE]), some of which are represented in the AST shown in Figure 6
- Model cross-domain integration within the underlying single source of truth
  - Information Model for an Authoritative Source of Truth
  - Requirement architectures that relate to ontologies
- Model Integrity – developing and accessing trust in model and simulation predictions
- Modeling methodologies
- Multidisciplinary Design, Analysis and Optimization (MDAO)
- Example models
- Modeling and Methods for Uncertainty Quantification
  - Dakota Sensitivity Analysis and Uncertainty Quantification (UQ)
  - Overview of Quantification of Margins and Uncertainty
- Modeling Methods for Risk

3 UC00: Ontologies and Semantic Web Technologies

This use case investigates the development and use of ontologies and more generally semantic web technologies (SWT) for reasoning about completeness and consistency across cross-domain models. These capabilities support enforcement of modeling methods and support for model integration through interoperability. We summarize some research efforts and findings related to SWT in this section. For example, we have developed the IoIF under RT-168 [30], which has been used for preliminary demonstrations such as the Cyber Ontology Pilot described in Section 2.1. IoIF provides a platform to load ontologies, such as a domain, application ontologies, for integration with discipline-specific tools and model agnostic decision ontology. Section 3.5 provides additional details about IoIF.

There is increased interest in the topic of ontologies and SWT as awareness has increased significantly in the past two years. Based on the Cyber Ontology Pilot, we have evidence that SWT can enable an AST, approaches to methodology enforcement, and conformance that also support model integrity as reflected in Figure 4. Barry Smith who led the team that developed the Open Biomedical Ontologies (OBO) joined our team in 2019. Barry also led the development of the Basic Formal Ontology [192]. OBO contributed to solving the human genome, but also exemplified how to develop modular and interoperable ontologies using BFO. We coordinated a working session in 2018 to develop a plan for creating interoperable Navy and DoD domain ontologies. Barry led the effort to develop the plan for creating the Navy SYSCOM and DoD ontology, which resulted in the Cyber Ontology Pilot and demonstration in 2019 discussed in Section 2.1.

This section summarizes relevant efforts researched over the past year on this topic in addition to the description and examples that explains how we are using the NASA/JPL IMCE ontologies [134] in the surrogate pilot (See RT-195). It is also important to note that SWT is an enabler for capabilities such as Artificial/Augmented Intelligence (AI) and Machine Learning, because they provide a means for representing knowledge as described in INCOSE Insight paper: Knowledge Representation with Ontologies and Semantic Web Technologies to Promote Augmented and Artificial Intelligence in Systems Engineering [94], and is also a related interest of our research task WRT-1025 Architecting Digital Twins for Model-Centric Engineering.

As described in earlier technical report such as RT-170, some organizations, like Airbus reported at the NASA/JPL MBSE Symposium in January 2019 on their evolving using of ontologies and SWT as part of their integration and interoperability strategy. Another recent example that was introduced at the September 2018 Navy and DoD Ontology Workshop involved an effort defining an ontology for the ISO 15288 Systems Engineering Process standard [155]. The SysML version 2.0 is looking to formal semantics for the metamodel and be able to round trip between SysML models and OWL2 [210].

Under our current CCDC-AC funding we have developed a number of interoperable ontologies, including the Cyber Ontology Pilot, that use ontologies to reason about information captured in different tool for different domains; notionally this is discussed in Section 3.1.

3.1 Challenge of Cross-Domain Model Integration

We believe that organizations should take advantage of tool-to-tool integration when possible, but in working with our sponsors and interacting with industry and government organizations, this is not always possible, or is known to be challenging [185]. The challenge of cross-domain modeling integration is illustrated using the following example. While an aircraft may have thousands of objects, consider the relationships for a refueling valve of a UAV, as shown in Figure 27. There is one object discussed in this example (i.e., Valve), however, there are many domains that bring in cross-domain relationships to that Value, along with other objects, such as:

- Mechanical **Domain**
  - Valve connects to a Pipe
- Electrical **Domain**
  - Switch opens/closes Value
  - Maybe using combinations of hardware and software
- Operator **Domain**
  - Pilot remotely sends message to control Value
- Communication **Domain**
  - Messages sent through networks: 1) within the aircraft system, and 2) from the remote operator
- Fire control **Domain**

- Independent detection to shut off Valve
- Safety **Domain**
  - Looks top-down at potential hazards through Fault Tree Analysis (FTA)
  - Looks bottom-up using Failure Models and Effects Analysis (FMEA) to analyze failure impacts from specific designs of components

Figure 27. Example of Cross Domain Relationships Needed for System Trades, Analysis and Design

A problem is understanding the cross-domain impacts of designs and analyses that might be needed if one object within these related domains change. In general, there are different tools used in different domains (e.g., electrical, mechanical, fluids), and the tools are often not integrated, nor are they able to share semantically-relevant data. Tool integrations are often dynamic consequences of customer requirements to continue improving the tools, thus the tools are constantly being updated, which further adds to the challenge of tool-to-tool integration. Tool integrations are not simply statically putting a certain set of tools together. Depending on the varying needs of tasks from particular stakeholders, the types of tools needed, their execution sequences, the interdependencies of data flow among them vary from case to case. In addition, the problem often gets worse when attempting to maintain an integration for different versions of tools. Figure 28 illustrates the dynamic nature of tool integration [185].

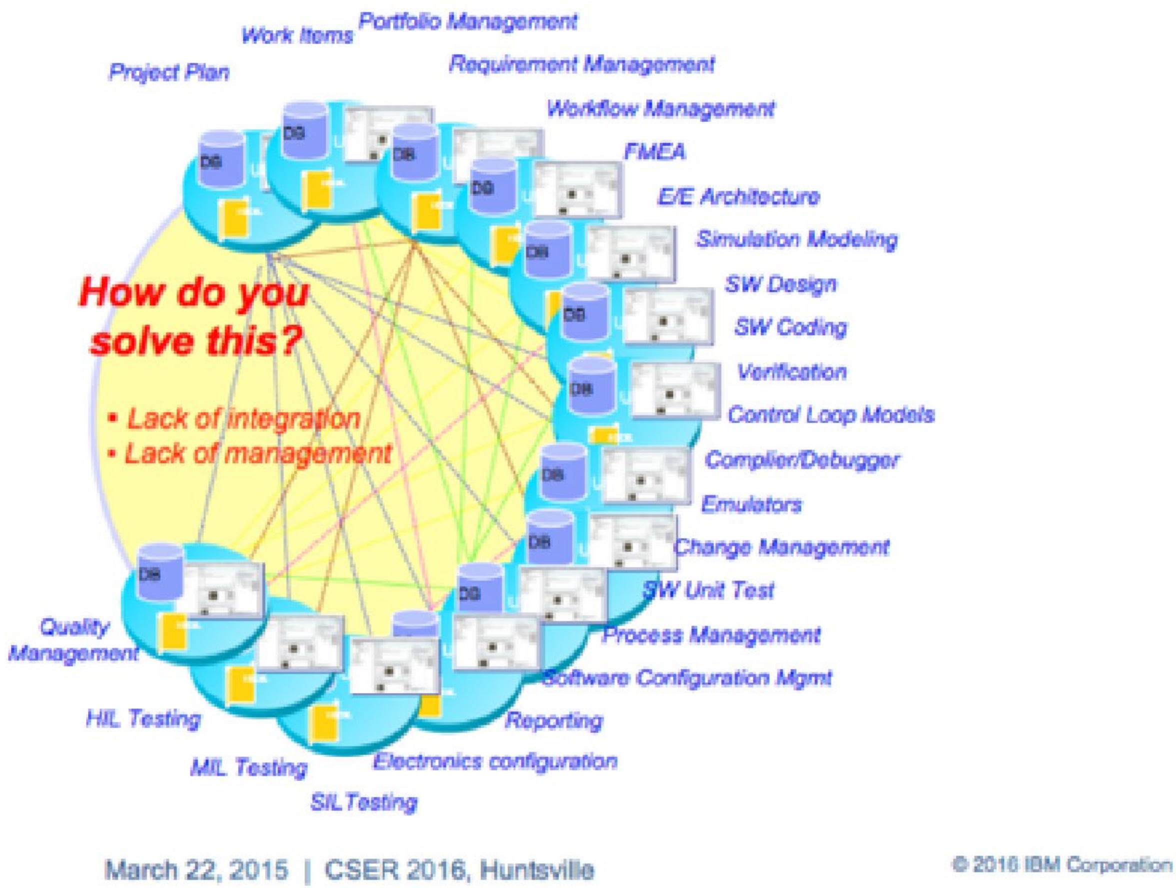


Figure 28. Coordination Across Tools Based on User Story

As shown in Figure 29 [63], there can be a very large set of tools that can be used to support analysis and to develop the needed data and information across all of the domains. Notionally the Reference Technology Platform (RTP) [7] is the collective set of tools that an organization has in their inventory. Any specific program creates a RTP instance. A key challenge is integrating the assembled tools, especially when they may not have been created to be integrated, and equally important is that the methods for assembling and using these analysis workflows is largely in the heads of a few subject matter experts, as explained by our sponsors. Therefore, it is important that appropriate methods are applied to the selected tools that are assembled for use on a project or program. As a secondary objective that is being demonstrated as a leading-edge approach by NASA/JPL is to ensure models are created that comply with established modeling patterns that have been formalized using ontologies. We provided information on the NASA/JPL approach, which transforms the model information into a tool-neutral AST based on ontologies, and then uses standard SWT to apply checks to ensure completeness and consistency [110].

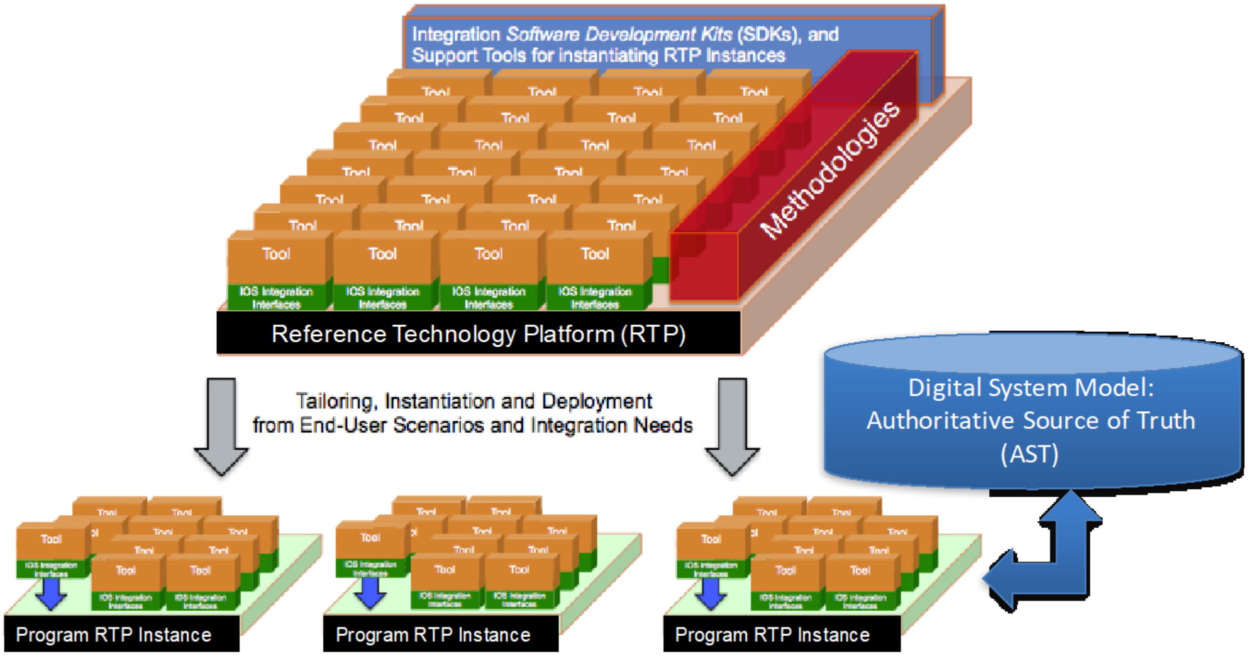


Figure 29. Appropriate Methods Needed Across Domains

3.2 Semantic Web Technologies and Ontologies

Briefly, the SWTs are based on a standard suite of languages, models, and tools that are suited to knowledge representation. Figure 30 provides a perspective on the SWT stack, which includes eXtended Markup Language (XML) [148], Resource Description Framework (RDF) [211], Web Ontology Language (OWL) [208] (i.e., OWL2), the SPARQL Protocol And RDF Query Language (SPARQL) [212], and others. RDF can describe instances of ontologies – that is, the data for particular model instances, where OWL relates more to metamodels describing the class of information and relationships that can be characterized as RDF instances. The SWT was created to extend the current Internet allowing combinations of metadata, structure, and various technologies enabling machines to derive meaning from information, both assisting and reducing human intervention. This technology is generally applicable to many different applications, and we discuss a few in the following section.

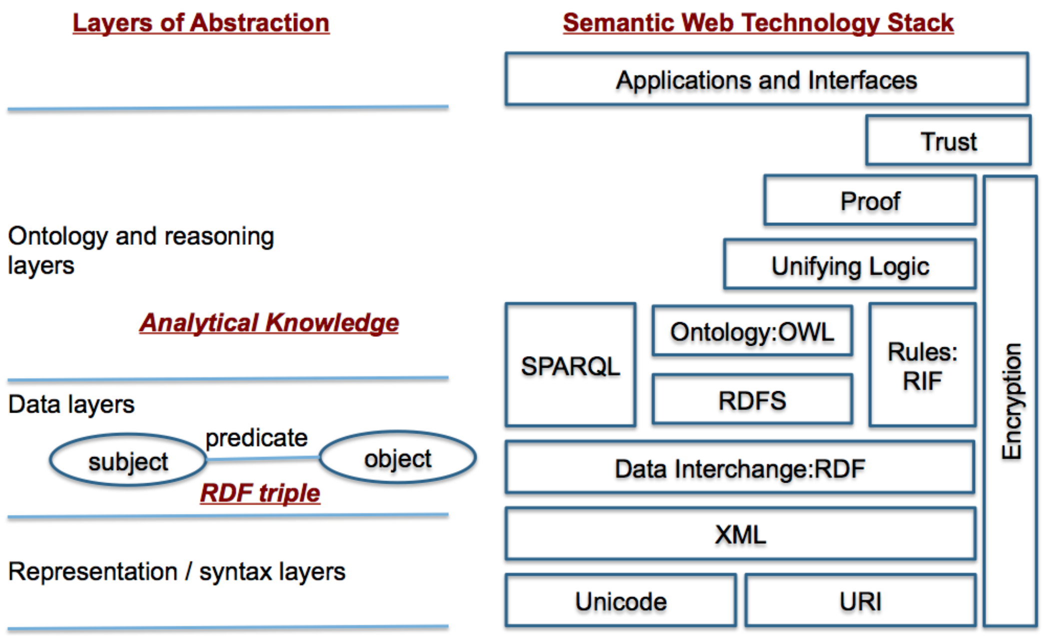


Figure 30. Semantic Web Technologies related to Layers of Abstraction

3.3 NASA/JPL Integrated Model Centric Engineering (IMCE) Ontology

Our research reflects through demonstrations and presentations some of the different uses of SWT and ontologies. The following figures have been taking from *Model-Centric Engineering, Part 3: Foundational Concepts for Building System Models*. Figure 32 shows the IMCE ontology concept that is being evolved by NASA/JPL. Their process involves:

- Creating the foundational IMCE systems engineering ontologies [134] derived from modeling patterns (reflected in Figure 31), including:
  - Mission ontologies
  - Project ontologies
  - Analysis ontologies
  - The rationale underlying these ontologies are currently being documented by NASA/JPL's Steve Jenkins are part of a new effort called the Semantic Technologies for Systems Engineering Foundation
- The ontologies can be created with any OWL modeling tool such as the open source Protégé
- The ontologies are transformed into SysML profiles
- The SysML profiles are loaded into a modeling tool (MagicDraw in this case) for creating models
- The profiled SysML models are exported back into OWL statements
- Checks for completeness, consistency and well-formedness can be performed

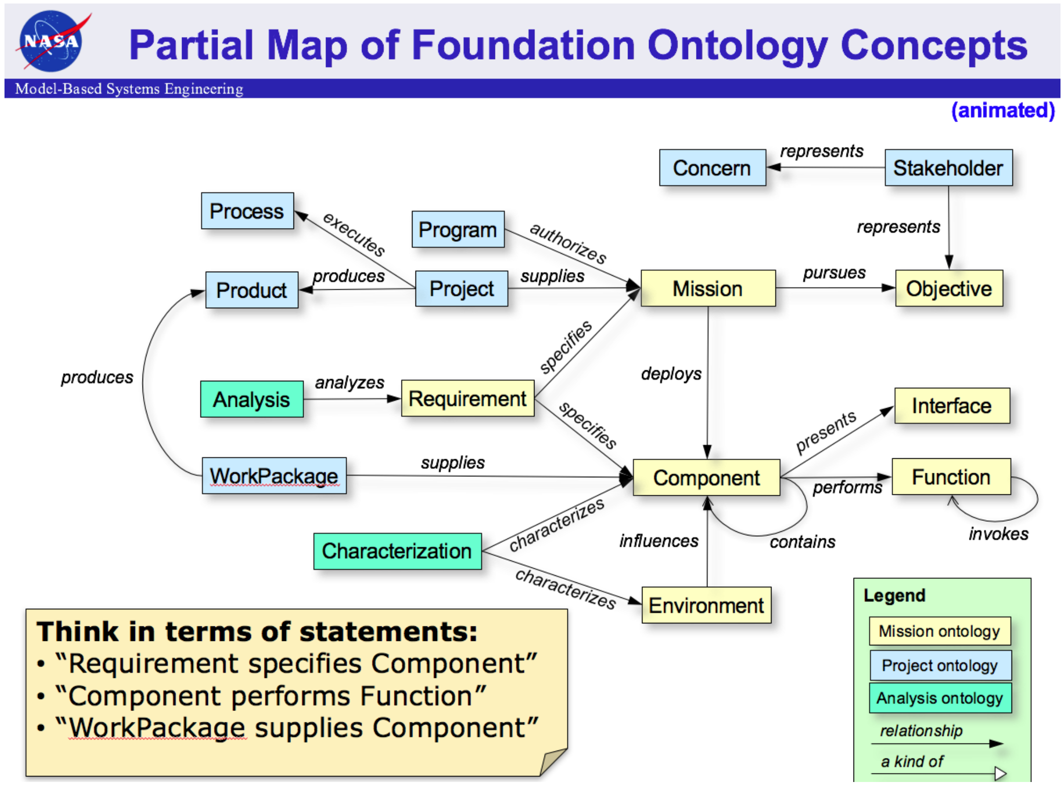


Figure 31. NASA/JPL Foundational Ontology for Systems Engineering

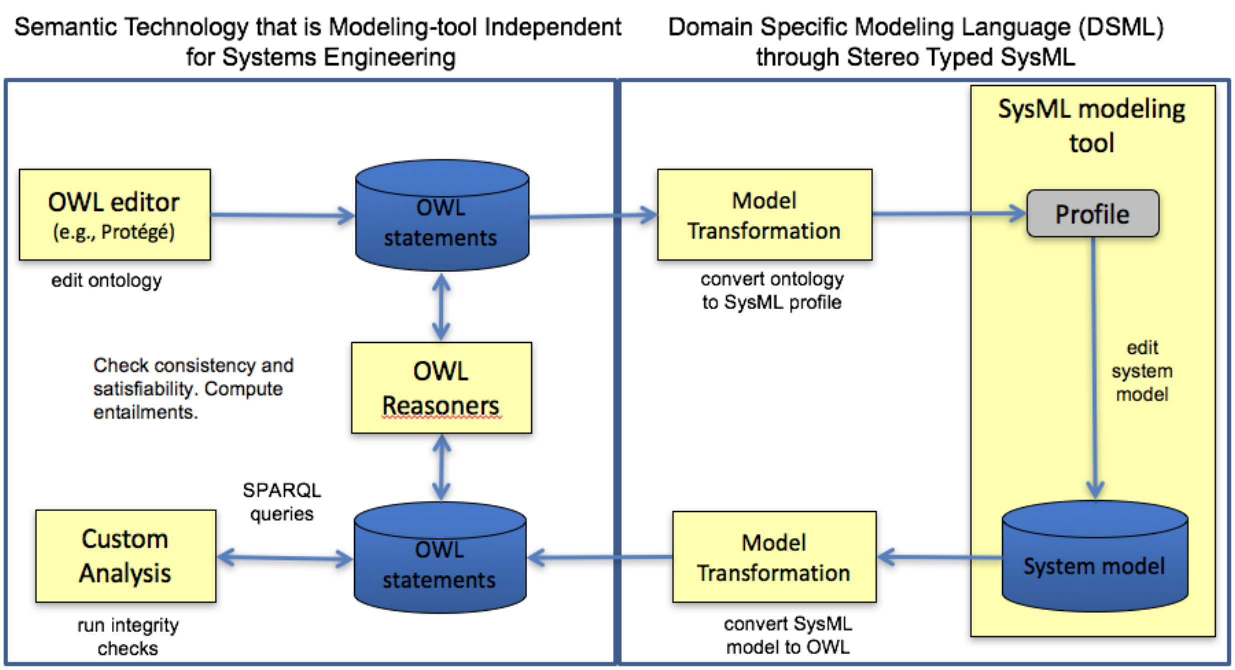


Figure 32. From Ontologies to SysML Profiles and Back to Analyzable OWL / RDF

Figure 33 shows the various representations associated with the concept described in Figure 32:

1. The modeled statement in English is: "Component performs Function"

2. The OWL/RDF representation of the statement in low-level XML for this same statement
3. The Profile and Stereotypes used in the model (loaded into a SysML model)
4. The Stereotypes used in a SysML Block Definition Diagram (BDD) – while SysML is the graphical language that is used, the stereotypes derived from the ontologies effectively make the use in SysML into a Domain-specific Modeling Language

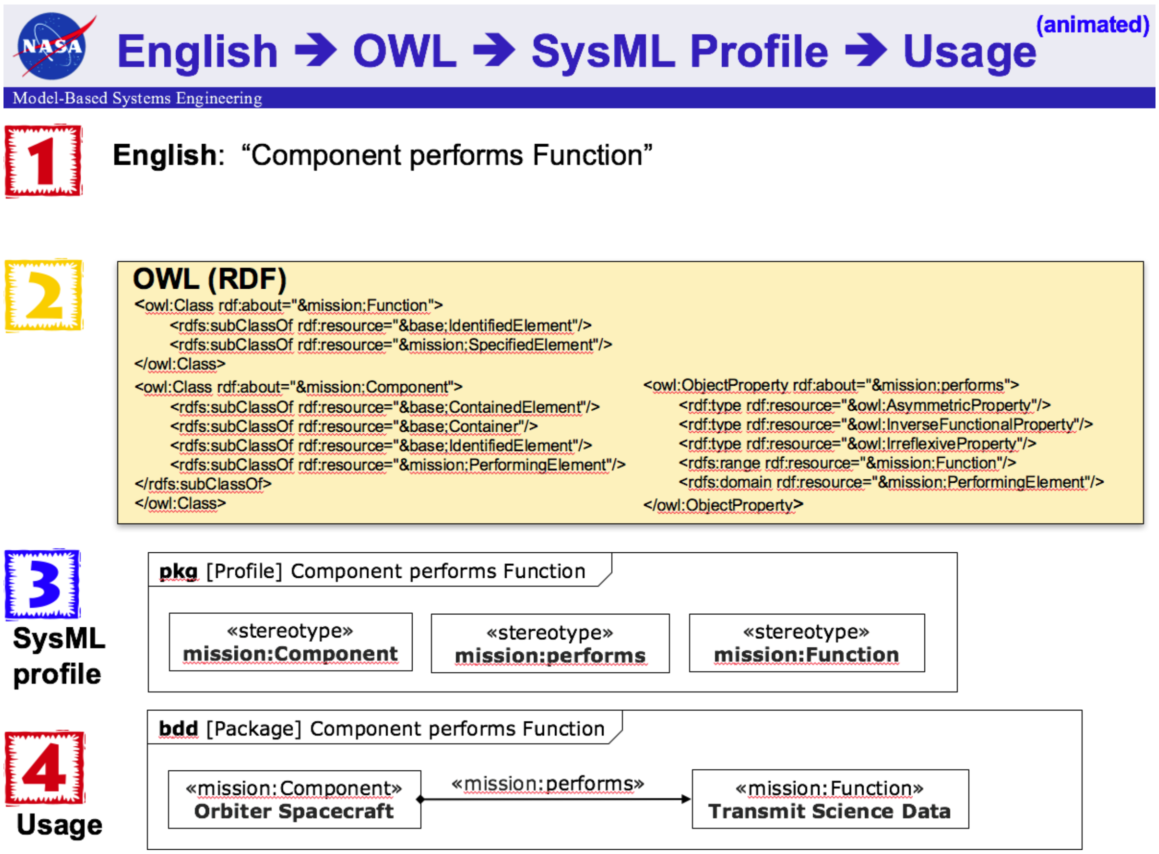


Figure 33. Multiple Representations in Process

3.4 Digital Environment at Airbus Space

We have discussed the importance of an underlying information model (e.g., ontology) to enable the cross-domain integration of information in an AST [27]. The concept of semantic analysis that is integrated within the Integrated Modeling Environment (IME) is not limited to NASA/JPL. Ralf Hartmann, the Vice President of Enterprise Digitization for Airbus, gave a presentation at the NASA/JPL Symposium and Workshop in Jan 2017 [94], continued the message at the Phoenix Integration International Users' Conference in April 2018 [96], and had three related presentations at the NASA/JPL Symposium and Workshop in Jan 2019. While there were many points made in these presentations, of particular interest was a historical perspective on how they have been assembling a system design engineering environment to cover the entire lifecycle. The representation of the environment as shown in Figure 34 was particularly interesting as it relates to the concept of a semantically rich information; this pertains to the box in the middle call RangeDB Data Management. This replaced a commercial product with their own infrastructure functionality (i.e., "secret sauce") that provides a Semantic Data Model for multi-disciplinary Integration as shown in Figure 36. This effort confirms why we believe SWT will play a key role to characterize the underlying information model for both ARDEC and NAVAIR, and again reflects positively on the NASA/JPL use of SWT as discussed in this section.

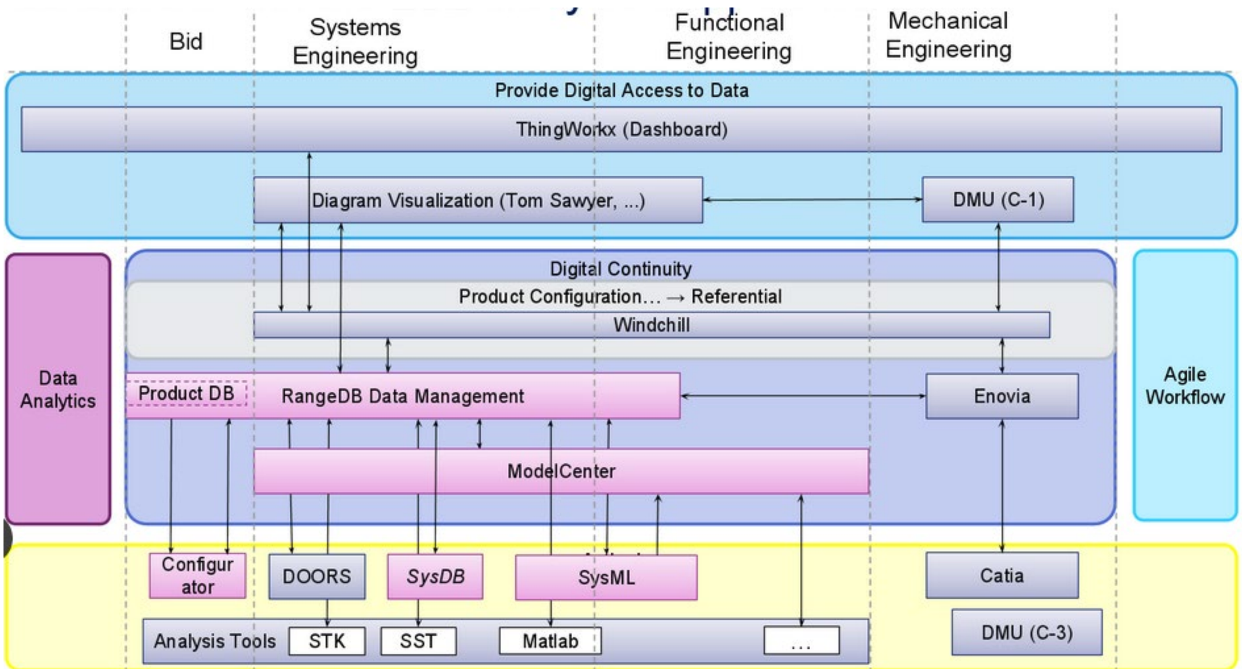


Figure 34. Airbus Digital End-to-End (System & Product) Engineering

Finally, the Hartmann briefing also included an associated roadmap as shown in Figure 35 that was structured in two dimensions:

- Technology clusters
  - Requirement engineering & V&V
  - MBSE and design
  - Engineering data lifecycle management
  - Collaborative engineering
- System engineering technology integration levels
  - Data integration (just connecting data)
  - Semantic integration (identifies rules how to connect and understand data)
  - End-to-end (knowledge management)

The key reflection on this roadmap is acknowledging the increased need to formalize the underlying information model as we move to the right (i.e., future), which can exploit more computational automation such as computational intelligence (i.e., AI, machine learning, etc.), enabled by high performance computing.

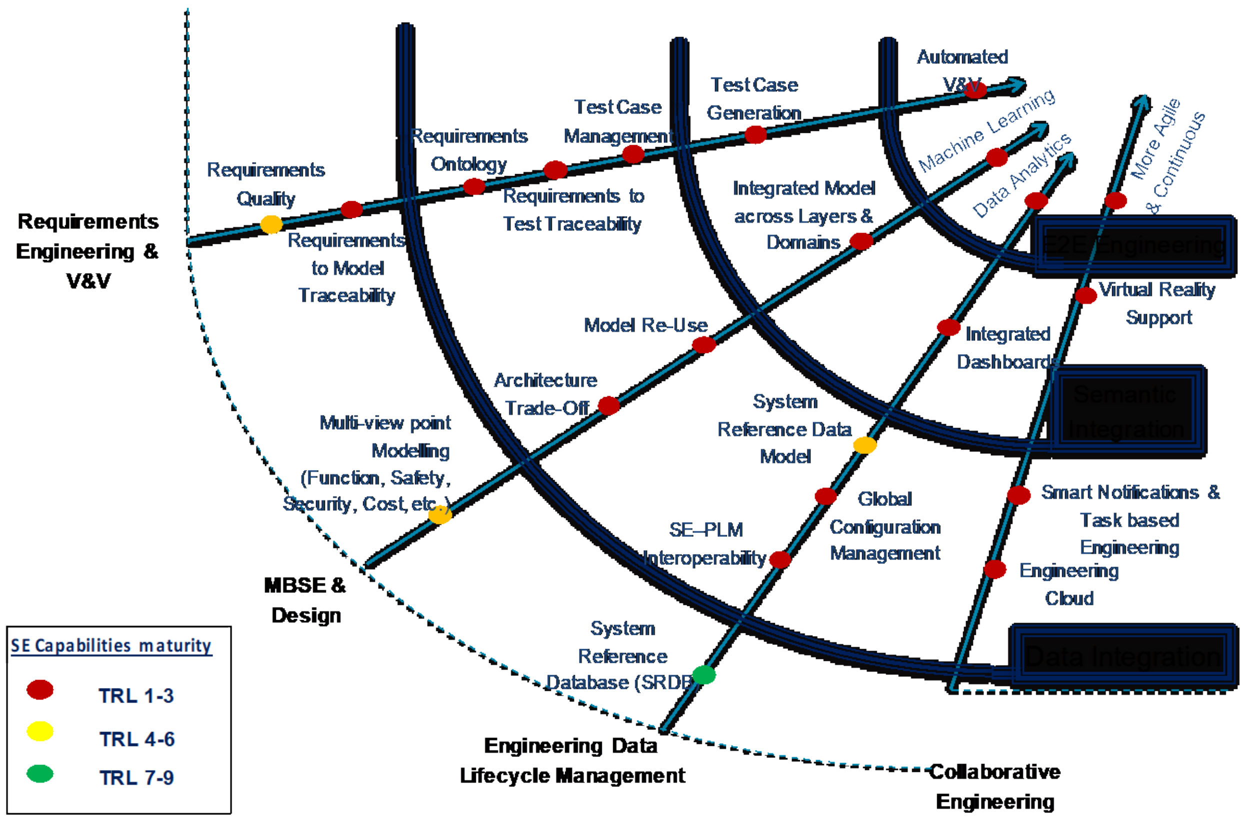


Figure 35. Airbus Roadmap Shown Bands of Digital Engineering Integration

3.5 Integration and Interoperability Framework (IoIF) with Semantic Web Technologies

The SERC RT-168 research team continues to evolve the IoIF and integrate other capabilities with emphasis of demonstrating interoperability through SWT [30], as discussed in Section 2.1 and shown in Figure 36. We demonstrated a Decision Framework enabled by SWT with a decision ontology starting from a system model in SysML. This system model represents a number of UAV alternatives derived from a book chapter developed by Matt Cilli [55]. We demonstrated tool-to-tool integrations, for example the UAV SysML model integrates with ModelCenter, through MBSEPak, to illustrate the MDAO concept for alternative analysis (see Section 4.6). The demonstration uses OpenMBEE MDK plugin to transfer SysML information to MMS. IoIF capabilities transform the SysML information stored in OpenMBEE MMS into the IoIF SWT (i.e., RDF4J triple store) to align with the decision ontology. The transformed information from MMS, now stored in IoIF SWT is transformed into a representation to support visualizations of the various tradeoffs in Tableau [197]. IoIF now provides a substantial foundation for follow-on research and other synergies that have been discussed with our sponsor about elevating the Decision Framework concept in the context of IoIF to mission scenarios, or combinations of mission scenarios given system capabilities that can be composed into mission capabilities.

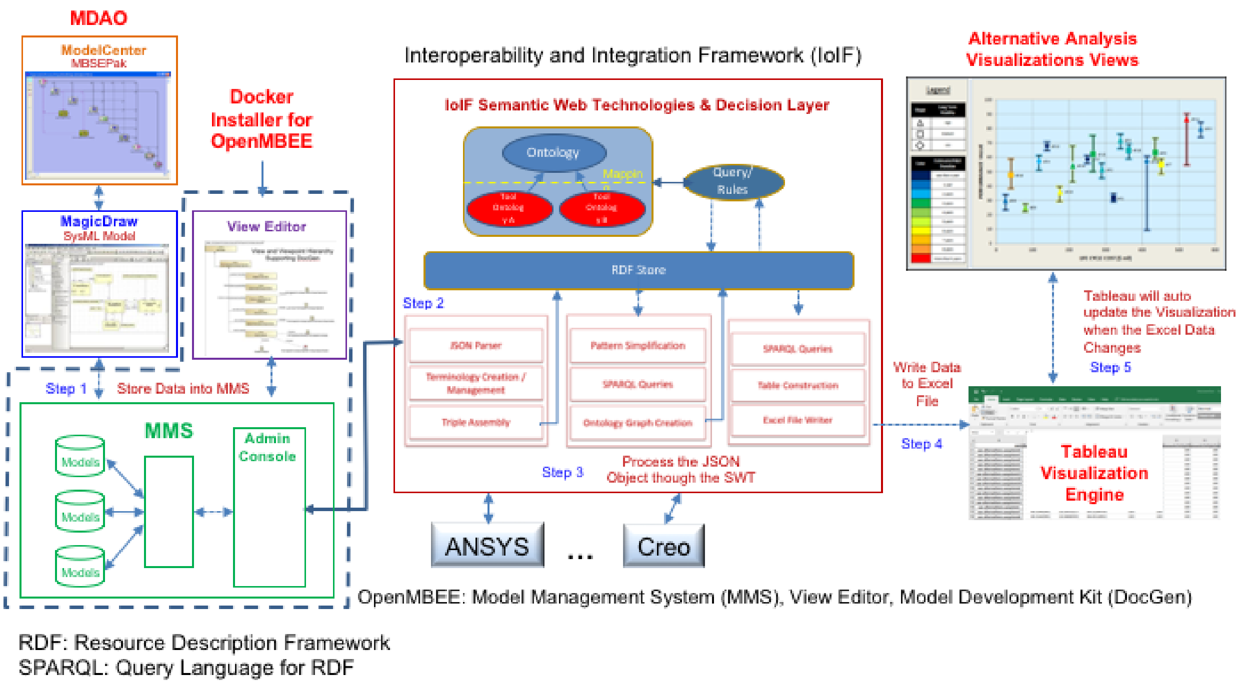


Figure 36. Interoperability and Integration Framework (IoIF)

3.6 DECISION FRAMEWORK RELATED TO CROSS-DOMAIN INTEGRATION

Working with our ARDEC sponsors and collaborators, we have advanced the concept of the Decision Framework and demonstrated the technical feasibility of capturing needed input information from models as discussed in Section 3.5. Figure 37 provides a perspective on tradition systems engineering flow to illustrate where the Decision Framework fits into the overarching analysis workflow:

- CONOPS derived from simulation and gaming technologies are used to look at scenarios for trade space analysis of mission alternative
- “What” we want – requirements and constraints for a system of System of Systems (SoS) mapping back to the mission requirements
- “How” (1 or more) – designs to achieve the “What”
- “How well” (usually many) to assess the “How” using analysis, testing, reviews and assessing how the design satisfies the requirements, given the constraints to achieve the mission concept
- The underlying Information Model (ontology) links the data or metadata from many different domains
- We have demonstrated the initial viability of this Decision Framework concept as implemented through IoIF as shown in Figure 36

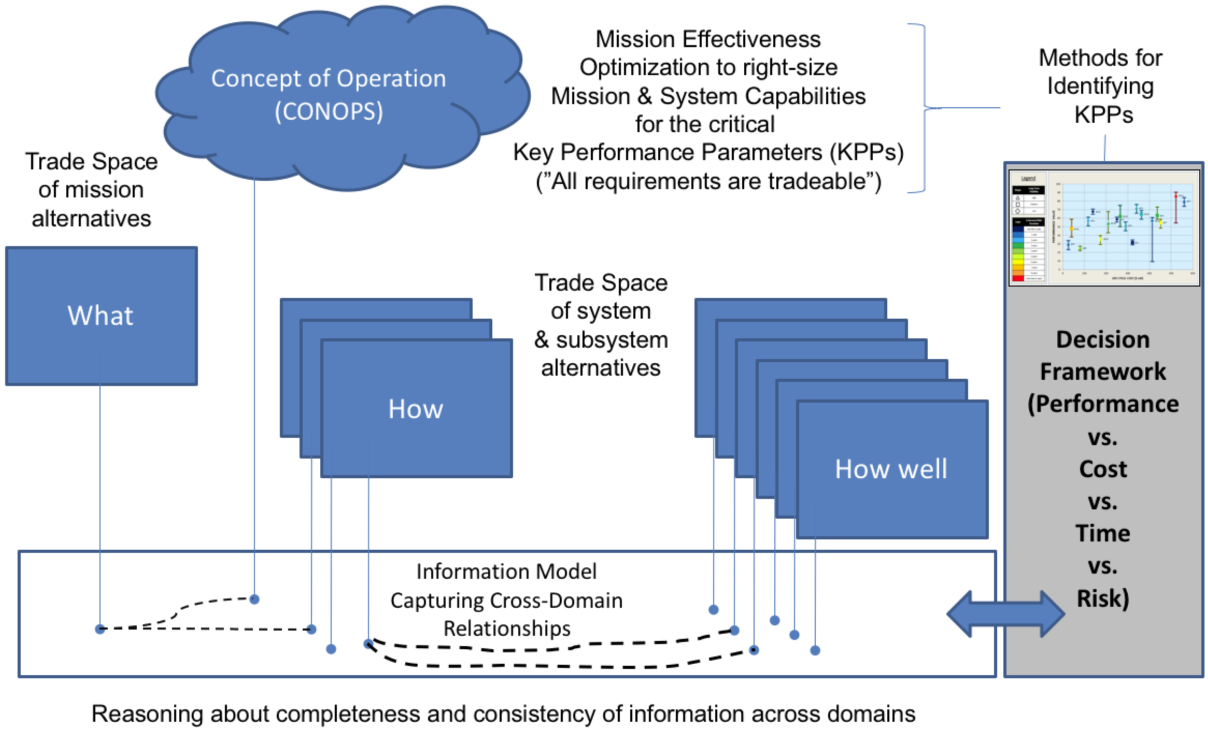


Figure 37. Context of System Engineering of Challenge Areas

As discussed in the next use case, we have developed using Phoenix Integration's ModelCenter [161] and MBSEPak, with SysML a way to formalize some of the inputs needed for the Decision Framework.

3.7 Semantic Integration Strategy for an Interoperable Systems Engineering Ecosystem

Dr. Douglas Orellana presented some research at the NDIA 2019 event that is being pursued with a start-up company SBE Vision that is looking to develop something that seems similar to the IoIF called the Semantic Data Broker. A demonstration at NDIA showed how the Semantic Data Broker uses interoperable ontologies, based on BFO to use interoperability through SWT to interface tools for exchanging different types of data such as: requirements, architectures, V&V, management and decision support. In conjunction with support from our CCDC-AC sponsor, we have established relationships with SBE Vision to test their tools in 2020.

4 UC01: Multidisciplinary Design, Analysis and Optimization (MDAO)

This use case discusses various uses of Multidisciplinary Design, Analysis and Optimization (MDAO) at the mission, system and subsystem levels, which provides a means for continuous assessment of trades (i.e., analysis of alternatives) to support KPP assessment; this also relates to representations within system models. This use case also investigates the methods to trace capabilities to the relevant design disciplines and to perform cross-domain analyses through MDAO for problem and design tradespace analyses. In addition, to characterizing elements of the framework, cross-domain relationships, but also characterize the methods used to support MDAO in a tool independent manner.

During Phase 1 of the surrogate pilot a small example using MDAO was developed as discussed in Section 4.7. For Phase 2, we look to use MDAO as part of the tradespace analysis investigating alternative for the landing gear deep dive; specifically, our plans are to use MDAO to analyze the trade between a hydraulic vs. electrical landing gear. For example, the possible benefits for an electric system are that it reduces weight of the aircraft, which might increase speed and endurance, but a hydraulic landing gear system might be better for landings with heavy payloads especially in high sea states, and therefore in the long run be more reliable.

MDAO is an approach for calculating optimal designs and understanding design trade-offs in an environment that simultaneously considers many types of simulations, evaluations, and objectives. For example, when designing an air vehicle, there is typically a trade-off between maximizing performance and maximizing efficiency, where calculating either of these objectives require multiple disciplinary models (geometry, weight, aerodynamics, propulsion). MDAO prescribes ways to integrate these models and explore the necessary trade-offs among the objectives to make a design decision. While the theoretical foundations of MDAO are well-established by academics, a number of barriers to practical implementation exist. Chief among these is the lack of model integration, which prevents designers of one subsystem from easily assessing how changing a design variable affects the results of other subsystems' models or simulations. A second challenge or need is to have the MDAO solvers be implemented and packaged in a way to be integrated in an MDAO workflow. MDAO analyses can be computationally demanding, and therefore a third area of research being investigated by our team is using an appropriate workflow architecture that balances the need for optimization and speed [53].

As illustrated by some of the examples shown below, we can extract the key parameters in these various mission and system simulations. These parameters are fundamental to the MDAO workflows. We need to combine those parameters for different elements of a workflow, but we must also characterize our KPPs; for example, a surveillance UAV range or endurance (e.g. number of hours of flight) would be examples of possible KPPs. These KPP are modeled as the outputs from running the MDAO through different optimizations. The other aspect of the method involves identifying the constraints that must be characterized with respect to KPPs (i.e. outputs) with respect to selected inputs.

4.1 MDAO Objectives

The following provides more specific objectives for MDAO use:

- Assessing the impacts of individual design changes on system capabilities
- Supporting early-phase (conceptual design), system-level trade-off analysis using previous evaluation results from existing models
- Develop strategies to transform the contracting process so that RFPs can be designed more flexibly toward value-based (rather than target-based) design

In pursuit of these objectives, the research activities entail:

- Develop generic multidisciplinary models of NAVAIR-relevant system examples, including analyses of the geometry, structure, aerodynamics, propulsion, stress, thermal and performance capabilities, to be used as an example case
- Investigate MDAO architectures such as multidisciplinary feasible and interdisciplinary feasible to compare simulation results when searching for optimized solutions [50][51][53]
- Explore using systems representations (e.g. SysML, Domain Specific Models) to map all inputs (parameters and variables) and outputs (objectives, constraints, intermediate parameters) among the individual models
- Conduct trade studies on the UAS design using established approaches and tools for MDAO, exploring different approaches, tools, and visualization techniques to most effectively display information and uncertainty for decision-makers
- Explore ways that previous trade study results on detail-phase product design can be useful toward new conceptual design of products with varying mission capability requirements
- Use the surrogate pilot to understand the barriers to implementing this type of MDAO, culturally and practically/theoretically
- Explore more general ways to map and coordinate subject matter experts (SMEs) and data, models, and meta-models for improved requirements setting for RFP or CONOPS, and value-driven design
- Explore the ways that MDAO and MBSE tools can work together

One of the objectives of this use case is to leverage the most powerful tools that are often used by industry as well as government organization. We have secured academic licenses to Phoenix Integration's ModelCenter [161]. Further, while research to date examines the use of MDAO at the systems level. We have received additional academic licenses to ModelCenter to investigate the use of MDAO at the mission and subsystem levels. Based on the concept of the SET Framework, MDAO analysis at the subsystem level will probably be carried out by industry that is developing the designs. We do include an example for the Surrogate Pilot contractor model in Phase 2 using ModelCenter.

4.2 MDAO Methods

Using tools like ModelCenter, we have investigated, demonstrated and described methods for applying such tools, and also identified relevant research questions in the context of those advanced tools. For example, the steps for an MDAO method may be characterized as:

- Describe a workflow (scenarios) for a KPP (e.g., range, notionally similar to surveillance time)
- Determine relevant set of inputs and outputs (parameters)
- Illustrate how to use a Design of Experiments (DoE) and use analyses such as sensitivity analysis and visualizations to understand the key parameter to use with optimizations
- Illustrate Optimization using solvers with key parameters and define different (key objective functions – on outputs) to determine set of solutions (results often provided as a table of possible solutions)

- Use visualizations to understand relationships of different solutions
- Investigate MDAO architectures alternatives such as multidisciplinary feasible and interdisciplinary feasible to compare simulation results when searching for optimized solutions [51][53]

A number of methods can be applied to formulate multidisciplinary optimization problems, develop useful surrogate models, and calculate optimal and Pareto-optimal solutions. Optimization problems can be formulated with a number of different objectives by converting some objectives to targets or constraints, summing the objectives with value-based and unit-consistent weighting schemes, or multiplying and dividing objectives by one another. Surrogate models are often used to quickly simulate the behavior of a more computationally-intensive simulation model, and some common methods include interpolation, response surface using regression models, artificial neural networks, kriging, and support vector machines. Finally, numerical optimization can be performed using a number of different algorithms and techniques, including gradient-based methods, pattern search methods, and population-based methods. For each of these, different techniques have been found to be more suitable to different applications, and part of this research directive will be to identify and demonstrate the best tools for this MCE architecture.

A research paper by Chell et al. [53] describes a comparison study of different ways to formulate a multidisciplinary design analysis and optimization (MDAO) problem. Two of these MDAO architectures as shown in Figure 38, multidisciplinary feasible (MDF) and interdisciplinary feasible (IDF), were tested on an aircraft case study. In contrast to previous MDAO architecture comparison studies, the system being optimized includes simulations. The case study for an aerodynamics discipline is modeled with computational fluid dynamics and the structures discipline is modeled with finite element analysis. The results show that the MDF architecture finds better solutions when it comes to optimality, but it requires more computing resources than does the IDF architecture.

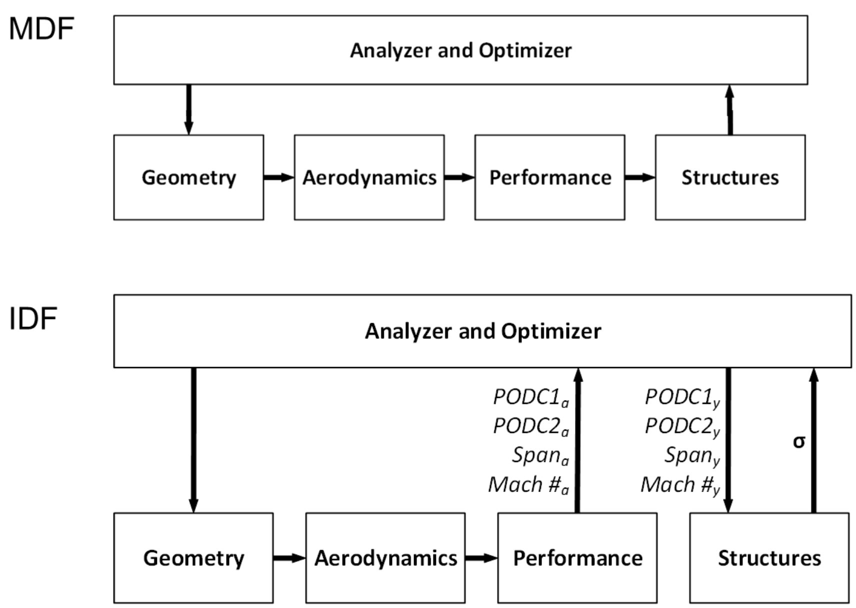


Figure 38. MDF and IDF Architecture Workflows

4.3 Integrations with Related Tasks

Through this project, and the creation of an MCE architecture that follows an AST and a consistent ontology, we investigate how to leverage MDAO techniques in the design decision-making process. A solid framework for MDAO can enable multi-objective optimization, showing product developers how different design objectives compete with one another. For example, we know that improving an objective like “minimize weight” typically requires a sacrifice in the objective to “maximize power.” The magnitude of that improvement-sacrifice relationship, which often involves different units and requires human judgement to make a mission-appropriate decision, can be revealed by combining different simulation models, surrogate models, and optimization routines. As this may involve balancing a large number of objectives, one of the key challenges is in visualization of the results to enable informed decision-making. This fits into all five tasks of the project, as the entire information architecture must be built to support cross-disciplinary analysis, and specific tools and techniques can be integrated and tested at different stages of the transformation.

4.4 MDAO UAV Examples and Use Cases

Examples and demonstration covering several of the objectives have been presented in several working sessions as well as several bi-weekly status meetings and at several events such as the Phoenix Integration International Users’ Group [23]. We have five use cases:

1. Developing MDAO workflows for KPP examples at system level
2. ModelCenter integrated with a Graphical Concept of Operation (CONOPS) example using Unity gaming engine at the mission level
3. Integrating MagicDraw SysML models with ModelCenter and MBSEPak for an underwater super cavitating modeling system
4. ModelCenter and MBSEPak, with MagicDraw SysML to formalize the concept of an Assessment Flow Diagram, which is part of the Decision Framework and process [56]
5. ModelCenter and MBSEPak, with SysML for two-Degree-of-Freedom (2DOF) for the surrogate pilot design

This section provides a summary of some of the evolving use of MDAO in our research.

4.4.1 MDAO Example for Fixed Wing UAV

The first demonstrated workflow shown in Figure 39 was developed using ModelCenter. This demonstration covered several aspects of the modeling objectives discussed in this section, including:

- Describe and execute a workflow analysis of UAS capabilities (e.g., range, velocity, and fuel consumption)
- Map relationships among parameters (inputs/outputs) in disciplinary models
- Illustrate use of Design of Experiments (DoE), sensitivity analysis, and visualizations to understand capability relationships/trade-offs

- Optimize using different solvers to find sets of Pareto-optimal solutions
- Take advantage of previous model analyses for use in early-phase design with new mission capability requirements

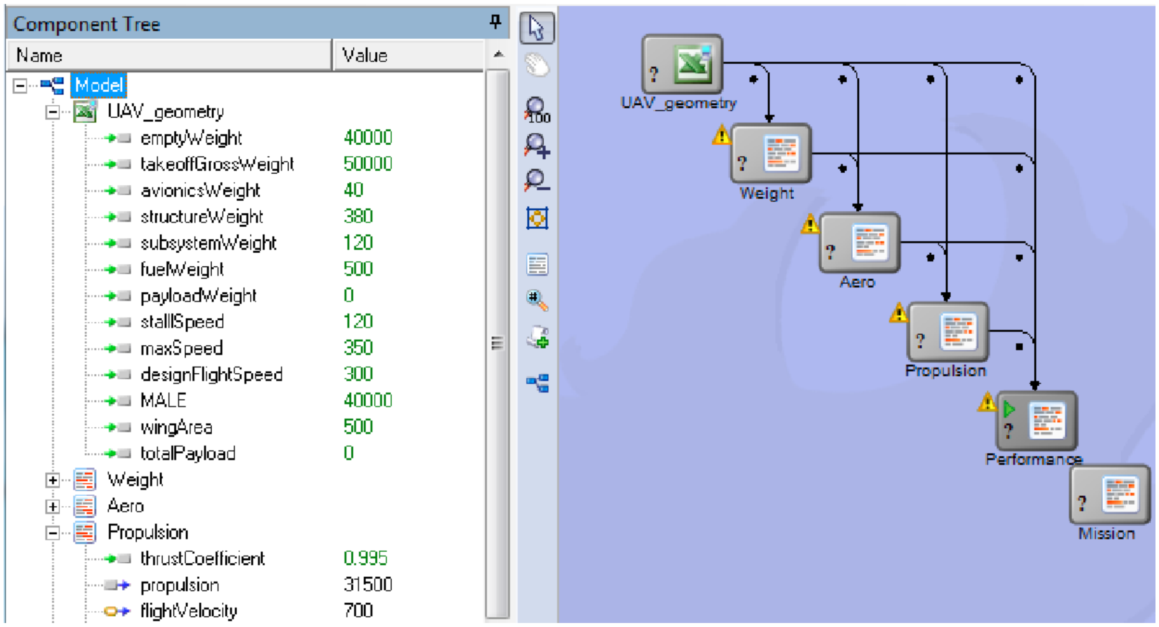


Figure 39. MDAO Example Workflow

As shown in Figure 40, the Pareto frontier (Pareto optimal set) shows the trade-off between range and propulsion. The blue points show the Pareto frontier/non-dominated solutions. The Pareto frontier was calculated using a bi-objective optimization using NSGA-II algorithm to:

- Maximize range
- Maximize propulsion
- Given 5 design variables
  - Wing area (ft2)
  - Wing span (ft)
  - Altitude (ft)
  - Speed (knots)
  - Efficiency factor

These results reflect on how much range one would have to give up in order to increase the propulsion by some amount. Based on the current set of equations characterized in the workflow, the sensitivity analysis shown in Figure 41 indicates that the wing area is the variable that exhibits the clearest trade-off. The wing span has the largest effect on range, but does not present a trade-off between these objectives.

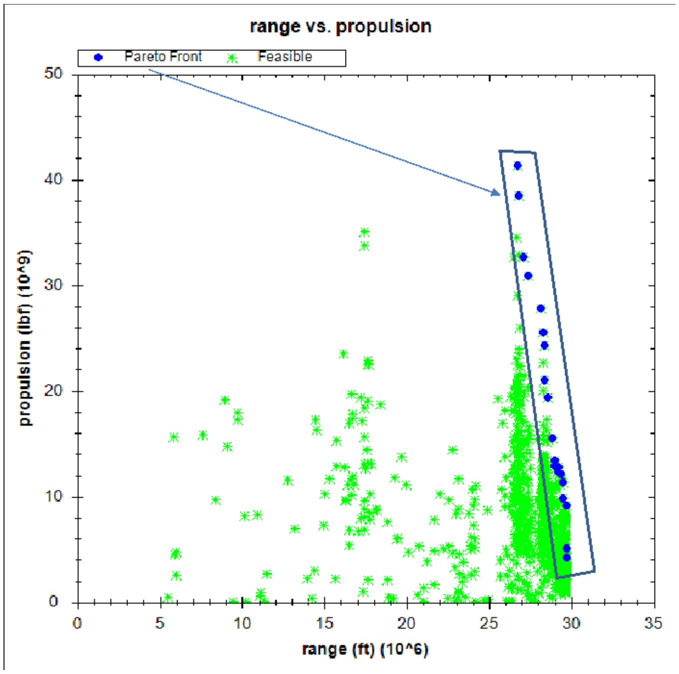


Figure 40. Pareto Frontier (Pareto Optimal Set) Shows Trade-off Between Range and Propulsion

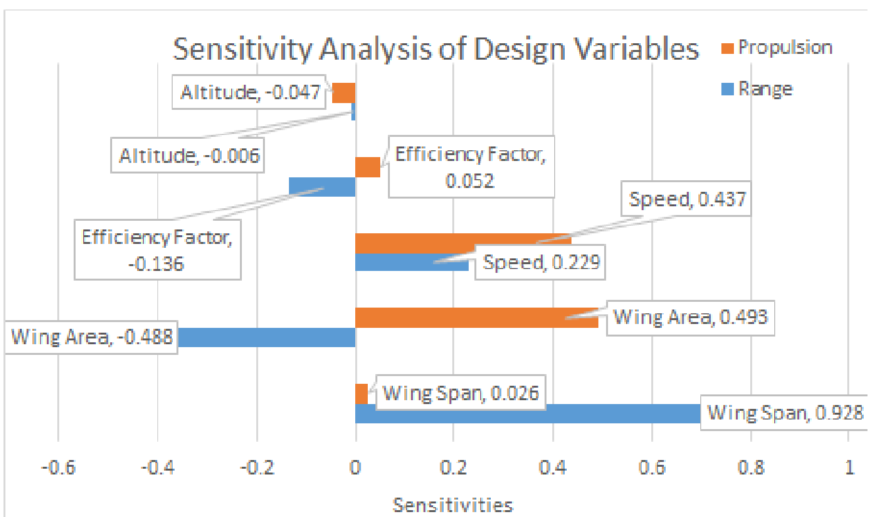


Figure 41. Sensitivity of Objectives to Design Variables

4.4.2 Extending the MDAO UAV Example 1

Brian Chell, a PhD candidate working with Dr. Steven Hoffenson, produced a number of different approach to MDAO architectures problems [50][51][52][53], for example an alternative workflows that leverage other types of solvers for different aspects of the problem including multi-physics. For example, one of the first steps looked at bringing SolidWorks into ModelCenter as shown in Figure 42. This provides a way to bring in detailed geometries to the analysis.

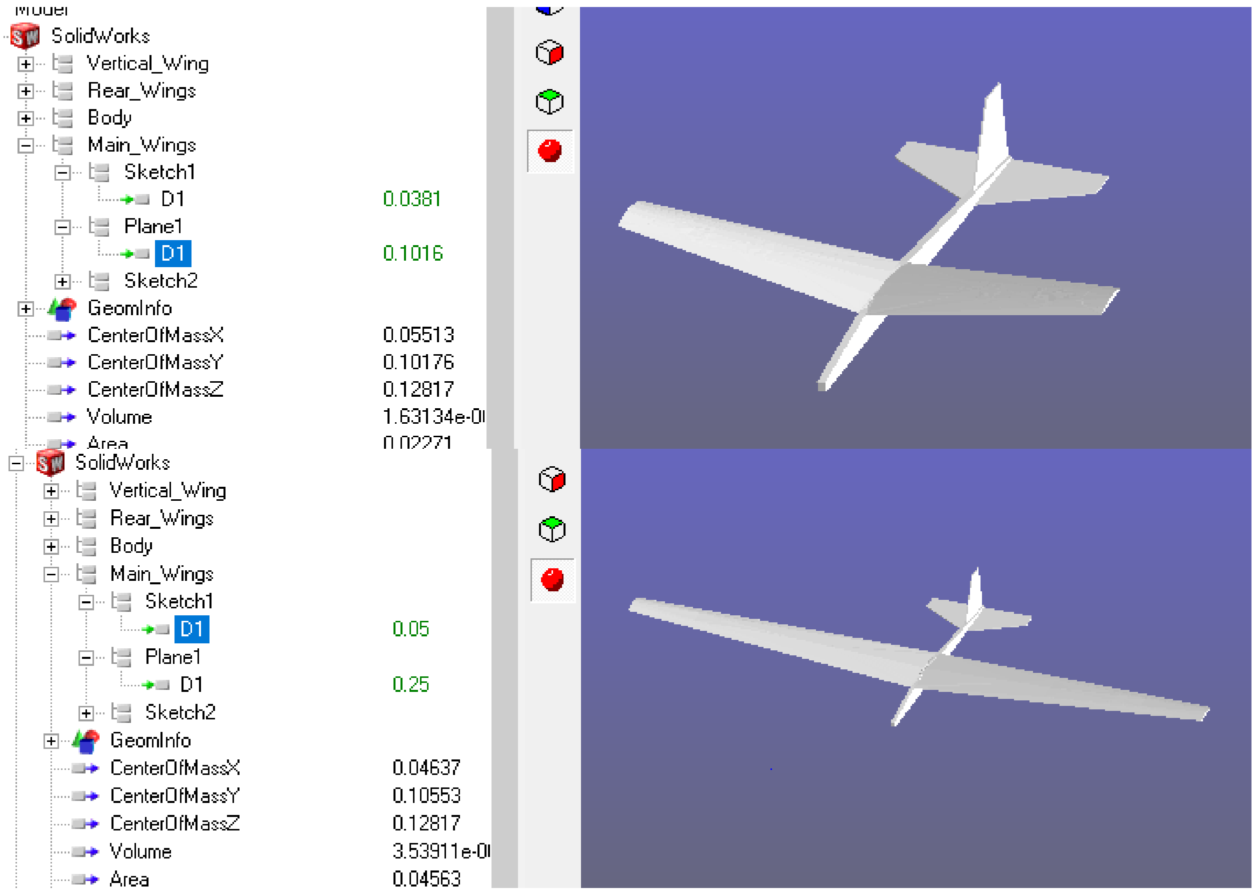


Figure 42. MDAO Workflow with SolidWords Computer Aided Design Model

There were a few challenges with the more complicated geometries, as well as:

- Open-source geometry validity is questionable
- Model variables
  - Most SolidWorks files found so far do not import variables into ModelCenter automatically
  - We assume that we can set the variables within SolidWorks, but this might be more difficult because manually setting values may not align structures (e.g., wing connect to fuselage to meeting correct)
- More complex
  - Computations solver (e.g., CFD) take longer to run on the laptops provided to students and this is another reason for considering different MDAO architectures

This has led to the following investigations:

- Equation-based models derived from the model shown in Section 4.4
  - Uses DLR Institute's Unmanned Combat Air Vehicles (UCAV) [121] parameters
  - Model is fully operational and based on weight fractions that are more scalable, and easier to change than DLR UCAV model
  - Model starting with payload weight vs. range vs. endurance tradeoffs
  - Merge CFD results with Finite Element Analysis (FEA)

- Simulation-based models
  - Difficulties with large number of variables automatically imported (12,000+)
  - Considering open source simulation OpenVSP [154] vs. Solidworks (CFD)
    - OpenVSP is a parametric aircraft geometry tool
    - OpenVSP allows the user to create a 3D model of an aircraft defined by common engineering parameters. This model can be processed into formats suitable for engineering analysis.
    - OpenVSP commonly used with ModelCenter
    - SolidWorks has stronger analysis capabilities
    - OpenVSP is limited to a standardized shape library
    - SolidWorks Flow Simulation can handle turbulence
    - OpenVSP CFD is most valid at nominal flight conditions (e.g. low angle of attack)
    - OpenVSP should be sufficient for conceptual design phase

OpenVSP is being used for CFD. It is easier to use with limited library of shapes of quadcopters and fixed wing, and can run 'headless' (i.e., without GUI) to make computations less expensive. NASA has been using this with ModelCenter. The current status is:

- Integrated parametric geometry and CFD into ModelCenter
- Performing optimization and DOE to characterize model
- Trying to find lowest-fidelity mesh that produces accurate results

Figure 43 show the CFD results from the same geometry under the same flight conditions with different fidelity meshes. The simulation on the left has a coefficient of lift many magnitudes higher than the one on the right.

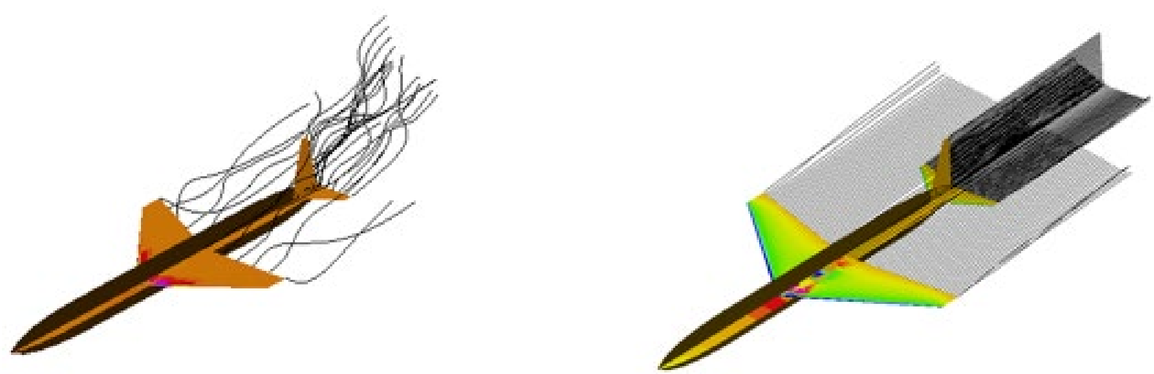


Figure 43. CFD Mesh Fidelity Importance

Updates to the first model include analysis for both CFD and FEA with the objective to maximize endurance and range, and minimize stress at every span-wise node. This is done with another workflow as shown in Figure 44, with the resulting aircraft shown in Figure 45.

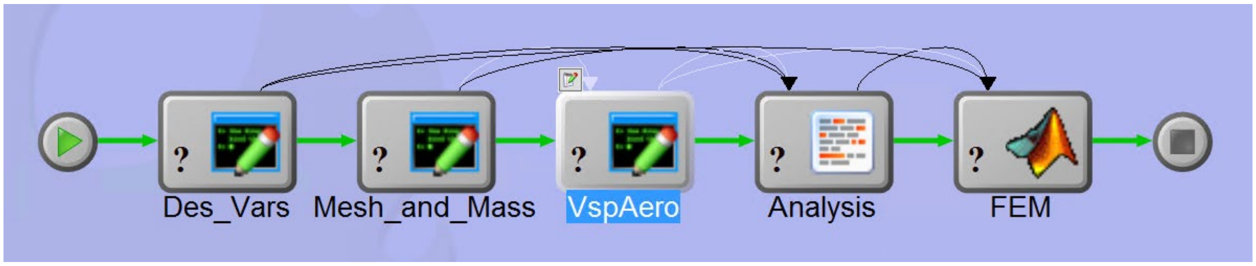


Figure 44. Update MDAO Workflow including CFD and FEA

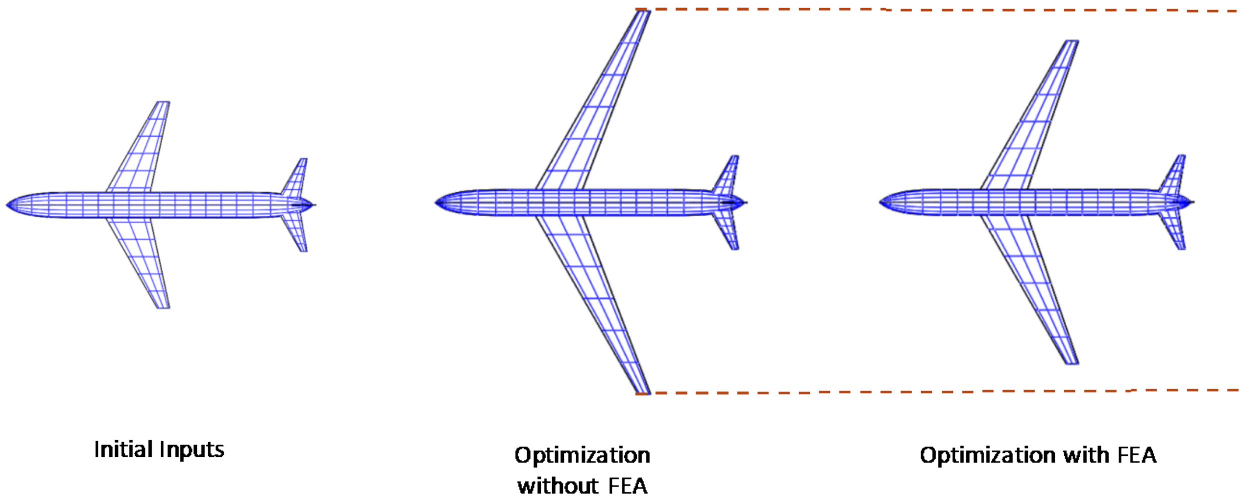


Figure 45. Resulting Aircraft Designs with and without FEA

4.5 MDAO AT THE MISSION LEVEL USING GRAPHICAL CONOPS

This use case investigates an extension of the prior work to using the Graphical CONOPS technologies Unity gaming engine with MDAO using ModelCenter. The MDAO methods used:

- Design of Experiments (DoE) to run the simulation over the entire range of every input variable
  - Choose an appropriate DoE sampling method to shorten run time
    - Full Factorial
    - Latin Hypercube
- Sensitivity Analysis
  - Find which outputs are most sensitive to which input variables
  - Can remove (or fix the value) of non-sensitive variables to save time during optimizations
- Optimization
  - Use algorithm to optimize desired objective(s)

While there were challenges that were overcome, the experiment demonstrated that it is possible to use MDAO to optimize for mission success, and the number of experiments (runs) to cover the DoE space of 1000s cases versus 10s of cases that would be covered by running the scenarios manually.

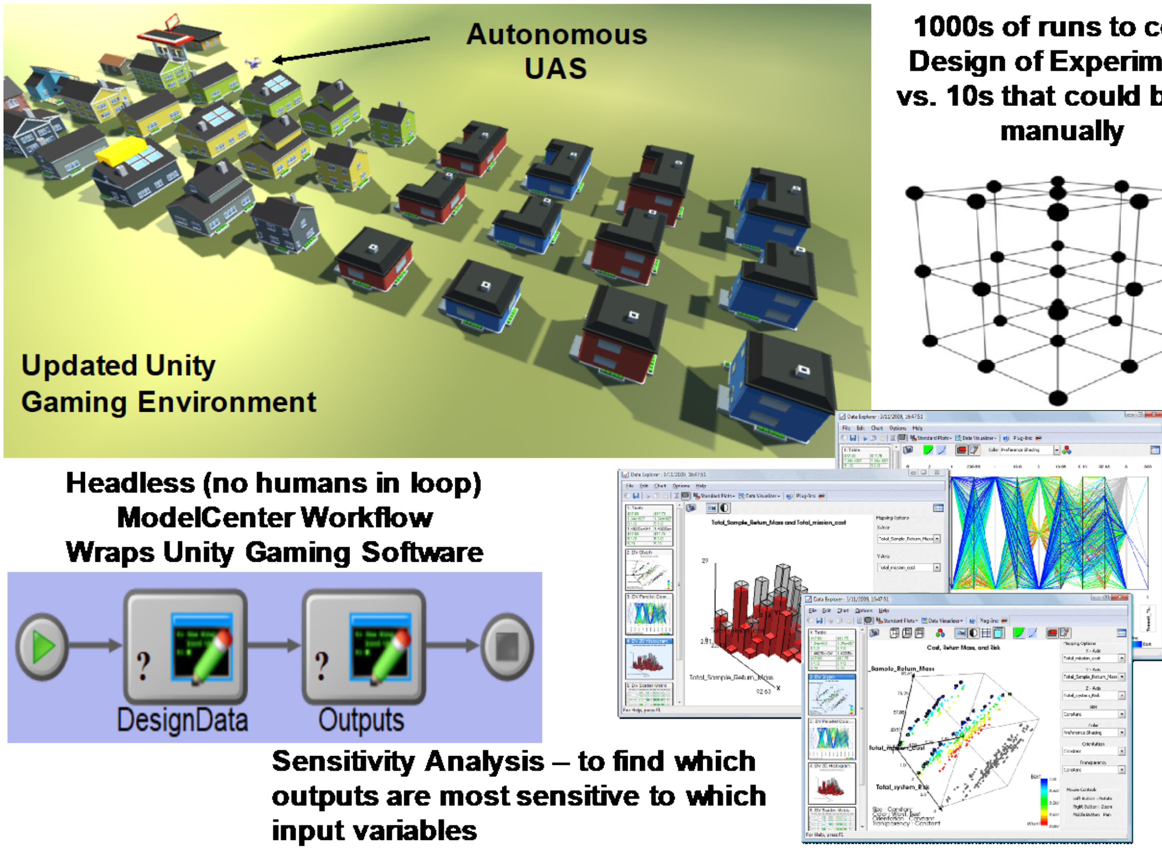


Figure 46. Explore the Integration of Graphical CONOPS Simulation with MDAO Tools

The capabilities focused on objectives to understand and overcome the challenges for a fully automated MDAO at the Graphical CONOPS level, including:

- Performance is measured by degree of success of a mission
- Artificial Intelligence (AI) is applied to counterparties so that they can adapt to and learn behavior of system
- Full automation – there was no humans in the loop, except for validation of behavior
- Simulated environment that includes counterparties was observed to behave in a surprising manner (e.g., there was emergent behavior)
- Software communicates programmatically through file transfer – as opposed to being directed manually
- Monte Carlo results in thousands of runs (vs. 10s when run manually) are made for each initial state to provide statistics
- Simulation can run at high speed to maximize statistics and in real time to allow for human validation of simulation behavior

The finding suggests that MDAO can be used to optimize for system-level mission success to study far more trades than can be performed manually. We created the simulation and removed the CONOPs visualization using a "headless" simulation that is wrapped by ModelCenter. Initially the architecture of the simulation was not enabled to operate in batch modes, and therefore the software had to be re-written to work with ModelCenter. When the simulation is running, the human cannot make edits, but the re-written and wrapped simulation can run thousands of design of experiments (DoE). The initial simulation ran in real-time, but a recent update now can run faster than real-time.

4.6 Formalizing Assessment Flow Diagrams as MDAO Workflow

For populating the Decision Framework [56] as discussed in Section 3.6, we collected the elements of information from a populated SysML model. The research objective is to determine how/where to collect the information reflected Figure 48 from rigorously specified models about alternative analysis for a set of small UAVs. The underlying computations are publicly available. This allowed us to perform most of the computation directly on the data stored in a triple store linked to IoIF, and then extract information directly for the visualization. These types of visualization provide senior leaders and program managers the type of information they need to consider technology capability tradeoff using Performance, Cost (Affordability), Time (delivery schedule) and Risk, as shown in Figure 47.

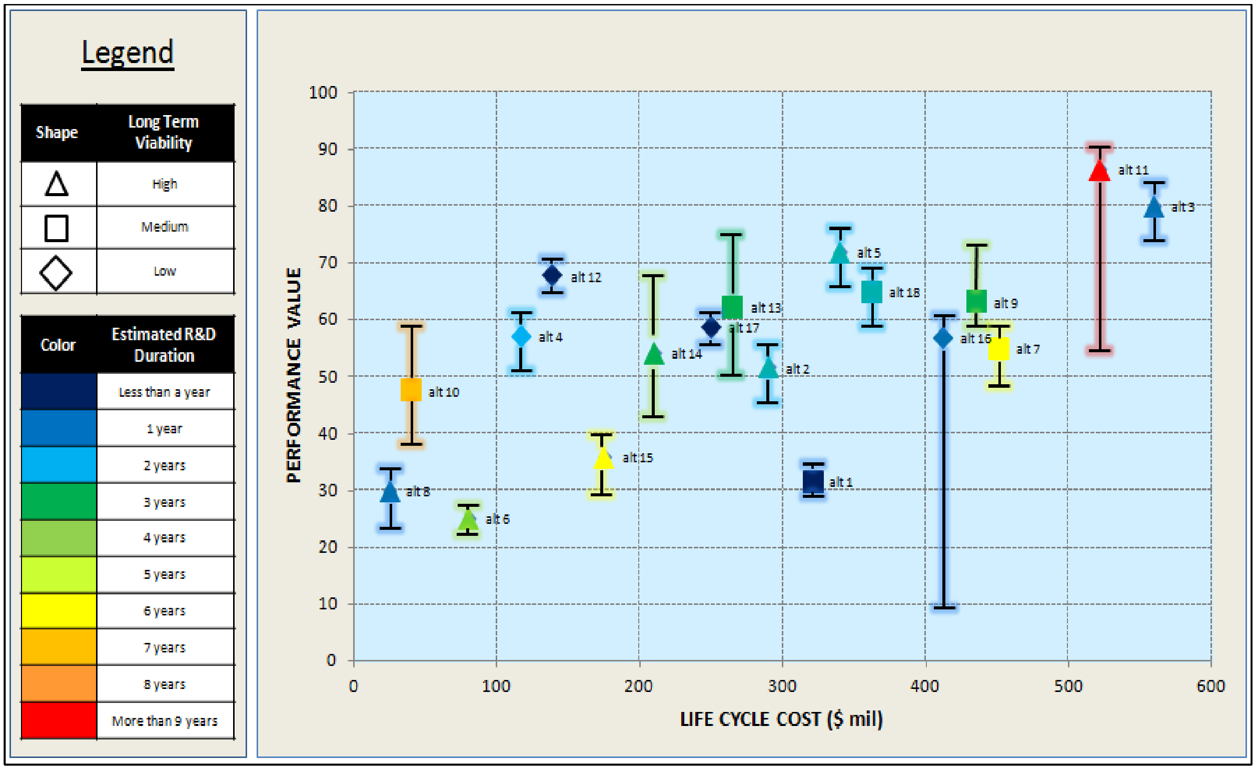


Figure 47. Visualizing Alternatives – Value Scatterplot with Assessing Impact of Uncertainty

Fundamentally, if a particular answer was unacceptable, using the concept discussed herein, we could trace linkages through the underlying information model back to all other related perspectives on the system in terms of operational, mission, system, and subsystem design alternatives and trades. These elements would include:

- Objective hierarchies
- Value functions

- Assessment Flow Diagrams (AFDs) trace the relationships between physical means, intermediate measures, and fundamental objectives
- Uncertainties

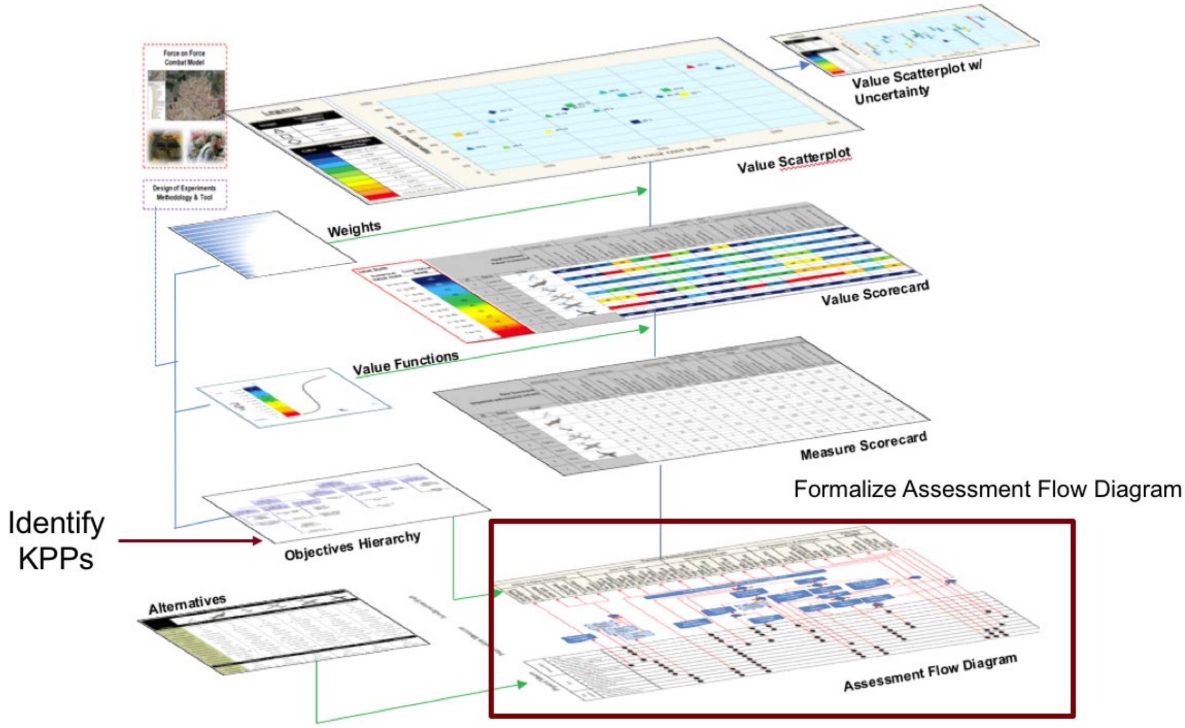


Figure 48. Decision Support Model Construct

We successfully formalized the AFD using SysML, which was previously done in PowerPoint, as shown in Figure 49. This research demonstrated that we can formalize the AFD in SysML and be transformed into an MDAO workflow. We started with SysML and used the MBSEPak to produce the MDAO workflow.

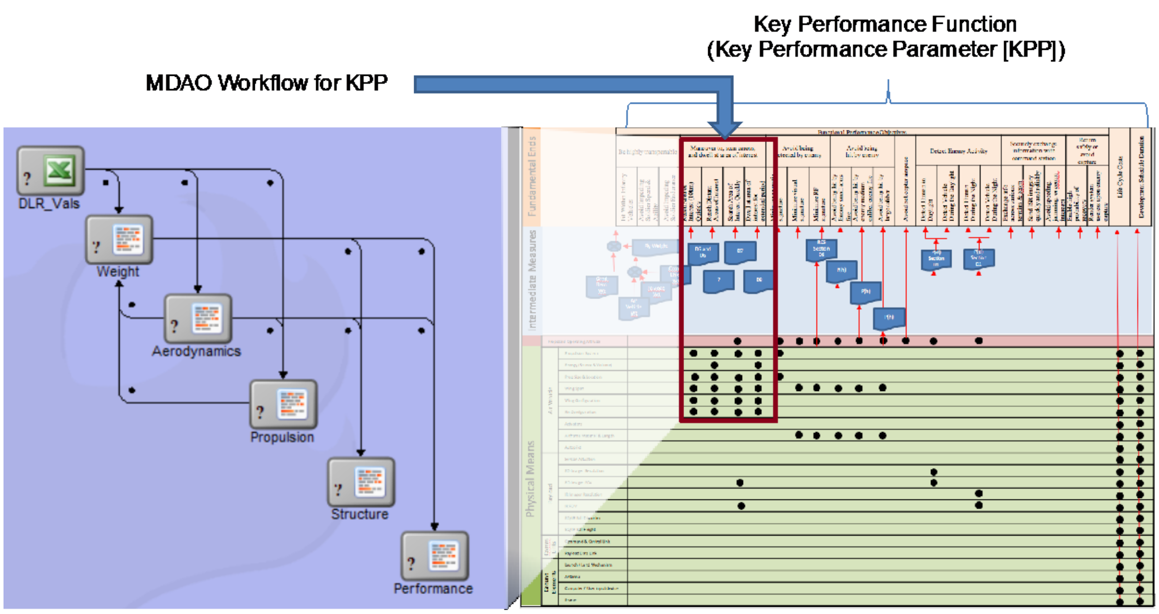


Figure 49. Formalizing the Assessment Flow Diagram

These results formalized the representations of AFD using SysML, MBSEPak and ModelCenter, because the KPPs can be mapped to one or more MDAO workflows as reflected in Figure 49, with some recommendation modeling practices that are needed when using MBSEPak with SysML from Phoenix Integration. A Webinar explaining this approach is provided at the Phoenix Integration website (https://www.phoenix-int.com/learn-more/webinars/) called "Applications for Three Research Use Cases in Model Centric Engineering using ModelCenter and MBSEPak."[22] For additional details, see Appendix C.

The modeling steps follow from the Decision Support Construct:

1. Model system structure in SysML
2. Model as derived value types in SysML decomposition
3. Add the needed Measure scorecard that contains the Metrics of interest in the analysis
4. Value scorecard provides basis to compare metrics as perceived by user

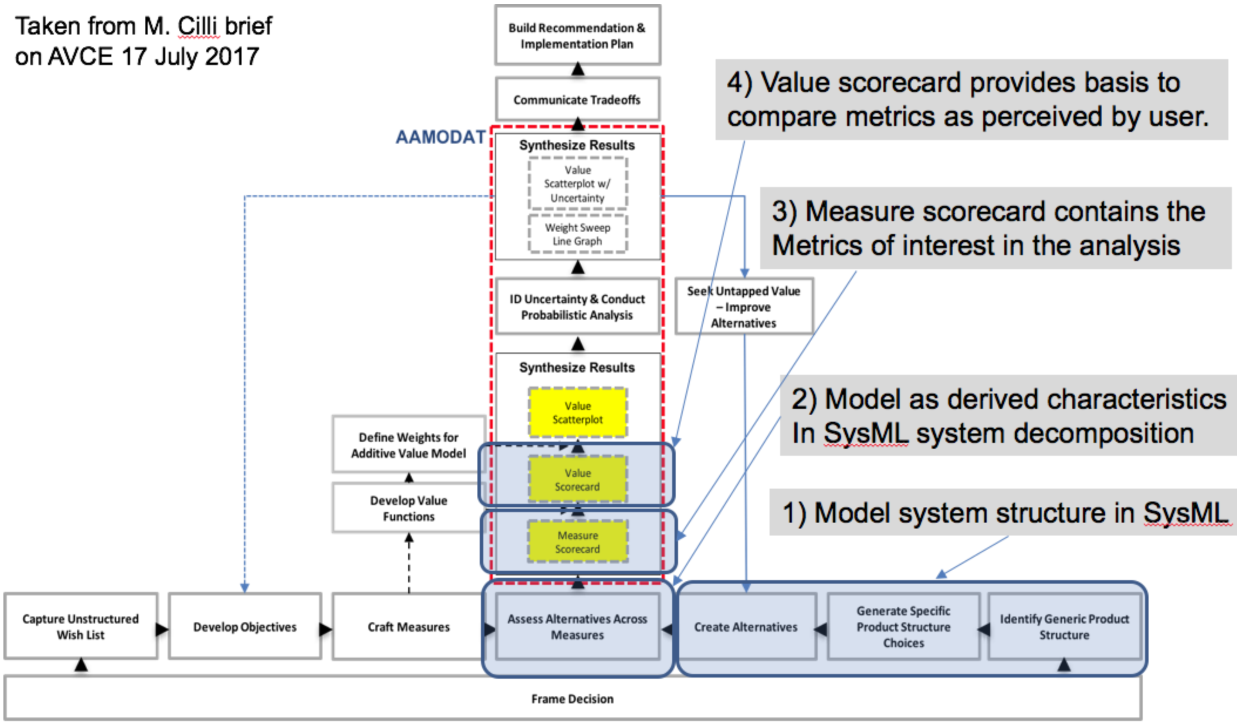


Figure 50. Decision Support Model Construct

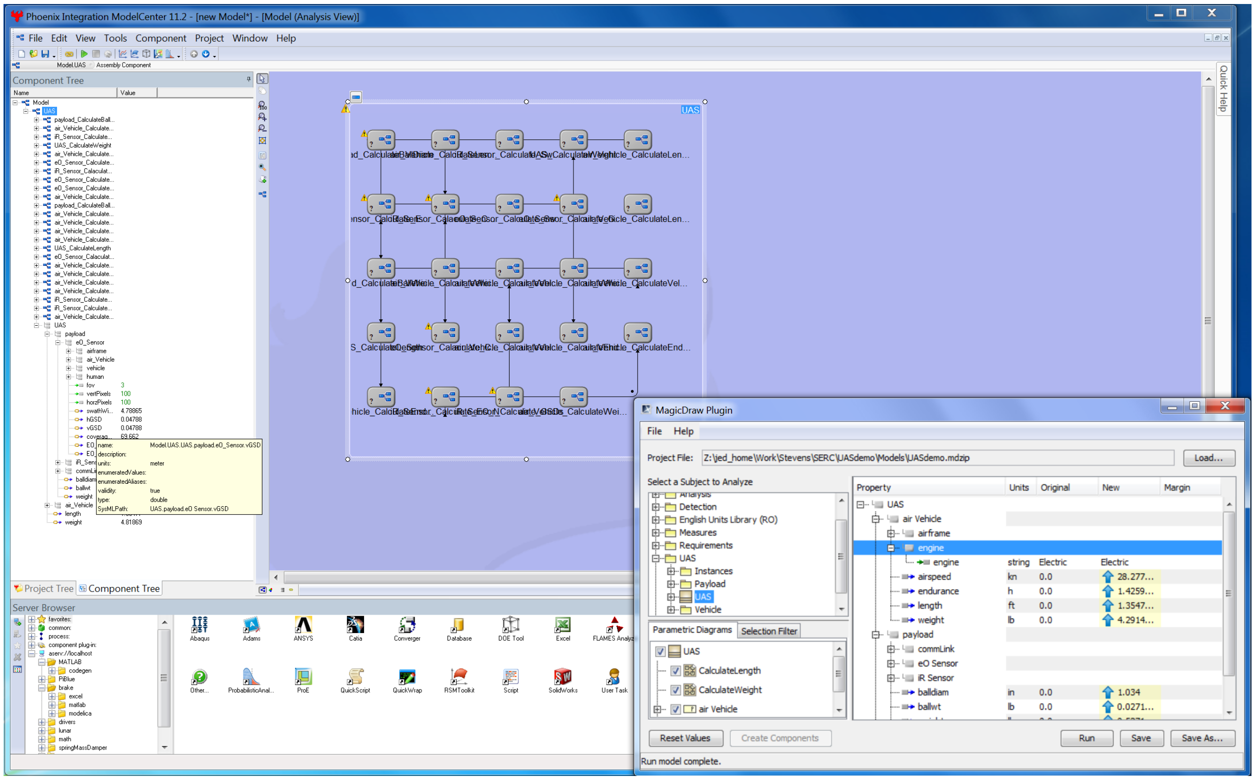


Figure 51. MBSEPak Creates Analysis Workflow and Checks Data Type Consistency

4.7 Surrogate Pilot Contractor MDAO Analysis for Design

This section provides the Phase 1 surrogate pilot example for the use of MDAO. Figure 52 illustrates the use of MDAO using ModelCenter that links to a two-Degree of Freedom (2DOF) dynamics model in Activate [5]. Activate supports modeling and simulating of multi-disciplinary systems in the form of 1D models (expressed as signal-based or physical block diagrams) that can be coupled to 3D models.

Our Surrogate Contractor team used MagicDraw starting from the GFI model provided by the government system modeling team with MBSEpak to create a constraint for endurance, that links to Activate. The surrogate design passes design variables (cruise speed/empty weight/rotor performance) into Activate model and returns endurance/fuel economy output from Activate model back into the MagicDraw, and it saves the output (endurance) in the system model.

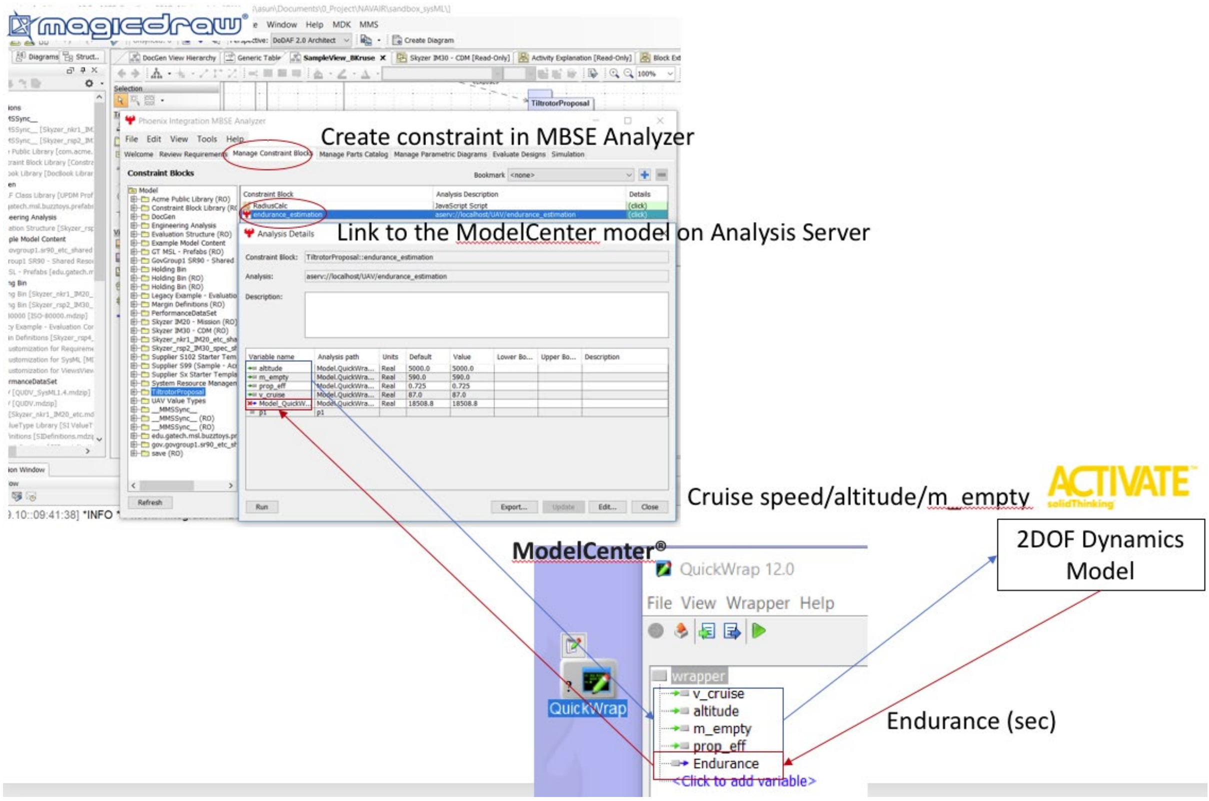


Figure 52. Surrogate Contractor MDAO Analysis[20]

5 UC02: Integrated Modeling Environment (IME)

This use case investigates topics for Integrated Modeling Environments (IMEs) (more recently referred to as the Digital Engineering Environment) with specific examples demonstrating collaborating in an AST for the surrogate pilot in the context of the research thrusts [117]. An AST captures consistent mission and system information, and models across disciplines, offering access in the form of stakeholder-specific views. Many of the details for this use case are discussed in Section 2.4, and in the broader set of capabilities to integrate OpenMBEE, SysML tools, MDAO tools, Visualization tools, with IoIF as shown in Figure 36.

The descriptive modeling tools used to develop SysML models for the surrogate pilot, which are committed to MMS and synchronized to Teamwork Cloud are represented in Figure 53 [119]. The specific tool versions are: Magicdraw and Teamwork Cloud version 19 and MDK v. 4.1.3.

[20] NAVAIR Public Release 2019-443. Distribution Statement A – "Approved for public release; distribution is unlimited"

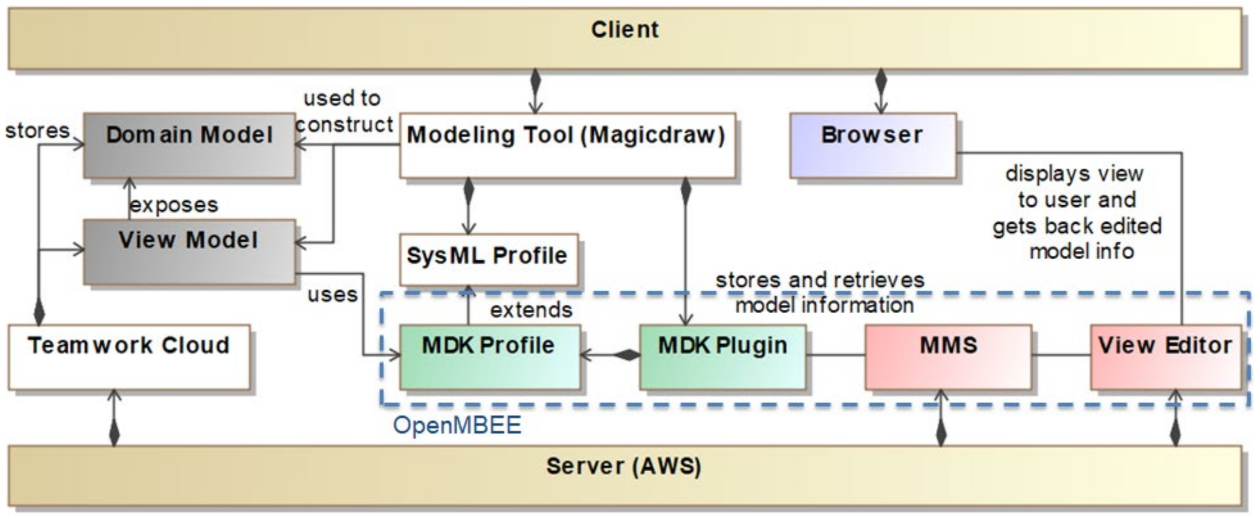


Figure 53. OpenMBEE Environment Implementation

6 UC03: Modeling Methods

This use case investigates the development and demonstrations of methods for technologies in the context of the IME workflows. As discussed in Section 2, we have made significant progress during Phase 2 to advance these methods by identifying the work products (i.e., artifacts) for:

- Mission model based on NAVSEM 1.0 & 2.0
- System model based on NAVSEM 3.0 & 4.0
- Contractor model based on NAVSEM 5.0
- Methods for modularizing models to support constraints needed for developing an authoritative source of truth, which relates to many other use cases
- Methods for model management
- Methods for representing and organizing reference models, process models, discipline-specific models
- Methods for MDAO modeling are discussed in Section 4
- Methods for traceability between different abstraction levels (i.e., mission, system, contractor)
- Alternative approaches to improve modeling methods, which is fundamental to ensuring model integrity
- Preliminary approaches for embedding digital signoffs within models, which have relationships to measure and metrics for digital signoffs and risks

6.1 Mission Model

The approach for developing the mission model for Phase 2 of the surrogate pilot planned to use the Integrated Capability Framework (ICF) Version 3.6, and the associated Mission Engineering schema. However, we instead aligned the current mission-based artifacts with the NAVSEM 1.0 and 2.0 process steps. The initial Skyzer Mission model is available publicly on the AWS server.

This approach demonstrates that modeling can be used and comply with existing standards that traditionally have been document-based. We were able to change the View and Viewpoint hierarchy for the mission model and reuse almost all of the model information created during Phase 1. We needed only a few new scenarios related to the interactions between the Skyzer UAV landing on the ship with interactions with the Launch and Recovery system.

The guidelines include:

- Define required mission capabilities, measures of effectiveness, and associated operational conditions and constraints
- Identify System of Systems (SoS) interfaces and measures of performance through structured decomposition of required mission capabilities
- Provide a common, cross-Systems Command (SYSCOM)/Program Executive Office (PEO) framework to facilitate enterprise level engineering across the SYSCOMs and enable efficient system integration and effective force interoperability
- Establish enterprise data structures and implementation guidance to enable iterative development of enterprise architectures
- The consistent implementation of ICF practices and guidance across assessments and stakeholders supports:
  - A common understanding of mission requirements and a structured process to identify and align systems and platforms capabilities to support missions.
  - System and platform owners with a thorough set of interoperability requirements and knowledge of what platforms, interfaces and behavior to which they need to design, along with associated standards.

We have a View and Viewpoint hierarchy that extracts information from the Skyzer Mission model to “generate a specification,” which aligns with the guidelines for NAVSEM 1.0 and 2.0. A portion of the initial View and Viewpoint hierarchy for Phase 1 is shown in Figure 54. The Phase 2 View and Viewpoint hierarchy is based on NAVSEM 1.0 and 2.0, and we do not have a Distribution A release number for that information.

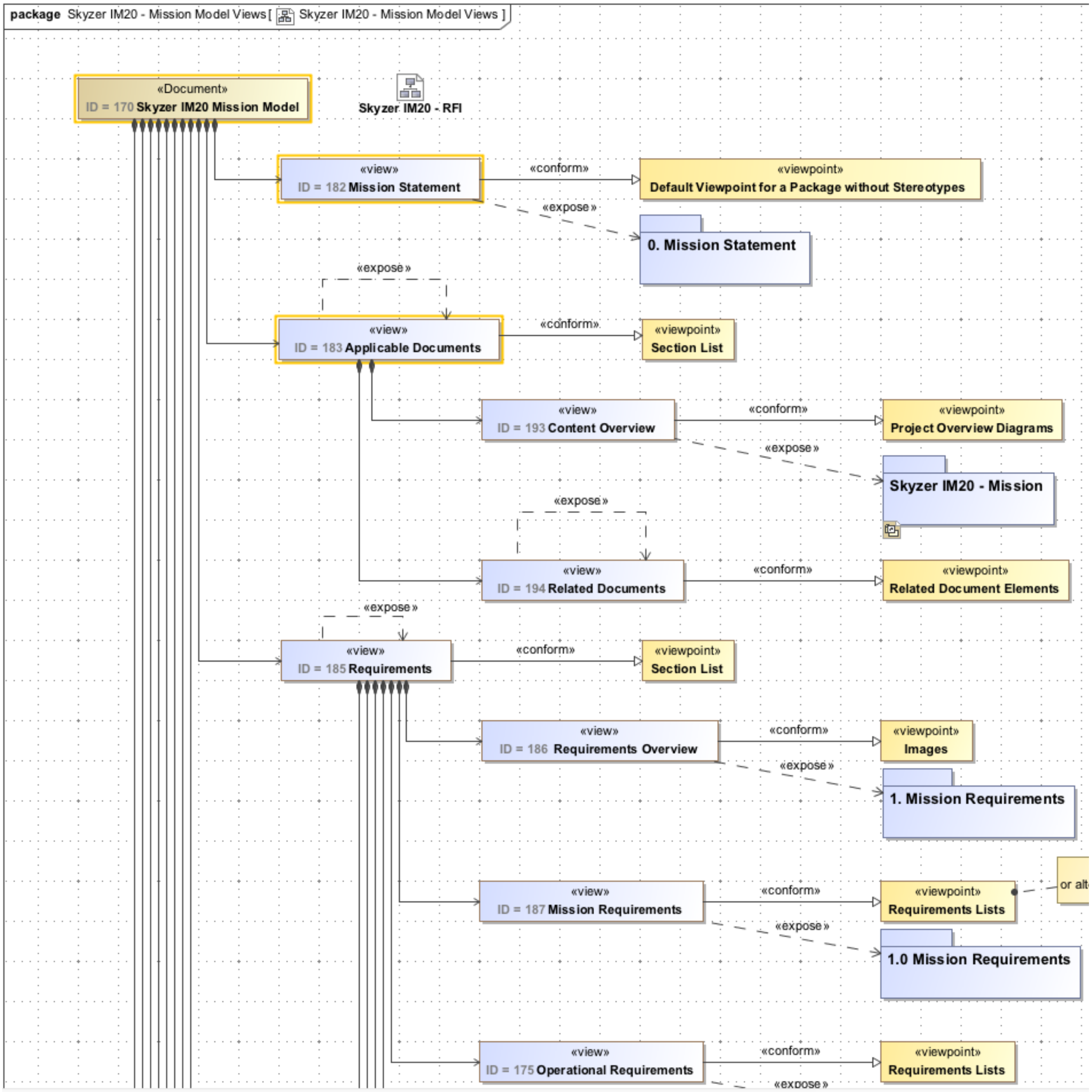


Figure 54. View and Viewpoint Hierarchy for Surrogate Pilot Mission Model

The concepts of view and viewpoint, as defined in ISO-42010 [107], exist to provide a model of the information to be presented to address stakeholders' concerns by focusing on how the information in a model is used by stakeholders [122]. Its views are defined as representations of a system from the perspective of a viewpoint. Viewpoints are defined as specifications of the conventions and rules for constructing a view for addressing stakeholder concerns. An example of a view hierarchy is shown in Figure 55. Each view stands for a chapter of the document, exposing model elements by conforming to a viewpoint. Each viewpoint has a method that describes how the view expresses the exposed model information. The viewpoints allow views to address different stakeholder concerns, while exposing identical model elements.

The viewpoint method on Figure 55 uses the DocGen [9] language for actions that collect, filter and expose the provided model elements. A possible result is shown with the chapter "View 2" containing a list of SysML block elements, which would be in the exposed "Domain Model" package. This way it is possible to automatically derive documents from SysML models that live outside of the modeling environment as the means to satisfy stakeholder concerns. Creating viewpoints for most basic types of documents works by using MDK's provided activity diagram elements, for example, as seen in Figure 55. Viewpoints allow for many types of "documentation" to be generated by extracting information from exposed model elements and then rendering that information as bullet points, diagrams as images, custom tables of model elements, insert sub-sections or paragraphs of text. The Object Constraint Language (OCL) [146] is useful, especially for collecting, sorting or filtering the specific model elements. However, OCL constraints can get more complicated, for example, when filtering for tagged values of custom stereotypes because of the way those properties are captured in the model.

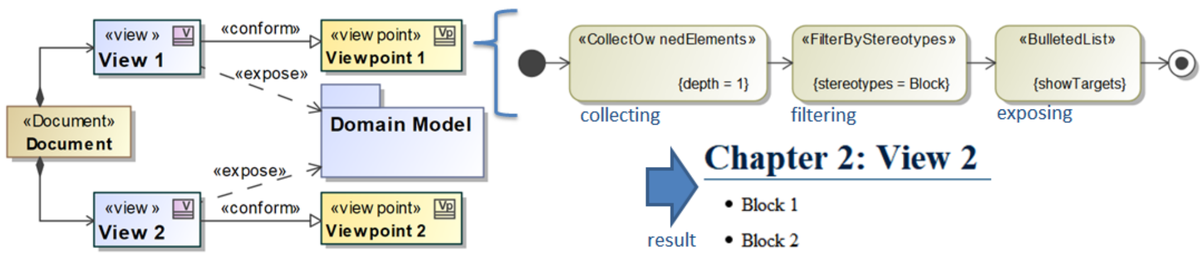


Figure 55. Generic DocGen view hierarchy example (left) with viewpoint behavior (top right) and excerpt of generated document (bottom right)

6.2 SYSTEM MODEL

The Skyzer System model is now aligned with NAVSEM process steps 3.0 and 4.0 as reflected in Figure 12. NAVSEM characterize process steps for characterizing mission models in process steps 3.0 and the logical and functional information from process steps 4.0. NAVSEM has alignment from OOSEM, which is shown in Figure 56. We will be able to use representations from NAVSEM once it is assigned a public release distribution marking.

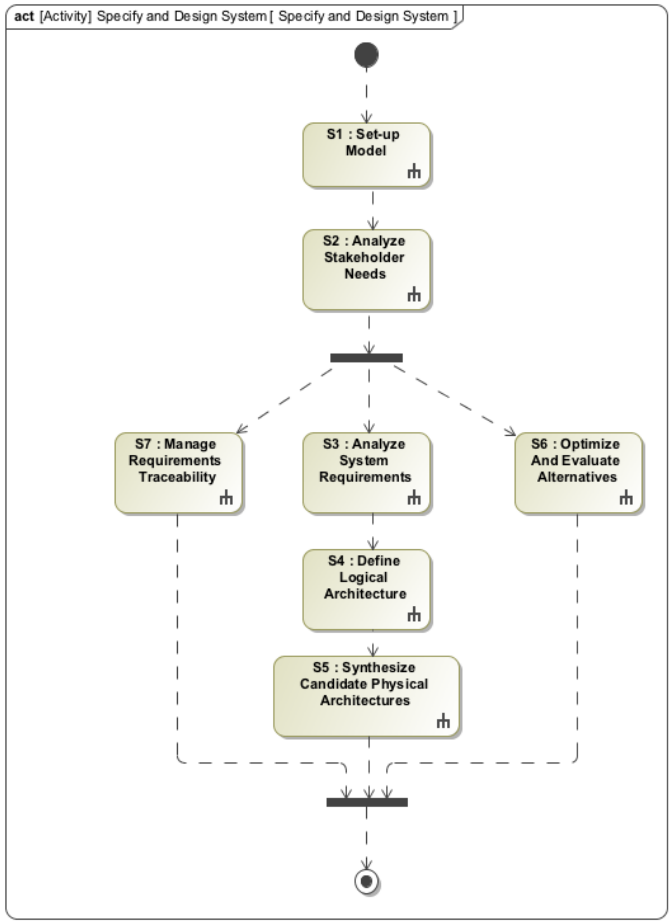


Figure 56. OOSEM Top Level Activities

6.3 MODULARIZING THE SYSML MODEL

The method for modularization models is also an important part of our surrogate pilot effort. As shown in Figure 57, we are using an approach for modularizing the surrogate pilot model that uses a "model reference" (Project Usage) concept so that the mission, system and other models can be created independently, but could be referenced in an overarching project/program model as reflected in Figure 23. Project usages provide a means for accessing shared elements of the used project. For example, in the containment tree on the left side of Figure 57, there are some packages, (e.g., Enterprise, Reference Models) that are in normal black font, but two models the Mission Level and System Level are slightly "grayed out," because these projects are references to separate models. In doing this, we can allow the Mission model and System model to be developed and updated separately, but when brought into the higher-level project model, we could view the entire model. In addition, as shown in the View and Viewpoint hierarchy, we can include these referenced models in one or more Views with Viewpoints, where DocGen can then generate a document or specification for the entire project or a subset of elements from various models. This concept of modularization would apply to other process models, such as those developed by competencies and reference models. We are investigating this evolving method, because it plays heavily with model management including tradeoff for both the Teamwork

Cloud and OpenMBEE MMS. Finally, the project usage mechanism can be used to reuse elements from model libraries, such as the DocGen Viewpoints.

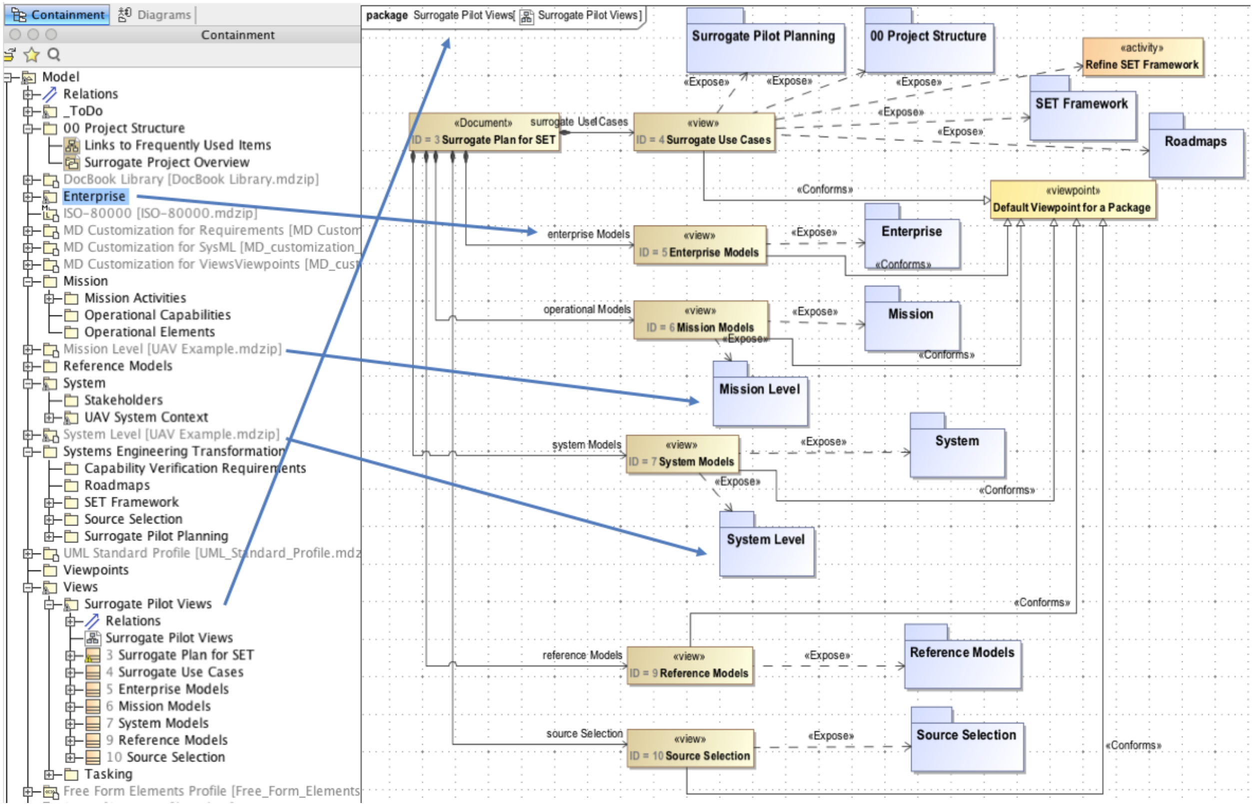


Figure 57. Modularizing Surrogate Pilot Model

A simplified excerpt of the project usage relations of the surrogate pilot with its separated view and domain models is shown in Figure 58. The composition relations represent project usage. The white domain models on the bottom use each other for traceability. They themselves are used by the view models to be exposed in view hierarchies, which requires the viewpoints from the used Viewpoint Library. The Issue Tracking model on the right again uses the two view models. The exemplary reviewer has full access on the Issue Tracking model and the Mission View Model, but read-only access on the Mission Model. That allows to edit and comment within the Mission View Model, without being able to directly change any exposed elements from the Mission Model. New issues can be created in the Issue Tracking model that reference any requirement or model object. Comments created in the Mission View Model can be directly inserted as issues, too.

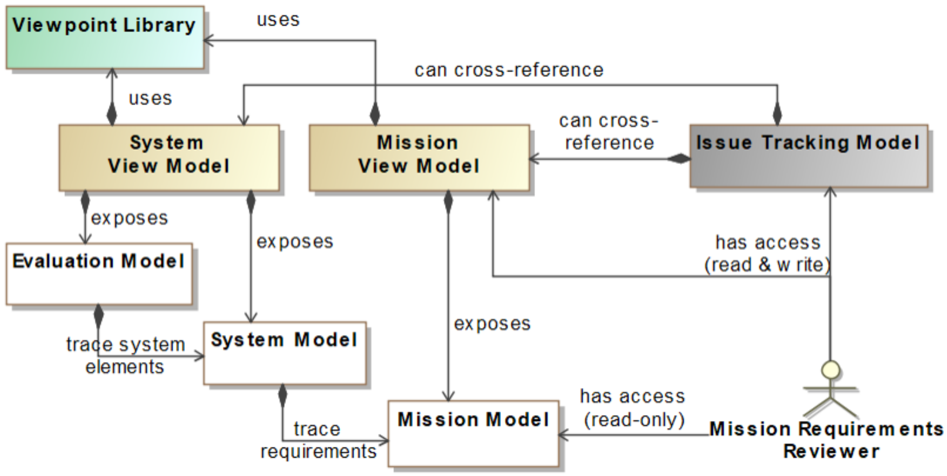


Figure 58. Example of Project Usage and User permissions for Mission Requirements Review

The ability to access elements from used projects allows traceability links, for example from UAV system elements back to specific mission requirements, which then can be exposed in the View Editor where model elements from used projects can be referenced. This is an important feature for the Issue Tracking model of the surrogate pilot. This model is fully handled in the View Editor with issues being created as class elements having a name and a description or by directly referencing existing comments created in documents of used projects. The description of an issue can also reference accessible model elements within the AST, for example, to link issues to impacted or problematic model elements as reflected in Figure 58. This again does not require detailed knowledge about the underlying models or SysML itself.

6.4 Views and Viewpoints

The basic elements, as shown in Figure 59 can be included within an overarching document, which includes:

- Document – the overarching model element
  - Document can include other documents, which also provides another level of modularization and support for reuse
- View (there can be one or more views in a document)
- A View uses the Exposes relationship to associate the View with some element in the model (e.g., Package, Diagram, etc.)
- View conforms to a Viewpoint
- Viewpoint defined using a special language created out of a profiled activity diagram that can collect, filter, and then produce a document through a DocBook standard

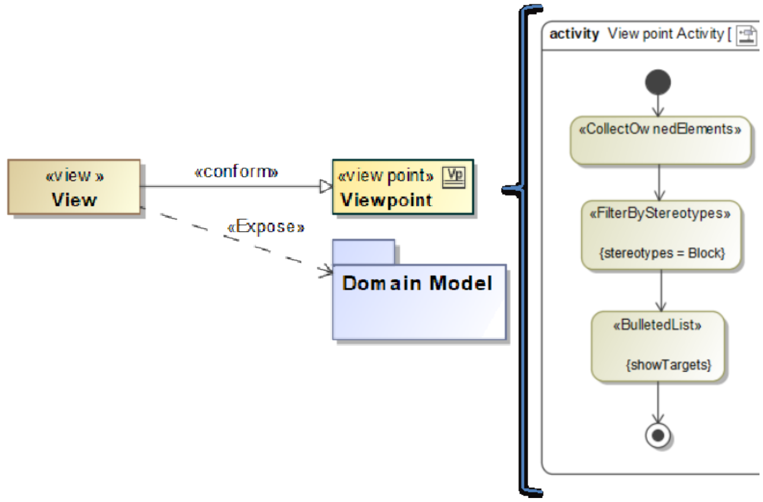


Figure 59. Element of View and Viewpoints

A document assembled from a number of Documents or Views can be generated into DocBook, which can then be generated into PDF, Word, HTML, and other formats. These Views can also be synchronized into the OpenMBEE MMS as shown in Figure 60. The View Editor can then be used to view the generated specification; in addition, it can export (generate) into Word, PDF, and HTML. The View Editor also allows for editing and updating a generated view that can also be pushed back into the MMS, as well as back into the model (for certain types of model elements).

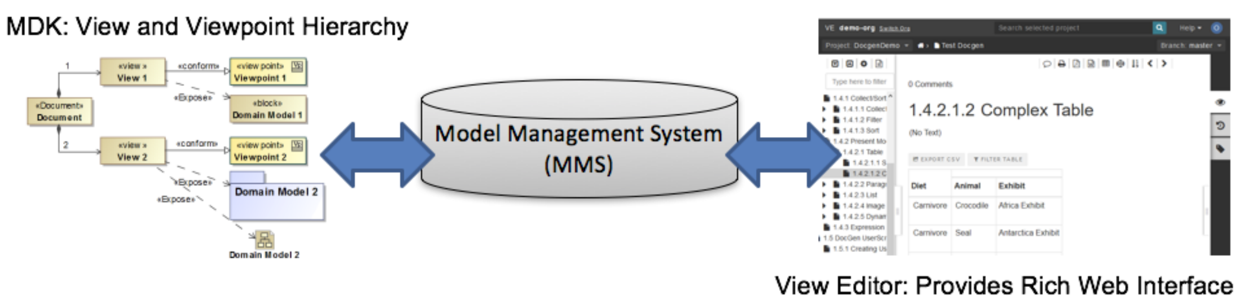


Figure 60. Views are Pushed into Model Management System and Viewable through View Editor

As shown in Figure 61, the View Editor runs in a standard web browser and lets users navigate the View hierarchy, and visualize specific Views within the hierarchy, edit the views and examine history associated with changes of the View. There are capabilities for branching those changes. This is part of the future research to investigate the combination of facets related to View and Viewpoint hierarchies, model management in MMS as well as in Teamwork cloud. We are working in conjunction with industry and our NAVAIR sponsors on the best methods for model management.

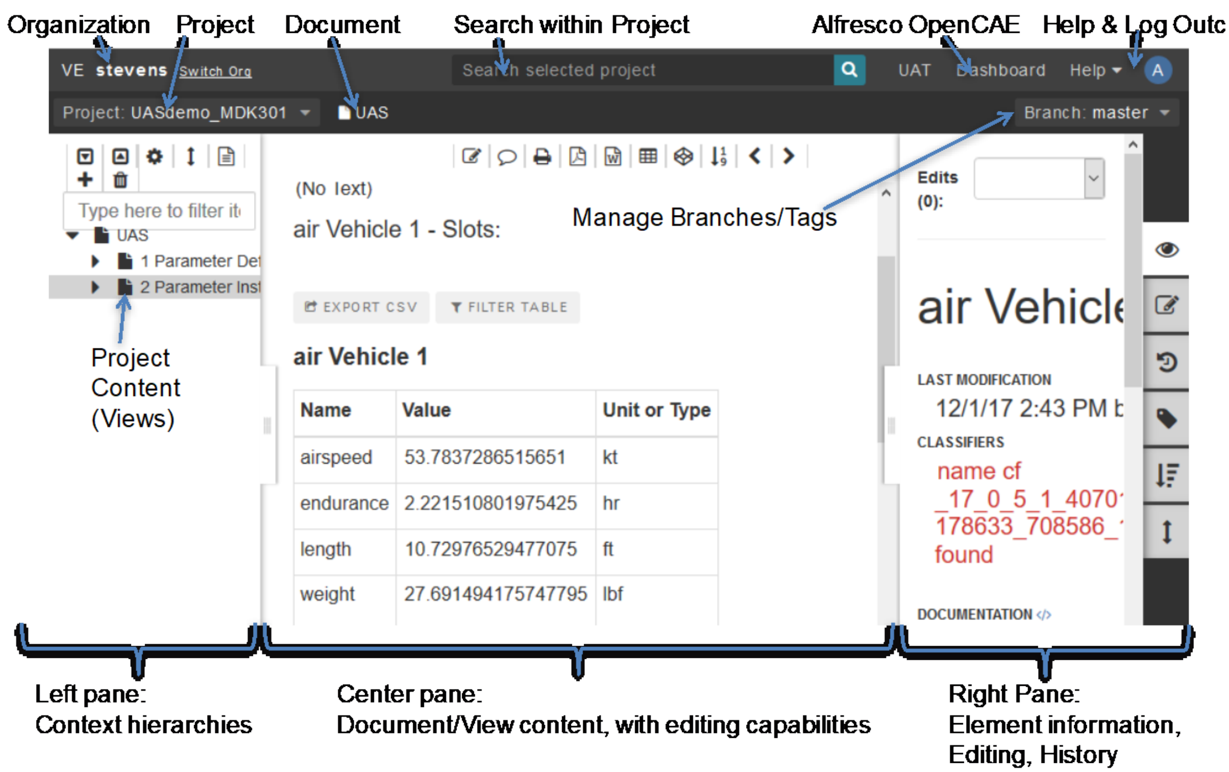
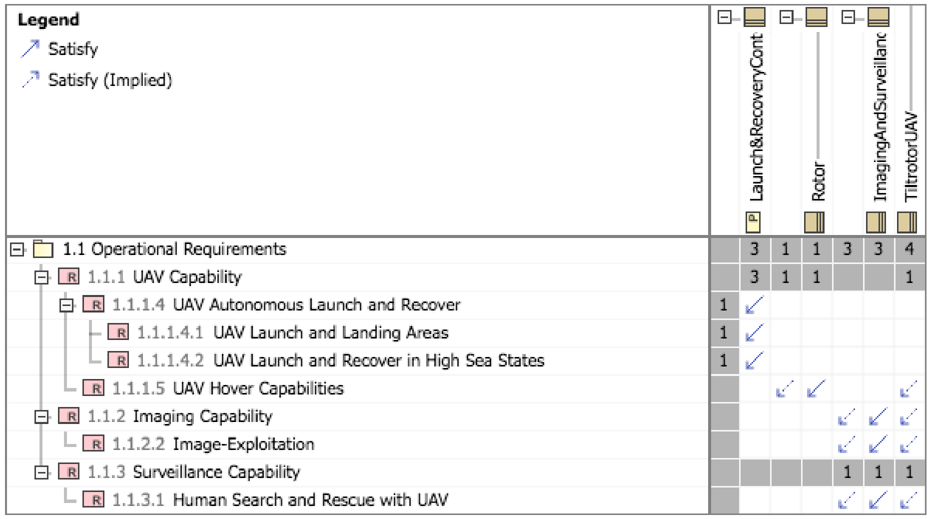


Figure 61. View Editor

6.5 METHODS FOR TRACEABILITY

As discussed in Section 2 and more specifically in Section 2.5, we developed the requirement traceability from the Skyzer System Model to the Skyzer Mission Model inside of the Skyzer System Model using Project Usages as a means to reference those exact requirements between the two models, which is shown in Figure 24.

We use a similar approach to link the Surrogate Contractor refinement of the Skyzer System Model. The Surrogate Contractor models developed and refined in Element 3 also use Project Usages of the Skyzer System Model. The surrogate contractor provides traceability linkages from the requirements in the Skyzer System Model to the behavior and analyses in the contractor models in a manner similar to that shown in Figure 62. The refined system proposed by Surrogate Contractor was generalized from the Skyzer System Model. It inherited properties from the System Model, with additional subsystems and properties. For instance, in the Airframe Assembly Subsystem, value properties (e.g., height, length, width) were created by Surrogate Contractor to define the bounding box of the airframe design. There are other traceability matrices for functional requirement and performance requirements, which is shown in Figure 63.



OperationRequirements

Figure 62. Traceability from Operational Requirements to Requirements in Surrogate Contractor Model

Figure 63 also illustrates how Digital Signoffs are associated with model information such as the Performance Traceability matrix, which relates the Mission Requirements associated with KPPs to design constraints that are analysis supporting evidence that the aircraft design should meet the KPPs. The Source Selection Evaluation Model traces to the specific performance information associated with the surrogate contractor responses, which link to the KPPs.

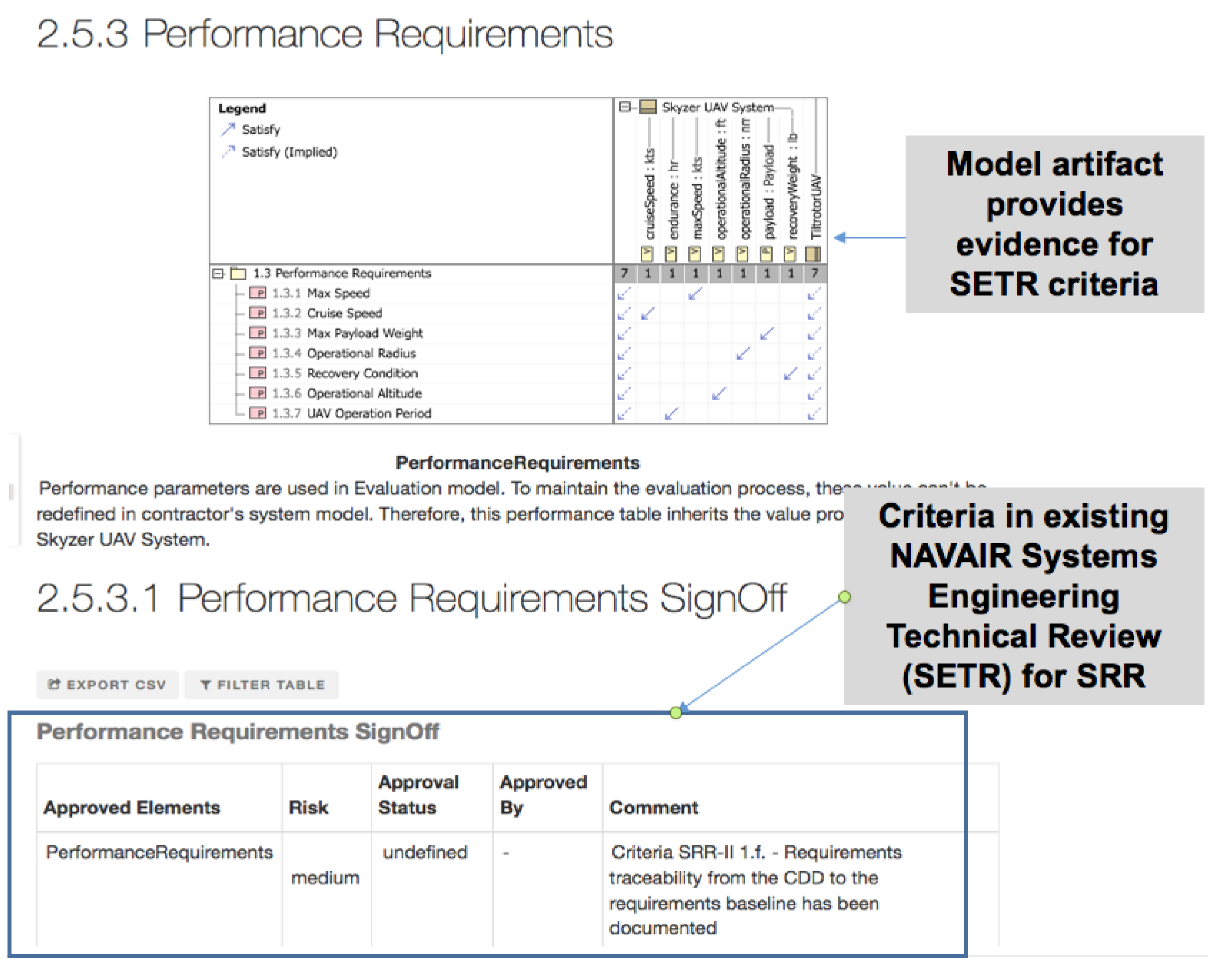


Figure 63. Digital Signoff for SRR-II Criteria in Skyzer RFP View[21]

7 UC04: MODEL-PHYSICS MODELING AND MODEL INTEGRITY

This use case investigates multi-physics modeling, MDAO and model integrity which is also supported by MDAO and approaches for assessing model integrity risks and uncertainty. Model integrity, from our sponsor's perspective, is a means to understand margins and uncertainty in what models and associated simulations "predict" or in other words when/how do we trust the models and associated simulation results. The objectives characterized by the sponsor are to ensure that the research covers the key objectives, which included:

- Include both models to assess "performance" and models for assessing "integrity" such as:
  - Performance: aero, propulsion, sensors, etc.
  - Integrity: Finite Element Analysis (FEA), Computational Fluid Dynamics (CFD), reliability, etc. – can we build it, can we trust it

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- A stated challenge was: how can "integrity" be accomplished when the current situation involves federations of models that are not integrated?

- Continuous hierarchical and vertical flow enabled by models and iterative refinement through tradespace analysis, concept engineering, and architecture and design analysis

7.1 Surrogate Pilot Design Model Constraint

We have imposed constraints on the mission scenarios, for example as KPPs, for the surrogate pilot to ensure that we have the opportunity to evaluate multi-physic designs and measures for understanding model integrity to support a production readiness decision. During Elements 1 and 2, we used MDAO type analysis such as described in Section 4.4. The more critical aspects that concern our sponsor are the ability to deal with designs in Element 3, that can support a producibility decision associated with Element 4 when multi-physics design elements are involved in the decision process; that is, can we make a production decision from various type of modeling and simulation analyses of a design. An example is shown in Figure 45, which shows that there can be significant differences in the system design tradespace when both CFD and FEA are used in the same MDAO workflow. Therefore, this is another key objective of the surrogate pilot. The objective is to define mission use cases that can be used to force analysis to better understand the feasible multi-physics design options.

7.2 Surrogate Contractor Multi-Physics Design

The surrogate contractor design is not yet complete, but there was a significant amount of design detail that was provided in the RFP response. However, during Phase 2, the research team also became the surrogate contractor due to funding constraints, we focused more on the descriptive model for NAVSEM process step 5.0 and determining the needed model-based artifacts.

The generated view from the Phase 1 RFP Response shown in Figure 64 reflects on the refinement of the design using a SysML block definition diagram. Like the mission and system model, the RFP uses the project usage mechanism to link to the requirements from the mission and system models. As shown in Figure 63, the traceability matrix relates the KPP performance requirements from the mission model to the parametric constraints derived from the multi-physics analyses. This particular traceability table provides evidence for the Digital Signoff against "Criteria SRR-II 1.f. - Requirements traceability from the Capability Description Document (CDD) to the requirements baseline has been documented." Figure 65 shows traceability from the mission requirements to the design constraints. This type of evidence is normally captured as one or more CDRLs and may be required as part of a System Engineering Technical Review. The approach used on the Surrogate Pilot demonstrates how the criteria can be captured as a Digital Signoff and associated with model evidence directly in a model. While those design constraints are captured in the SysML model, they are derived from the multi-physics analysis done in discipline-specific tools. We demonstrated approaches for linking the contractor system model to discipline-specific models such as Computer Aided Engineering (CAE) information, CFD, FEA for tools that do not have direct integrations with the system models. Figure 66 shows a View from the RFP Response model, where the third column of the matrix provide links to a tool and environment, where a subject matter expert could hyperlink into a discipline-specific model analysis to view the details; a CFD analysis is shown in Figure 10.

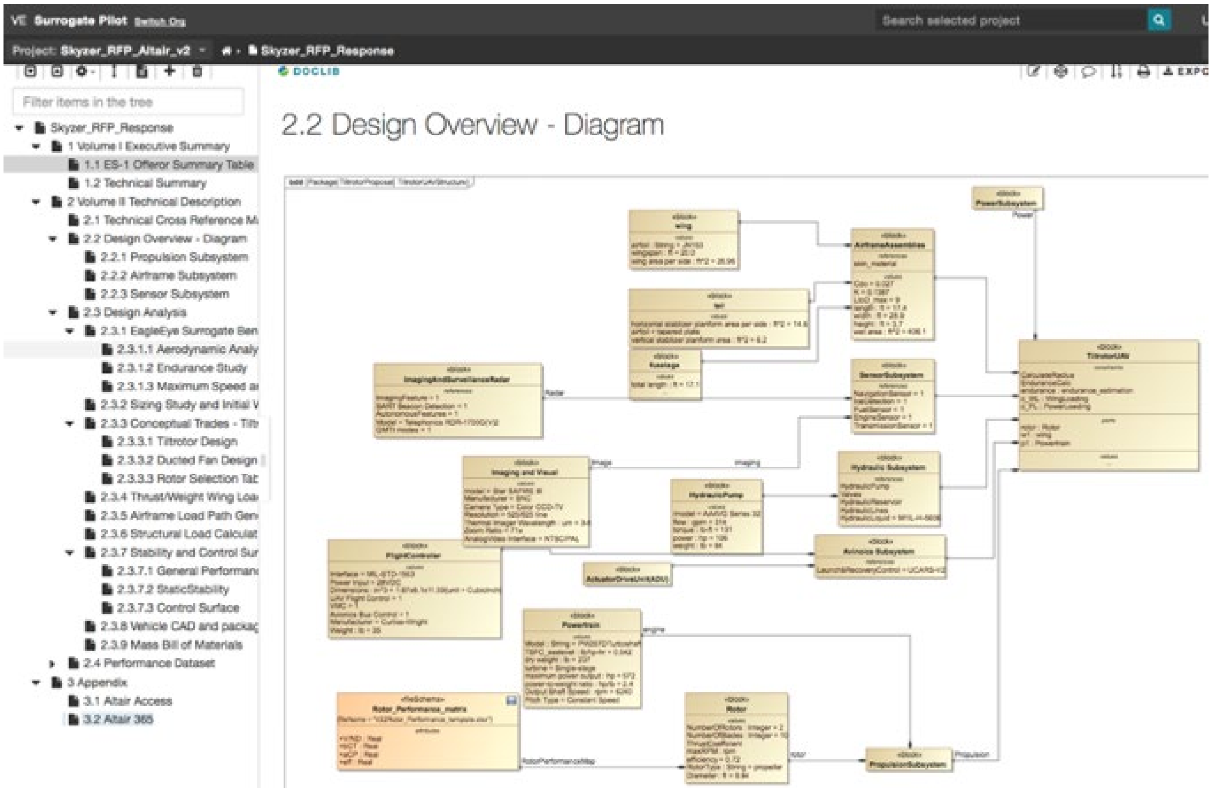

Figure 64. RFP Response Extends and Refines Skyzer System Model provided by Government as GFI[22]

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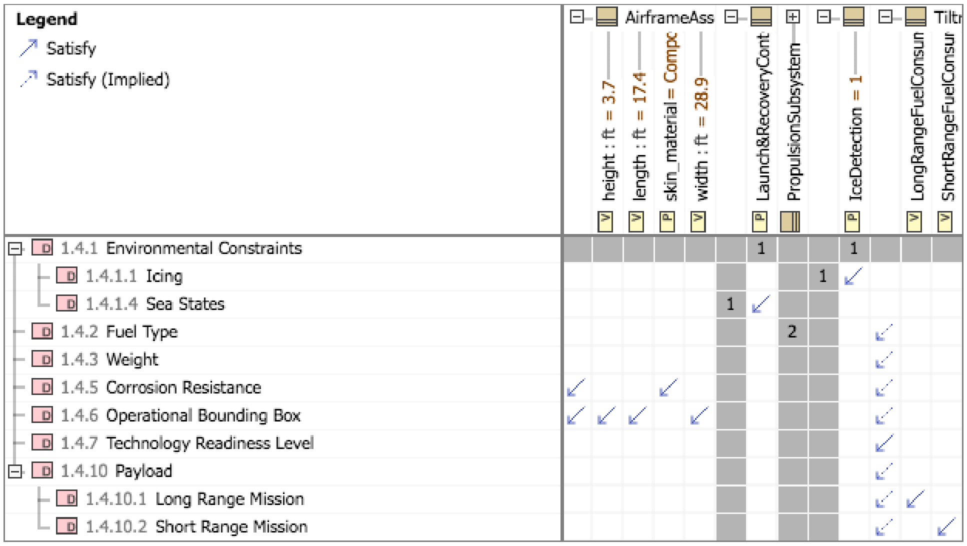
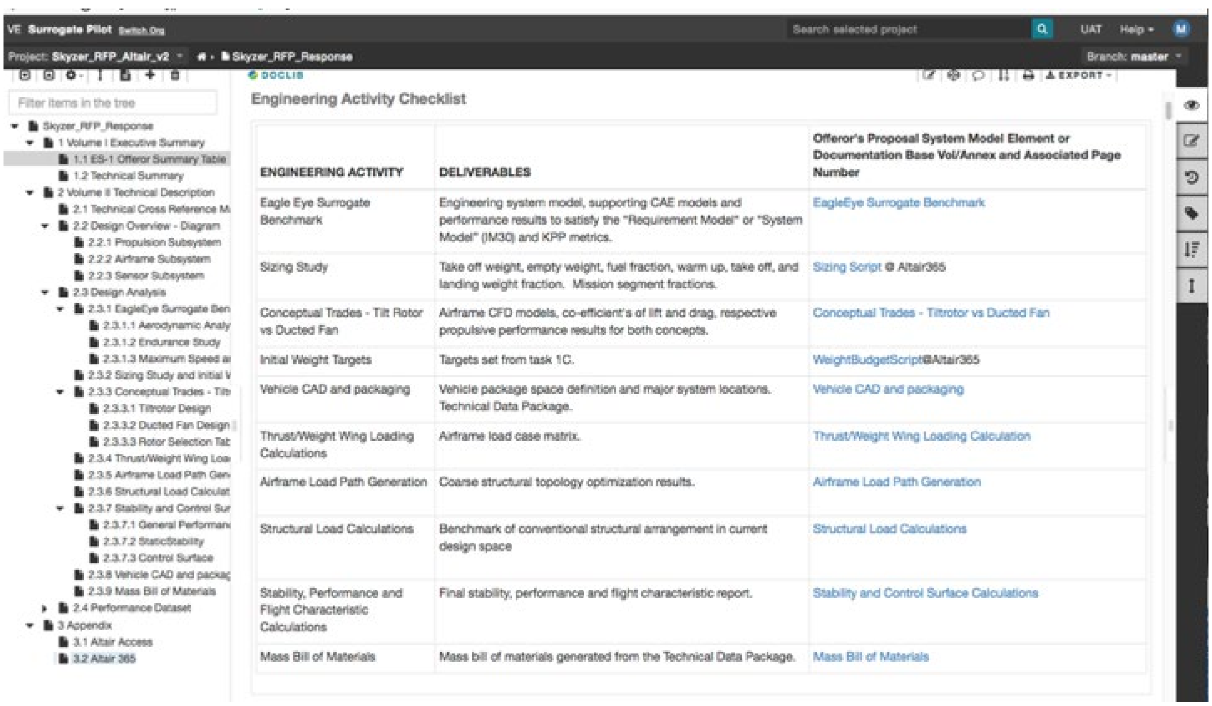


Figure 65. Traceability from Mission Design Constraints to RFP Response Design Constraints[23]



ENGINEERING ACTIVITY	DELIVERABLES	Offeror's Proposal System Model Element or Documentation Base Vol/Annex and Associated Page Number
Eagle Eye Surrogate Benchmark	Engineering system model, supporting CAE models and performance results to satisfy the "Requirement Model" or "System Model" (IM30) and KPP metrics.	EagleEye Surrogate Benchmark
Sizing Study	Take off weight, empty weight, fuel fraction, warm up, take off, and landing weight fraction. Mission segment fractions.	Sizing Script @ Altair365
Conceptual Trades - Tilt Rotor vs Ducted Fan	Airframe CFD models, co-efficient's of lift and drag, respective propulsive performance results for both concepts.	Conceptual Trades - Tiltrotor vs Ducted Fan
Initial Weight Targets	Targets set from task 1C.	WeightBudgetScript@Altair365
Vehicle CAD and packaging	Vehicle package space definition and major system locations. Technical Data Package.	Vehicle CAD and packaging
Thrust/Weight Wing Loading Calculations	Airframe load case matrix.	Thrust/Weight Wing Loading Calculation
Airframe Load Path Generation	Coarse structural topology optimization results.	Airframe Load Path Generation
Structural Load Calculations	Benchmark of conventional structural arrangement in current design space	Structural Load Calculations
Stability, Performance and Flight Characteristic Calculations	Final stability, performance and flight characteristic report.	Stability and Control Surface Calculations
Mass Bill of Materials	Mass bill of materials generated from the Technical Data Package.	Mass Bill of Materials

Figure 66. View of RFP Response Hyperlinks to Discipline-Specific Models Provided in Generated View[24]

As part of the surrogate pilot we are working on the Collaboration Use Case in the AST, linking from Government models on AWS to contractor models. Engineering models supporting the RFP response are viewable through hyperlinks into two Altair virtual collaboration environments (this does require a user account and password).

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[24] NAVAIR Public Release 2019-443. Distribution Statement A – "Approved for public release; distribution is unlimited"

- Altair 365 for CAD models and mathematics scripts in open-matrix language
- Altair Access for CAE models (e.g. CFD, structural)

There are videos on APAN to illustrate how these environments work. Other analyses completed as part of the RFP response include:

- Performance
- Preliminary Sizing
- Trade of Tilt Rotor vs. Ducted Fan
- Initial Vehicle Weight estimates relative to performance requirements
- Vehicle Packaging considerations
- Demonstrating how using MDAO can support decision making

7.3 ADVANCED APPROACHES TO MODEL INTEGRITY

It is currently unclear if NAVAIR, in the context of the SET Framework, will ever deal with multi-physics consideration during Element 1 and 2 of the SET framework. Most of the analysis will likely be parametric in nature during Element 1 and 2. However, we do know that Sandia National Laboratory has discussed some of the most advanced approaches for supporting uncertainty quantification (UQ) to enable risk-informed decision-making [139]. Their methods and tooling address the subjects of margins, sensitivities, and uncertainties. The information they provided reflects on the advanced nature of their efforts and continuous evolution through modeling and simulations capabilities that operate on some of the most powerful high-performance computing (HPC) resources in the world. We heard about their HPC capabilities, methodologies on Quantification of Margins and Uncertainty (QMU), an enabling framework called Design Analysis Kit for Optimization and Terascale Applications (DAKOTA) Toolkit [181], and the need and challenge of Model Validation and Simulation Qualification [175]. They also discussed the movement towards Common Engineering Environment that makes these capabilities pervasively available to their entire engineering team (i.e., the designing system in our terminology). We think their capabilities provide substantial evidence for the types of capabilities that should be part of the risk framework. This section provides additional details.

New approaches and new tools are being made available from SMARTUQ [190], and we should be able to take advantage of these capabilities in the context of the surrogate pilot. SMARTUQ provides modeling capabilities for uncertainty quantification (UQ) and analytics that incorporates real world variability and probabilistic behavior into engineering and systems analyses.

Traditional approaches referred to as Verification, Validation and Accreditation (VV&A) of modeling and simulation capabilities are still relevant and used by organizations. VV&A, in principle, is a process for reducing risk; in that sense VV&A provides a way for establishing whether a particular modeling and simulation and its input data are suitable and credible for a particular use [77]. The words “tool qualification” [78] and “simulation qualification” [175] have also been used by organizations regarding the trust in models and simulations capabilities. A more extension discussion of this subject is provided in RT-141 [35] and RT-157 [28].

8 UC05: Representation to Formalize Monterey Phoenix for Requirement Verification and Validation

This use case investigated the development of SysML representations to formalize the Monterey Phoenix (MP) research under RT-176 to support requirement verification and validation [84]. RT-176 is now completed. However, this section provides a summary of the effort. MCE does provide some unique opportunity to be more effective at contributing V&V evidence in early design. Rigorously defined models can directly support V&V, and this could both subsume cost and risks.

8.1 SysML Representation for Monterey Phoenix

The basic concept is to formalize using SysML graphics, and in this case activity diagrams and then transform into the MP language as shown in Figure 67. MP then uses the formal language to generate graphical representations of the behaviors, as shown in Figure 68 that can be derived from the language of the formalized behavior to a given scope level (e.g., Scope 2 in Figure 67). The verification step does require a person to check the different behavioral representations for correctness. This concept is similar to model checking.

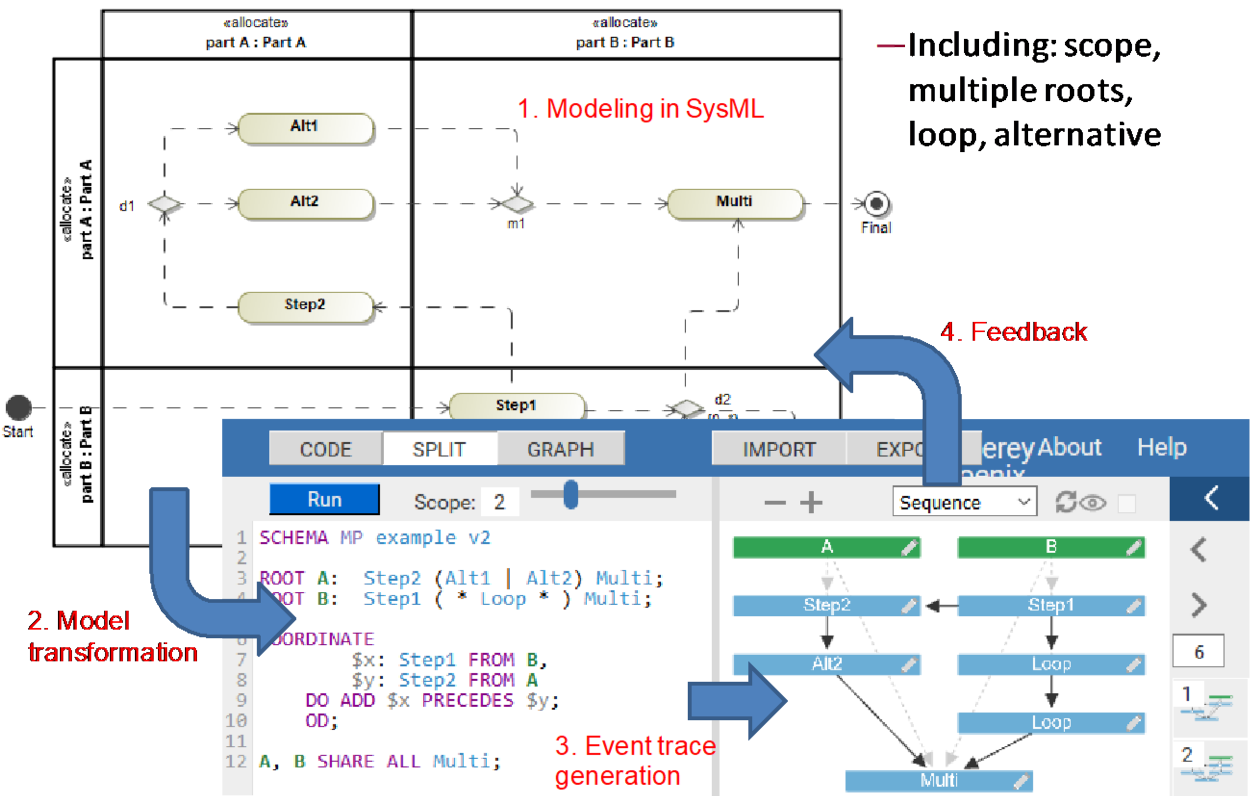


Figure 67. Representation and Transformation from SysML Activity Diagrams to MP

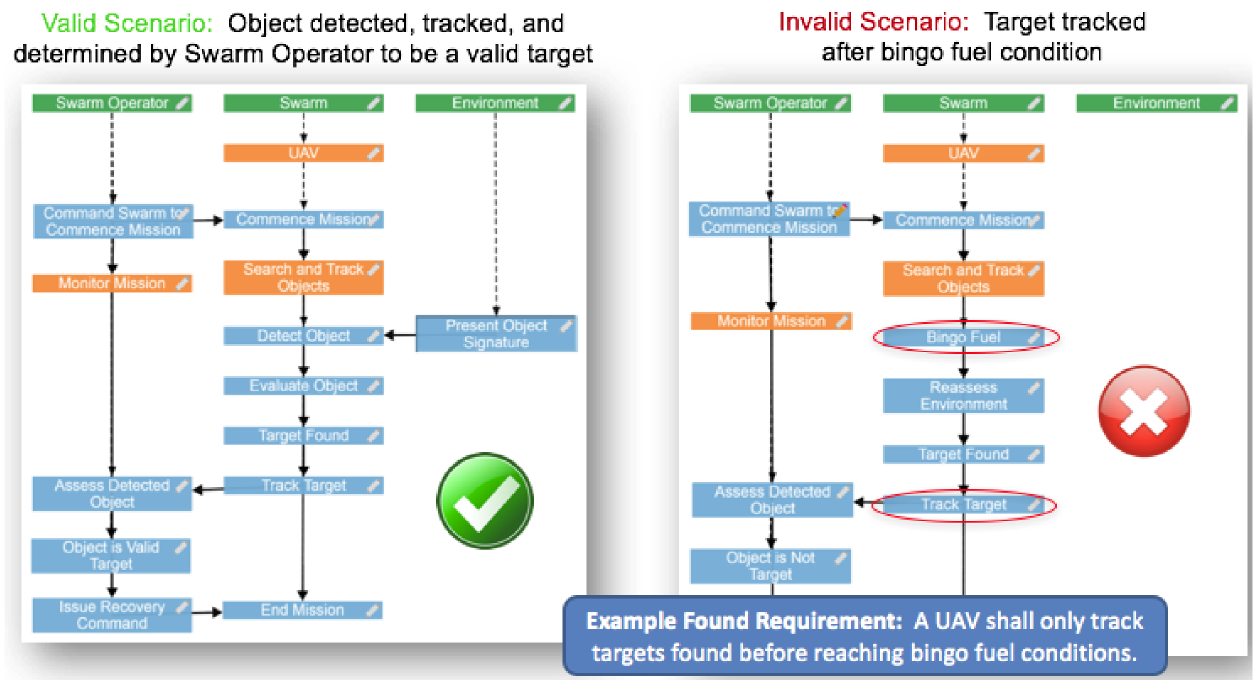


Figure 68. Generated Visualization of Scenarios by Monterey Phoenix

More information on Monterey Phoenix can be found:

- MP Public Website: wiki.nps.edu/display/MP/
- MP Analyzer on Firebird: http://firebird.nps.edu

8.2 SURROGATE PILOT EXAMPLES ANALYZED WITH MONTEREY PHOENIX

As an initial demonstration of the scenario discussed in Section 8.1 has been applied to an activity diagram from the Skyzer Mission Model. The RT-176 team extracted information from Skyzer Mission Model called the Non-Combat Operations scenario, which is represented as a multi-swim lane activity diagram as shown in Figure 69. We know that the model is difficult to read in the figure, but it can be accessed from APAN. Figure 70 shows one of the generated scenarios produced by MP from this activity diagram. The scenario for the process would be to automatically transform the activity diagram to MP, and then analyze the MP generated scenarios to validate the possible interpretations of the modeled activity diagram behavior.

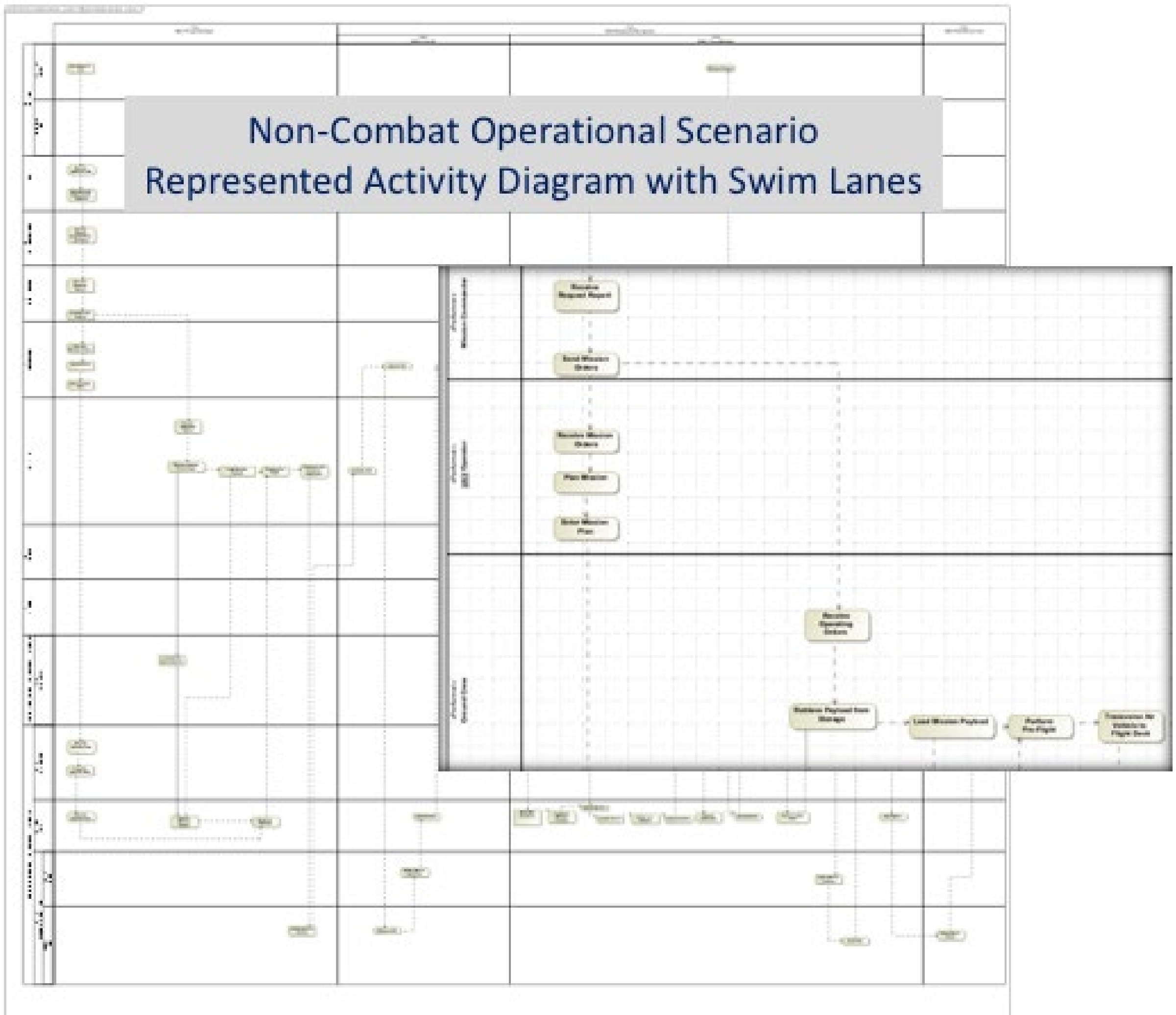


Figure 69. Non-Combat Operational Scenario Represented Activity Diagram with Swim Lanes

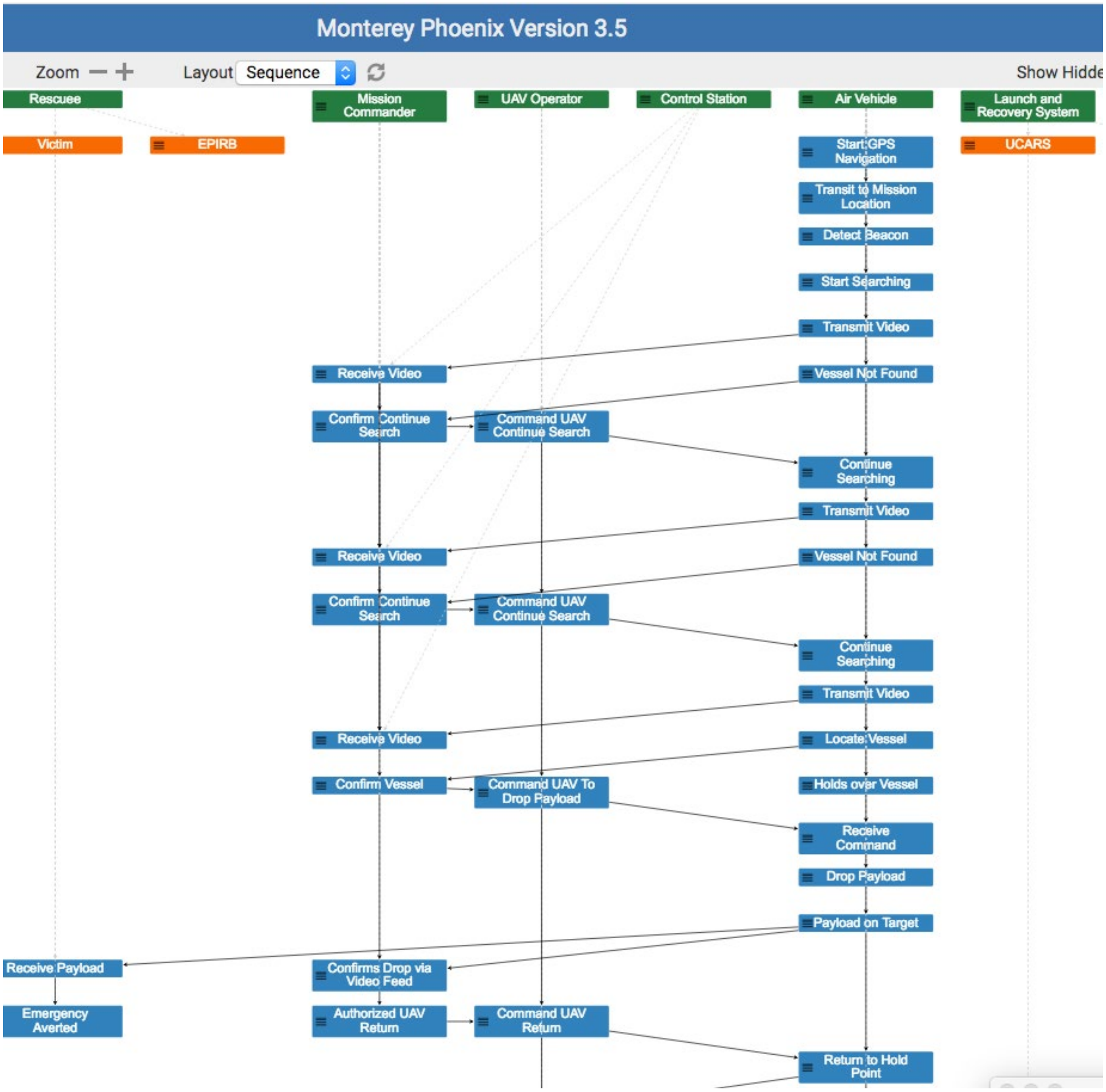


Figure 70. Monterey Phoenix Analysis of Event Generated Scenario

9 UC06: EXPERIMENTATION AND LEARNING FOR RESEARCH TOPICS IN THE EXECUTION OF SET

This use case investigates experimentation with the SET Framework concept using the SET surrogate pilot. Much of the information about this use case approach, results and lessons learned is in Part I of this report or described with additional details throughout this report in the context of the research use cases. Figure 71 shows some of the high-level use cases for the Surrogate Pilot Project. We use DocGen to automatically generate a report from the Surrogate Pilot Project model, which is provided in Appendix A of RT-195 [25]. The surrogate pilot contributed initial results to all uses cases shown in Figure 71, except 07 (i.e., Define Dependability Model) and 08 (i.e., Define Logistics Model); we are still interested in these use cases, but did not have the time or resources during Phase 1.

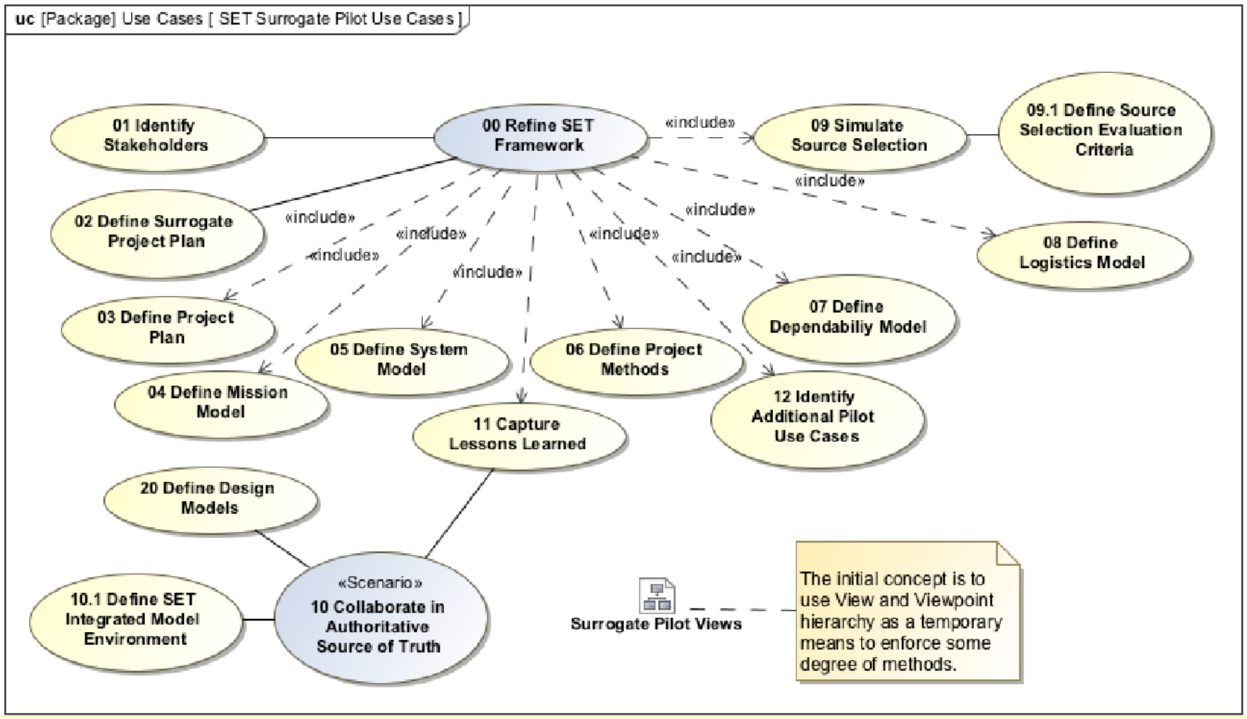


Figure 71. Identify Experimental Objectives for Use Cases

The best reference for the information stored in the project is captured in a full stack of model as shown in Figure 72, which was rendered earlier in Figure 9. This image is extracted from the project model discussed more in Section 10.1.

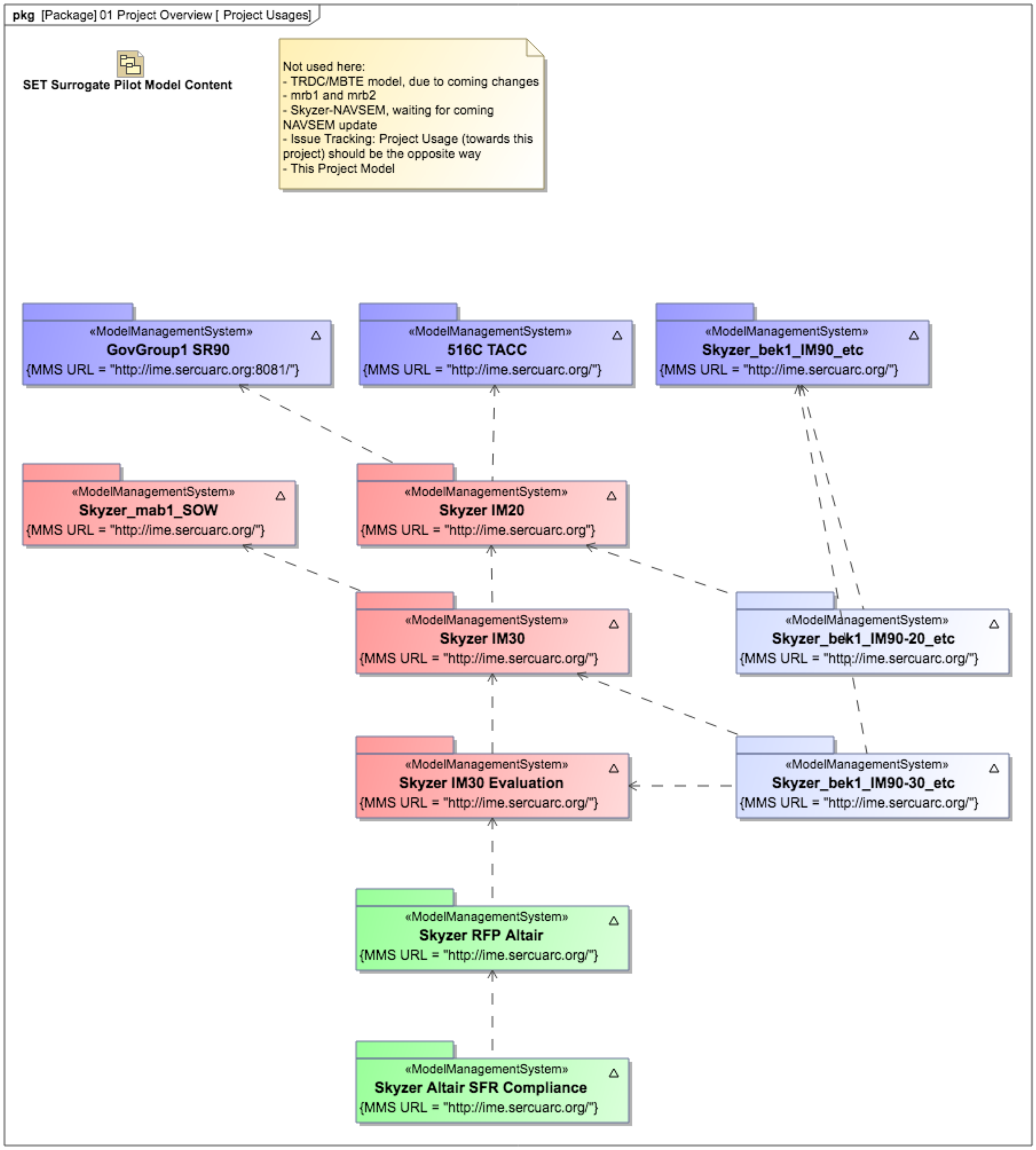


Figure 72. Full Stack of Models for the Surrogate Pilot Project

10 UC07: ENTERPRISE TRANSFORMATION TO SUPPORT GOVERNANCE AND WORKFORCE DEVELOPMENT

Enterprises undergoing digital transformation face many challenges related to governance and workforce development. For this use case, the research team conducted a preliminary investigation into potential useful frameworks, strategies and techniques that have resulted from recent research in the area of enterprise transformation. The resulting insights have potential to inform NAVAIR's implementation plans for the continuing transformation. We also cover some preliminary efforts for Model Curation for facet of Enterprise Governance using the Skyzer Surrogate Pilot case study in Section 10.2.

Transformation research has proven that failure to take a whole enterprise perspective leads to insufficiently evaluated, sub-optimized initiatives to complex enterprise challenges. One useful framework for taking a holistic approach to transformation has emerged from over a decade of research at MIT called ARIES (ARchitecting Innovative Enterprise Strategy) is discussed in Section 10.3.

10.1 Collaborative Management of Research Projects in SysML

Prior research with the US Army created a model for the System Engineering Technical and Management Plan [118]. We used a similar approach for the research use cases and pilot case study to demonstrate how the management of systems engineering can be done in SysML models within the Open Model-Based Engineering Environment (OpenMBEE). Figure 73 provides an overview of the packages and model elements contained in this model. We created these elements and provide continuous updates from this DocGen instantiation to support web-based collaboration, model-based report generation, and enabled semantic reasoning.

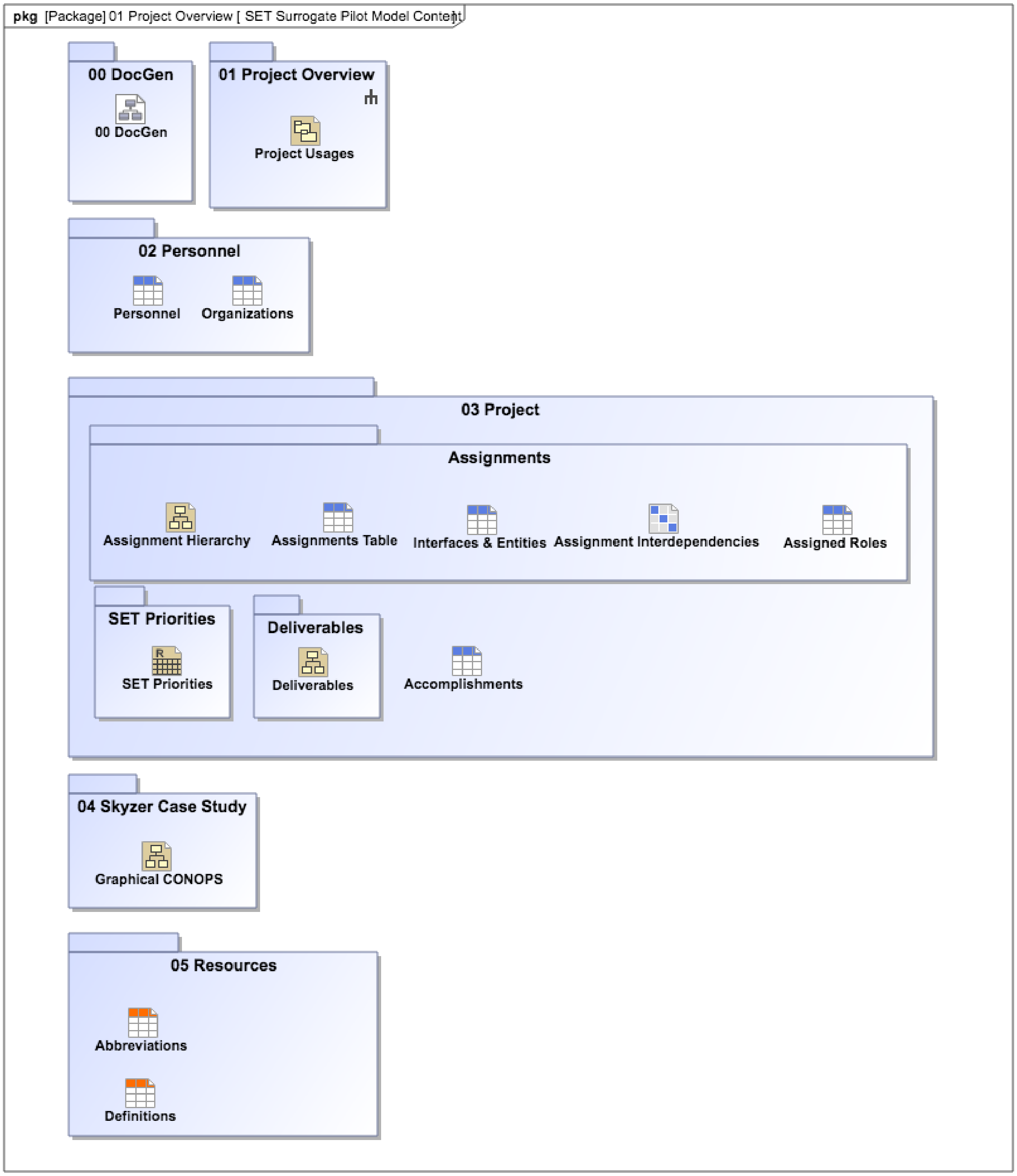


Figure 73. Model Packages and Elements for the System Engineering Technical and Management Plan Model

We have an underlying ontology that provides for semantic reasoning, which is seen as a key enabler and accomplished using a SysML profile that is aligned to an underlying project ontology. This results in not only using the advantages of a model-based engineering environment for managing the project, but also demonstrates the benefit of semantic enabled reasoning that is a focus of research of the research project. The research used a process of creating ontology and

SysML profile iteratively, seeking a compromise between parsimonious and correct ontology and profile as well as modeling convenience. Analog to the ecosystem of ontologies, there can also be multiple interrelated profiles, e.g., for mission models, as a related domain with another ontology.

Excerpts of the ontology as well as the profile are shown in Figure 74 (b). The figure shows the ontology terms "Agent," as the bearer of a "Role of Responsibility," which gets prescribed by an "Assignment" that is to accomplish further things. On the SysML profile side there is the "perform" dependency with its tagged value, called "role of responsibility." This relation is used below to specify that an "Agent" called Researcher performs the role of responsibility of the task lead for the "Assignment" Research Task 1. This example shows that there is not a one-to-one mapping between the terms of the project ontology and the matching project profile. For example, the term "Role of Responsibility" gets realized in form of a subsidiary property and the relations "bearer of" and "prescribes" are only realized implicitly through the "perform" dependency.

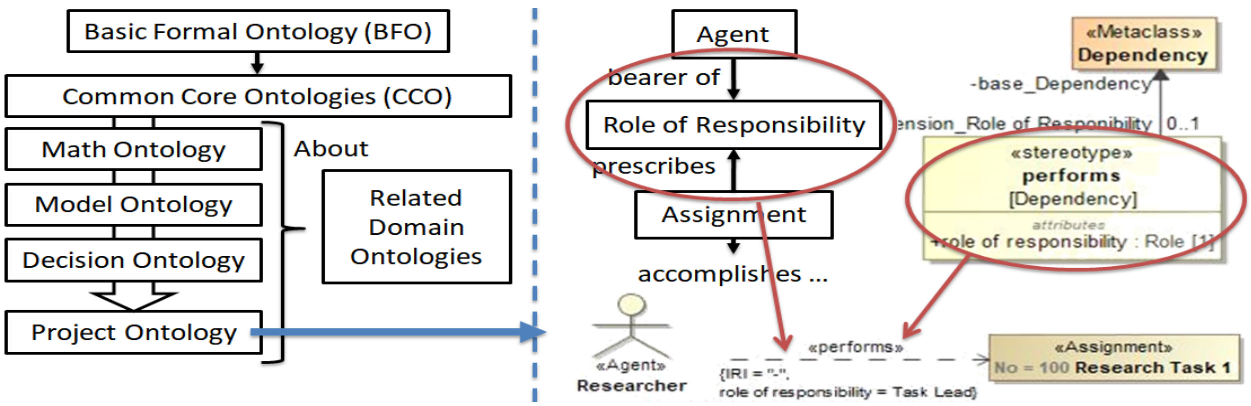


Figure 74. (a) Project ontology ecosystem under BFO; (b) Excerpt of project ontology elements with a corresponding SysML profile element and its application (bottom)

The content of the project SysML model includes a hierarchy of assignment elements. Each assignment has a property for its status and can use its documentation for a textual description that also becomes part of the documents. Linked to the assignments are researchers and other stakeholders as "agents" that perform certain roles of responsibility, as shown in Figure 74 (b). The interrelations between the different assignments as well as their required inputs and outputs, i.e., the deliverables, are modeled using internal block diagrams, as shown Figure 75. Figure 75 shows an assignment to align and refactor the "Skyzer Mission Model" and "Skyzer System Model" according to the "NAVSEM Starter" process model, while investigating their use and applicability as well as documenting any lessons learned, e.g., about identified unnecessary process steps, as shown as a subsidiary assignment. By specifying the assignments as specialized class elements in the profile, they can be modeled as shown in Figure 75 with their interrelations and deliverables, in contrast to, e.g., extended requirements or activity elements.

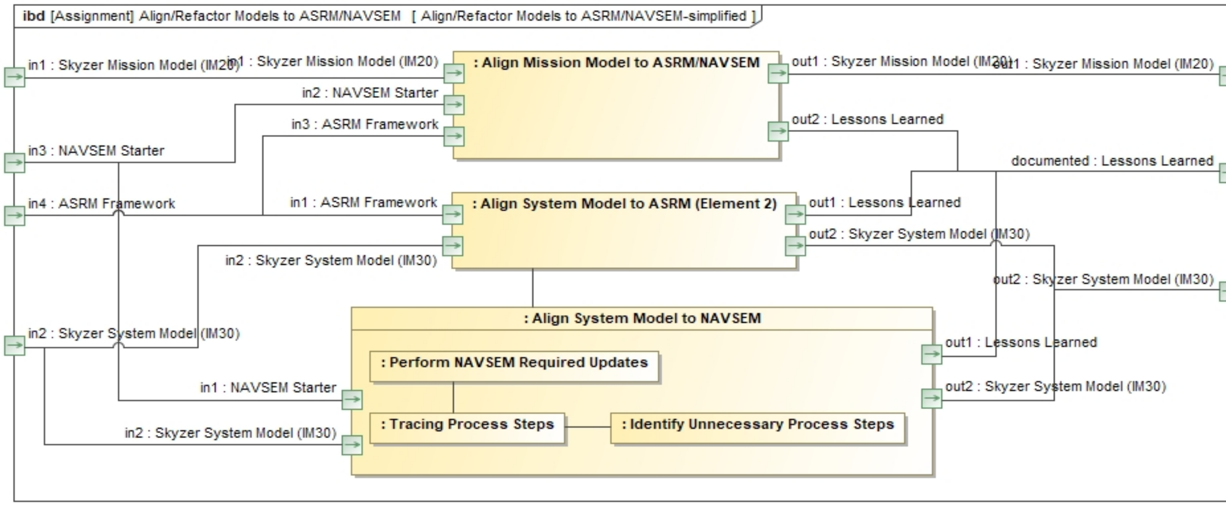
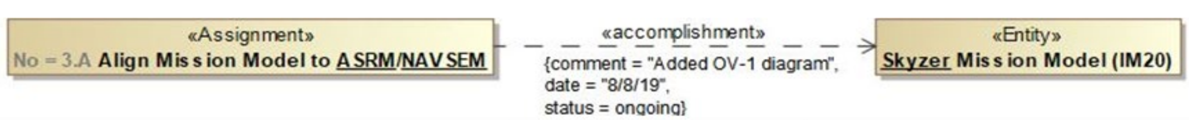


Figure 75. Simplified internal block diagram of assignments with their interrelations and deliverables

The accomplishments of the project are modeled as shown on top of Figure 76, by using a stereotyped dependency with comment, date and status properties. The dependency relates the accomplished entity with the achieving assignment. Having a project usage relation in the modeling tool gives direct access to all other used SysML models of the project. This allows to directly refer to the used models, their content or their documents when capturing accomplishments. Examples are given on the bottom of Figure 76 with an excerpt from the View Editor showing an accomplished addition to the mission model in the form of an added diagram for the ongoing alignment to ASRM and the completed change of the mission model document's view hierarchy. The shown representation in the View Editor allows researchers to edit the date, status, comment, as well as the names of the accomplished entity and the assignment in the table in a web browser, without a SysML modeling tool. It is also possible to adapt generic placeholder elements, as seen in Figure 76, into new accomplishments. Similar placeholder elements also exist for assignment elements in the project backlog. Yet, to properly integrate the renamed placeholder elements, additional work in the SysML modeling tool is required.



Accomplishment	Part of Assignment	Date Accomplished	Status	Comment
Placeholder01	Align Mission Model to ASRM/NAVSEM	-	unknown	-
Skyzer Mission Model (IM20)	Align Mission Model to ASRM/NAVSEM	8/8/19	ongoing	Added OV-1 diagram
Skyzer Mission Model Document (IM90-20)	Align Mission Model to ASRM/NAVSEM	8/1/19	complete	View hierarchy updated to reflect ASRM structure, while still exposing original Mission Model content

Figure 76. Example accomplishment in SysML (top) and derived View Editor table (bottom) with placeholder for adaption

Finally, the project model contains additional resources about the project goals, the investigated case study in form of an Unmanned Air System (UAS), called Skyzer and a glossary with a list of used acronyms. Based on the model data several metrics are calculated and exposed within the documents for example the number and status of accomplishments. This example demonstrates that a System Engineering Technical and Management Plan can be modeled as a descriptive model and be potentially included as part of the AST.

10.2 Model Curation Skyzer System Model

The SERC has investigated model curation over the past several years, most recently in SERC WRT-1009, *Model Curation Innovation and Implementation[166]*. Model Curation can be defined as the lifecycle management, control, preservation and active enhancement of models and associated information to ensure value for current and future use, as well as repurposing beyond initial purpose and context. Curation practices promote formalism and provide for the strategic management and control of models and associated digital artifacts, particularly when managed as a collection at the enterprise level. Curation activities include model governance, accession, acquisition, valuation, preservation, active enhancement, model discovery, deaccessioning, and archiving. Curation practices promote formalism and provide for the management and control of models and associated digital artifacts, particularly when managed as a collection, at the enterprise level. Information associated with a model includes technical data, model metadata, and model pedigree [165] [166].

Presently, there are few enterprise-level collections of models. Looking to the future, as models become increasingly valuable it is anticipated that enterprises will have large model collections under formal governance. Not all models are suitable for an enterprise collection, so a formal process will be needed to make decisions on placing models under curation. A first category of models suitable for curation includes models that will be used throughout the lifespan of a major program, for example models comprising a digital twin. A second category includes models designed (or enhanced) to be intentionally reused for a new purpose and/or within a new context. Examples are reference architectures and models, and “platform” models that enable the enterprise to effectively re-purpose and reuse models. A potential third category is models suitable for curation at the community level, as exemplars that can be used for knowledge sharing, as teaching resources, and for supporting research. Akin to how the systems biology community makes models available for researchers to exchange published peer-reviewed models [167], it is possible in the future that there will be curated model collections for the benefit of model sharing across the digital engineering research community [166].

A model collection is valuable only if the benefits of maintaining it outweigh the costs and models are perceived as having integrity and credibility [168]. An enterprise model collection could include models for programs under development, models used by active programs in operations phase, models archived for historical or objective evidence purposes, reference models, surrogate models, demonstration models, and others [Rhodes, 2020]. Once an initial decision is made to place a model under curation, the enterprise will need to use specific criteria to assess its readiness and acceptability for the model collection. As experience is gained with enterprise model curation, the systems community can evolve a standard set of criteria for this purpose.

An initial set of criteria was developed as part of SERC WRT-1009 project [166]. As an illustrative example of curation, the criteria are applied to the Skyzer System Model in a scenario where it is under consideration for a hypothetical enterprise-level model collection.

10.2.1 Illustrative Example: Readiness and Acceptability of Skyzer System Model for an Enterprise Model Collection

For the purposes of providing an illustrative example, the criteria are applied to the *Skyzer System Model* in a scenario with the following basic assumptions:

- DoD has established a *DoD Exemplar Model Collection (DEMC)* for use in defense-sponsored research projects and education classes.
- The DEMC "model collection packages" are exemplars that are available to any authorized user for purposes of research and education.
- The DEMC *Chief Model Curation Officer (CMCO)* is an appointed leader from an FFRDC, who carries out curation governance and oversight.
- The CMCO chairs a *DEMC Governing Board* of appointed representatives qualified to make decisions about engineering models.
- Periodically, the CMCO convenes the governing board to decide if models proposed for the DEMC should be accepted into the collection.
- It is assumed that each DEMC collection object (complete "model collection package") will "reside" in a centralized repository (implementation of this is beyond the scope of this example).

For this scenario, the *Skyzer System Model* has been identified as a candidate for the DEMC, and the CMCO's staff have prepared the information for an evaluation against the formal DEMC decision criteria. The CMCO convenes the DEMC Governing Board to review justification and make a decision on acceptance of the model into the model collection.

As shown in Table 2 there appears to be excellent justification for the Skyzer System Model's readiness and acceptability for this hypothetical DEMC model collection.

Note about this illustrative example: While the criteria used here are preliminary and incomplete, this example aims to provide a starting point for use in workshops and further research to evolve complete and validated criteria. The justification provided here is abbreviated; it is envisioned that results of a real-world evaluation using the criteria would include selected objective evidence.

Table 2. Justification for Decision to Accept Skyzer System Model for the DoD Exemplar Model Collection (hypothetical)

Criteria for Placing Model Under Curation		Skyzer System Model - Justification
1. Relevance to Enterprise and/or Program Mission	a. *Is the model relevant to specific current or future program mission and/or enterprise mission?*	Yes, the Skyzer System Model is directly relevant to the defense community's need to educate the workforce on digital engineering, and investigate technology-enabled best practices. This model was

Criteria for Placing Model Under Curation		Skyzer System Model - Justification
		developed as part of the DoD Systems Engineering Research Center (SERC) University Affiliated Research Center (UARC). Placing the model under curation is consistent with SERC mission. Experiments accomplished using Skyzer Surrogate models support discovery of best practice and technology innovation.
	b. *Does model (including metadata, data, representation, documentation) fall within model collection scope?*	The purpose of the DEMC is to share exemplar models within the defense systems community to support research and education. The Skyzer System Model is uniquely suited to this purpose, as a product of sustained research that detailed outcomes and reflections throughout the project.
	c. *Are there legal requirements or guidelines related to placing model under curation?*	While there is no legal requirement to place the Skyzer System Model under curation, recent guidance from DoD encourages models resulting from DoD-sponsored research to be submitted for consideration for DEMC.
	d. *Is there authoritative evidence of current value to engineering field?*	The Skyzer Surrogate Project, including development of the Skyzer System Model, has been funded by SERC and NAVAIR over a sustained period, and undergone many sponsor reviews. The continuation of sponsorship, peer-reviewed publications, and invited talks on the project are evidence of its value to the engineering field.
	e. *Is there future value in having documented evidence of the model's use/reuse?*	Transformation of engineering to a model-centric discipline is ongoing. An important aspect of this is knowledge sharing across the systems community. Understanding how the Skyzer System Model is reused over time will contribute to the body of knowledge for the field. Documented evidence can be used to improve practice and educate future workforce.

Criteria for Placing Model Under Curation		Skyzer System Model - Justification
2. Completeness of Metadata, Data, and Documentation	a. *Does model documentation span lifecycle phases during which the model was conceived, generated and used?*	Comprehensive model documentation exists for all phases of the system model, including SERC reports and complete set of system model versions. Videos and briefings provide supplemental documentation through lifecycle phases. The Project Planning Model for Skyzer provided a comprehensive technical and management plan to guide completion of metadata, data and documentation.
	b. *Is model information and metadata complete and accessible?*	Yes, all information and metadata is complete and currently accessible through the Skyzer Surrogate Pilot infrastructure. Research team videos are available in APAN that have captured information and decisions throughout model lifecycle phases.
	c. *Is there sufficient documentation to support sharing, access and re-use of the model?*	The documentation for this model is extensive. Information is also available in SERC reports including RT-118, RT141, RT-157, RT-170, RT-195, WRT-1008. Documentation includes instructions on where and how to access the model and related information.
	d. *Is there sufficient data associated with the model to enable clear understanding and replication of results?*	Yes, model data is fully accessible to authorized users. It is organized to enable understanding, with detailed appendices (e.g., requirements). Access is provided to supporting models, including Skyzer Mission Model, Surrogate Contractor Model and Surrogate Contractor Design Models, and Capability-Based Test & Evaluation/Mission-Based Test Design Model
3. Completeness of Model Pedigree	a. *Does the model pedigree information indicate the originating individual/organization?*	The pedigree information can be compiled from SERC technical reports and briefings. Originating organization and involved individuals are named in reports and Project Planning Model.
	b. *Are the assumptions and context information*	Weekly video sessions capture a record of individuals involved in evolution of the

Criteria for Placing Model Under Curation		Skyzer System Model - Justification
	associated with the model documented and accessible?	model and their assumptions. These are presently available through APAN. Context information has also been put into the model, itself.
	c. *Is the complete model pedigree current and fully accessible?*	The complete set of SERC reports (including technical reports for RT-48, RT-118, RT-141, RT-157, RT-170, RT-195, WRT-1008) provides for complete pedigree information. These are open public access, available on the SERC website. Additional information is available within the existing models and related artifacts.
	d. *Is there sufficient pedigree information to enable a model consumer to judge its credibility?*	The extensive reports, papers and videos provide significant indication of expertise that went into the Skyzer models. This provides transparency into assumptions and insight into decisions, as well as the extensive reviews used in the effort.
4. Potential for Redistribution, Reuse, and/or Repurposing	*a. Are there IP issues, data rights issues, human subject issues or restrictions that are not addressable?*	This model was developed under SERC UARC research with NAVAIR sponsorship. DoD UARCs as "not-for-profit organizations maintain long-term strategic relationships with their sponsors and operate in the public interest, free from real or perceived conflicts of interest" (sercuarc.org). Accordingly, IP issues, data rights issues and human subject issues were considered in proposal/contracting phase of the research that produced the Skyzer System Model.
	b. Is there evidence of model reliability and usability?	Video discussions available through APAN include questions and explanations that foster usability. Various SERC experiments using the Skyzer System Model indicate its reliability for its intended purpose. SERC technical reports provide detailed supporting evidence.

Criteria for Placing Model Under Curation		Skyzer System Model - Justification
	c. Does the model have evidence of verification and validation?	Traceability to requirements is provided in documentation. V&V evidence is clearly documented and comprehensive, including Capability-Based Test & Evaluation/Mission-Based Test Design Model. Digital signoffs were used and recorded within the model itself.
	d. Is the "model package" complete (model, data, metadata, documentation, digital artifacts, etc.)?	Skyzer Surrogate Pilot resulted in a very complete "model package" given extensive planning and attention to detail in capturing all aspects of the model, processes, and artifacts produced. Links are provided to the Project Planning Model for Skyzer, Mission Model for Search and Rescue Scenarios, Surrogate Contractor System Model, and Surrogate Contractor Design Models, and Capability-Based Test & Evaluation/Mission Test Design Model.
	e. Is there sufficient information to judge integrity and credibility of the model package?	Surrogate Pilot experiments, models, specifications, results, and lessons learned are shared with industry and government on APAN. The Surrogate Pilot group captured weekly progress throughout research providing transparency to interim review results. Involved knowledge experts are listed in SERC reports.
	f. Does the model meet standards and other technical criteria to allow its easy redistribution?	The Surrogate Pilot established SysML modeling guidelines and developed basd on the NAVAIR Systems Engineering Method (NAVSEM). Use of OpenMBEE, ontologies for systems engineering and semantic technologies have facilitated the ease of potential redistribution. The team gave significant thought to how to make the model accessible to various model consumers.
5. Uniqueness of Model/ Non-Replicability	a. *Is the model the sole existing source of its content?*	There is justification to accept the Skyzer System Model into the DEMC, as the sole source of content. All specifications are generated directly from the model.

Criteria for Placing Model Under Curation		Skyzer System Model - Justification
	b. *Can the model be easily replicated or recreated?*	The level of expert knowledge and interactions that went into developing the model make it unlikely that this model could be replicated or recreated by another enterprise.
	c. *Is the cost of replicating the model financially viable?*	The magnitude of resources expended and level of expertise that went into developing the model makes it unlikely it could be replicated.
	d. Is there historic value and/or education value for future workforce?	This model is the first of its kind in the systems community, having historic value for evolution of model-based methodology. The model is very valuable for future research and education.
6. Economic Business Case	a. *Does benefit of placing model under curation exceed required cost?*	The benefits of this model as an exemplar that can be shared across the defense systems community far exceed cost of placing under enterprise-level curation.
	b. *Has total cost of retaining the model package over active lifespan been considered?*	Once the Skyzer Surrogate Pilot effort completes, the cost of retaining it for active use in research and education are expected to be minimal, as the model would remain unchanged except for period updates on its use.
	c. *Has funding source for model retention and curation activities been agreed upon?*	DoD has arranged funding for DEMC operations and infrastructure. SERC has agreed to provide resources for transitioning the appropriate models/model information to the DEMC, if the model is accepted for the collection.
	d. *Have security and risk been considered in the economic case?*	As this is a surrogate pilot project, the model is not being used in an actual program; security is not considered to be an issue. The model documentation has clearly expressed disclaimers and limitations, which minimizes risk in use.
	e. Has cost of archiving model after deaccession been considered?	Deaccession of the model is not likely for some time. Digital engineering transformation is expected to continue

Criteria for Placing Model Under Curation		Skyzer System Model - Justification
		over a long period so the model will remain useful for historical and educational purposes. Cost of archiving is expected to be low. If there is a need to remove from DEMC, it is likely an FFRDC or professional society could retain the archived model.
Surrogate Pilot experiments, models, generated specifications, results, and lessons learned are shared with industry and government on the All Partners Network (APAN.org). APAN was setup and is managed by Defense Information Services Agency (DISA). DoD organizations can request their own groups, and NAVAIR has several groups for the SET. Some are internal for NAVAIR people and their contractors, but the Surrogate Pilot Group (https://community.apan.org/wg/navair-set/set-surrogate-pilot/) is open to the public with the proper registration in APAN.		

10.3 ARCHITECTING INNOVATIVE ENTERPRISE STRATEGY

Resulting from transformation studies of more than 100 enterprises, the *ARIES Framework*, is applied to generate a holistic blueprint for achieving a desired transformation. The work was motivated by transformation failures, often resulting from going from a transformation need to jump directly to (an incomplete) solution.

> **What is the ARIES Framework:** The **ARIES (ARCHITECTING INNOVATIVE ENTERPRISE STRATEGY)** Framework is comprised of: (1) the enterprise element model, specifying ten unique elements for seeing the whole enterprise; (2) the architecting process model having seven activities; and (3) selected techniques and templates. ARIES is grounded in the belief that an enterprise is a complex system, and accordingly must be treated holistically. Enterprise elements make it possible to isolate unique areas of focus, and doing this makes it possible to reduce complexity so that the whole enterprise can be examined. The ten elements emerging from a decade of research are: ecosystem, stakeholders, organization, process, knowledge, infrastructure, information, products and services. Culture, rather than being an element of the enterprise, is viewed as rooted in organization but cross-cutting the ten entangled elements. The ARIES architecting process includes seven activities: (1) understand the enterprise landscape; (2) perform stakeholder analysis; (3) capture current architecture; (4) create a holistic vision of the future; (5) generate alternative architectures; (6) decide on a future architecture; and (7) develop the implementation plan ("blueprint"). Applying the framework results in transformation strategies and initiatives, which are derived using enriched knowledge of the present, attributes of the desired future, and the evaluation of alternatives.

In this phase of the project, the research team has investigated how enterprise transformation research can contribute in two areas of particular importance: (1) enterprise governance in context of SE enterprise deployment; and (2) workforce development.

10.3.1 Governance and Workforce Development Challenges

Governance is the structure for providing strategic oversight of the transformation effort to achieve results (independent of who the leader might be). It includes ensuring consistent practices, cohesive policies, guidance, processes, and decision making. As stated by Nightingale & Rhodes [140], governance should enable, not create barriers. The transformation governance structure, according to Nightingale & Srinivasan [141] has to "ensure not only the monitoring and control of progress, but also make it possible to reassess strategically the overall direction and constituent projects".

Governance in regard to enterprise transformation necessitates a dual-strategy approach [186]. The first is that the transformation team needs to understand how to fit within current governance structure of the enterprise. Second, there will be a need to establish adjunct and/or independent governance. Governance involves the formal structures and bodies for performing governance activities, as well as the overarching philosophy and supporting policies and enablers.

Research has shown that in establishing governance for sustainment of transformation outcomes, it is very important to take a holistic perspective [140]. The *ARIES Framework Enterprise Element Model is useful* to holistically consider complex enterprises by investigation through various elements (viewpoints/lenses) and relationships of these. The ten elements are shown in Figure 77. Complexity of an enterprise makes it difficult to understand enterprise-level characteristic and behaviors. The benefit of this enabler is that considering transformation using viewpoints enhances the tractability of addressing the myriad aspects of enterprise governance, rather than taking a silo-ed view (e.g., only processes).

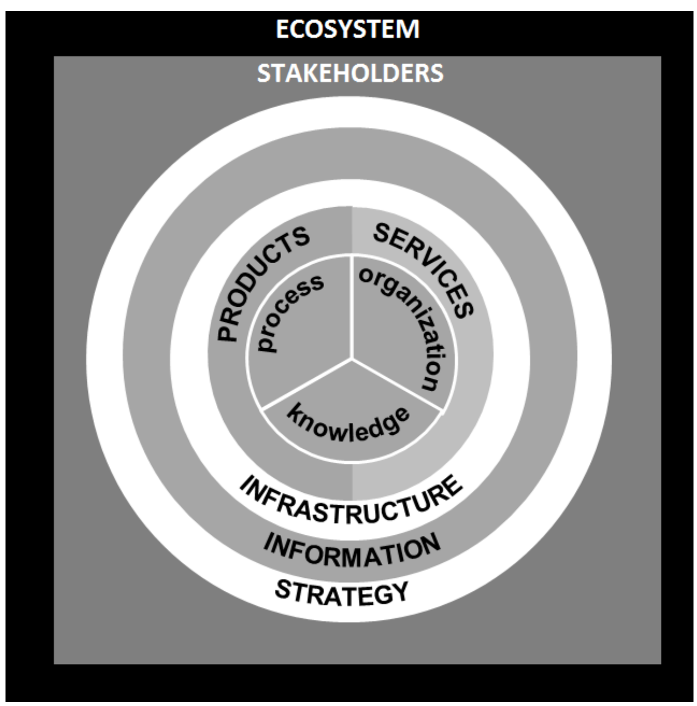


Figure 77. ARIES Framework Ten Enterprise Elements [140]

Table 3 shows examples of questions that may relate to the governance function and activities, when taking the perspective (or viewpoint) of each enterprise element. There are many additional questions to be raised and considered in context of SE transformation governance. These example questions are representative of the questions that might be raised by a transformation team.

Enterprise transformation research has indicated that a team workshop activity with representation from various stakeholder groups can be an effective approach to generate a rich set of questions. These are then used to formulate implementation actions, which can be ordered and prioritized based on team consensus.

Table 3. Holistic Investigation of Governance through Viewpoints

Enterprise Element	Example questions related to governance
Ecosystem	• What external constituents impose constraints and requirements on NAVAIR governance? • What governance models are other enterprises using in context of digital transformation?
Stakeholders	• Who are the various stakeholder groups who will have responsibility and authority for governance activities? • Will any stakeholders have increased or decreased authorities following transformation?
Strategy	• What business models will be used for acquiring and supporting the digital engineering infrastructure? • What strategy will be taken in forming a governance body/function?
Process	• What new processes (e.g., curation) will need to be developed and deployed? • What existing processes will need to be modified and deployed?
Organization	• Will any current leadership roles need to be changed and/or created to address governance? • What actions will leadership need to take to sustain transformation outcomes?
Knowledge	• How will digital artifacts be handled from an IP perspective? • How will governance-related lessons learned be captured and shared?
Information	• What existing/new measures will the governance body need to monitor SE Transformation deployment? • What information from other enterprises will be useful for the governance team?
Infrastructure	• What model-based toolsets will be governed at the enterprise level? • Who will be responsible for approving infrastructure decisions (e.g., acquire and retire toolsets)?
Products	• What governance role is needed in the case of digital artifacts being provided as products across organizational units within the enterprise?

Enterprise Element	Example questions related to governance
	• How will internal model-based products (e.g., reference models) be controlled?
Services	• What enterprise-level support services (e.g., tool help desk, tool installation) will be provided? • How will the governance body assess cost-effectiveness of providing these services?

Table 4 shows examples of questions that may relate to the workforce development, when taking the perspective (or viewpoint) of each enterprise element. There are many additional questions to be raised and considered in context of SE transformation and workforce. These example questions are representative of the questions that might be raised.

Table 4. Holistic Investigation of Workforce Development through Viewpoints

Enterprise Element	Example questions related to workforce development
Ecosystem	• How are other government enterprises developing their workforce for digital engineering practice? • What external constituents (toolset vendors, universities, training/ consultants) are potential providers for workforce development?
Stakeholders	• Who are the various stakeholder groups who will have responsibility and authority for workforce development activities? • Will any stakeholders have increased or decreased roles and responsibilities following transformation and what will be needed to address this?
Strategy	• What business models will be used for developing (e.g., training, certification) and/or acquiring (hiring, consulting services) digital engineering competency? • What strategy will be taken to develop the workforce (e.g., organization-wide, program-specific, role specific) and sustain competency over time? • How will workforce development investment be allocated respective to program needs and priorities, enterprise-level needs and priorities, etc.
Process	• How will the workforce be educated on new/modified digital engineering practices? • What will be the approach to develop processes that are tool-neutral?
Organization	• What approach will be used in developing the workforce from an organizational perspective (e.g., organization-wide, program-specific, role specific)? • Will any organizational re-alignment or re-assignments be needed to achieve workforce development objectives?

Enterprise Element	Example questions related to workforce development
Knowledge	• What are the knowledge, skills and abilities that are needed in the workforce in the near-term and longer term? • How will the workforce learning on one project be transferred to other future projects?
Information	• What information from other enterprises will be useful to inform workforce development? • How will individuals be informed about opportunities to develop their model-based skills?
Infrastructure	• How will the workforce be informed and educated as digital engineering infrastructure is set up and evolved? • Will individuals need new infrastructure (e.g., desktop computer) to have access to new infrastructure and toolsets?
Products	• What internal products for workforce development (e.g., self-study course, templates, guides) will be available to programs and individuals? • What external products (e.g., INCOSE Competency Framework) are available to support workforce development?
Services	• What enterprise-level skill development support services (e.g., mentoring, communities of practice) will be available? • How will social media technology services (APAN, blogs, etc.) be made available?

10.3.2 Enterprise Alignment

A governance body performs ongoing oversight to ensure transformation progresses according to plan. Accordingly, there is a need to continuously assess alignment across strategic objectives, stakeholders' value, key processes, and the metrics used to assess the enterprise. The X-Matrix is a construct that has proven to be useful for taking a big-picture view of an enterprise, and finding gaps and misalignment. It is a qualitative tool that shows weak and strong alignment in a visual manner [142][141][140].

The Enterprise Strategic Analysis and Transition (ESAT) Guide describes the Enterprise X-Matrix method, as used to determine the alignment of an enterprise's objectives, metrics, processes, and stakeholder values [142]. The X-Matrix provides a means to concisely visualize the alignment of these aspects of the enterprise by assigning a strong or weak alignment between the different aspects of the enterprise. The upper right quadrant shows how well the enterprise has aligned their strategic objectives with the stakeholder values. The lower right quadrant evaluates the alignment of the enterprise processes with the stakeholder value. The lower left quadrant evaluates the ability of the enterprise's metrics to accurately measure the key processes. And, the upper left quadrant of the X-Matrix shows whether the metrics are accurately evaluating the performance of the enterprise in relationship to the strategic objectives.

Figure 78 shows an example of an X-Matrix for a current state enterprise (a military flight school) resulting from a prior research investigation [79]. The gold-shaded cells present weak alignment and the blue-shaded cells represent strong alignment. While not every empty cell is meant to be filled, the matrix helps to identify gaps and misalignment. For example, the process for "Provision of CSC Simulators" is not measured by any existing metric, and there are no metrics that assess the strategic goal "Enhance Professional Military Education".

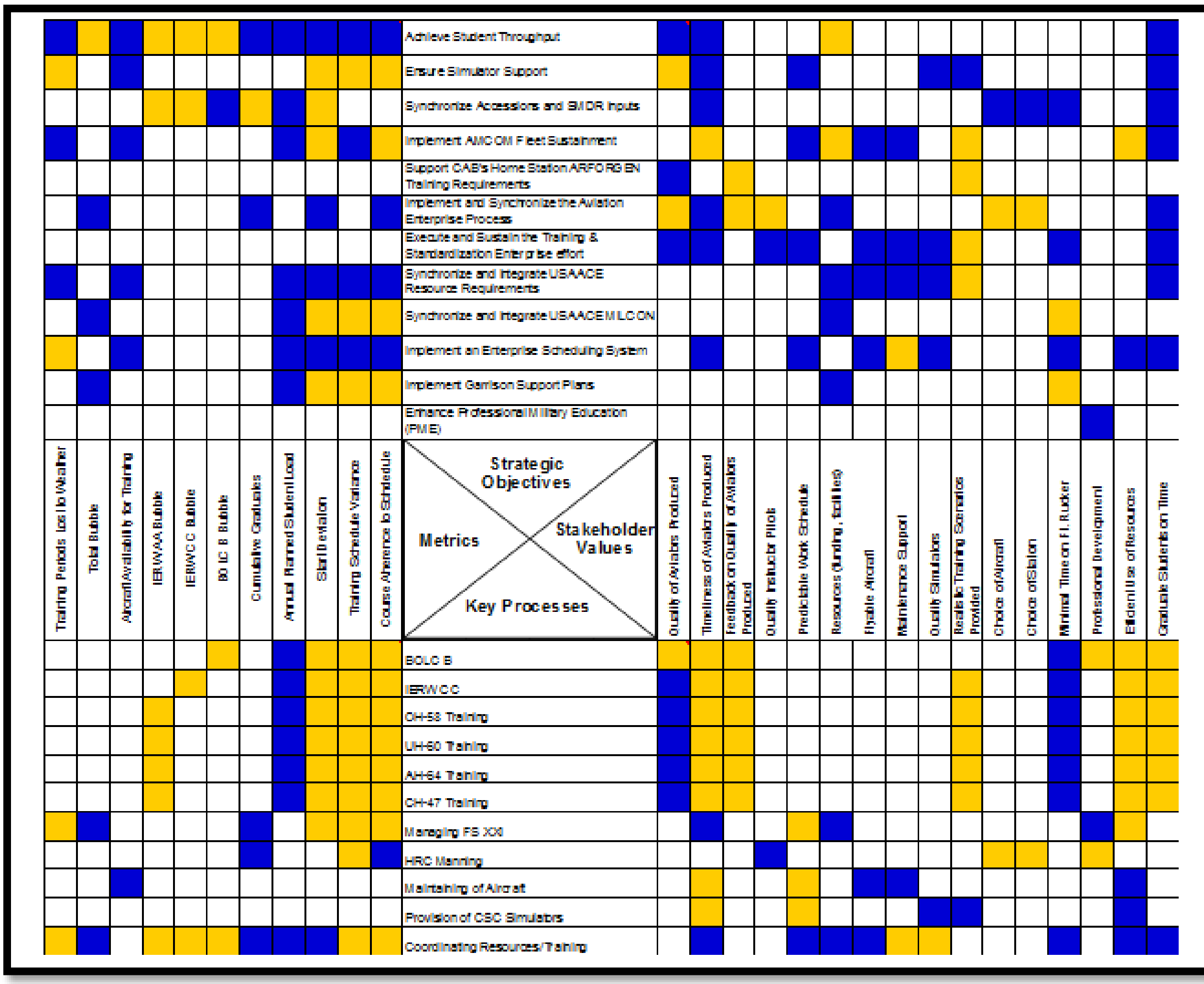


Figure 78. Example X-Matrix of an Enterprise [79]

The X-Matrix can be viewed as a framing technique, and can be customized for the needs of the transformation. The quadrants may vary based on the specific enterprise transformation. Another example of quadrant information used is (1) strategic objectives, (2) stakeholder needs, (3) key initiatives, and (4) metrics (measures). In some transformation programs, specific metrics may not yet be defined so in place of transformation specific metrics, current programs providing measurable information for strategic objectives might be used Song [195].

The X-Matrix offers a potential enabler in the governance team's role in monitoring and assessing transformation over time. The transformation team would produce an X-Matrix of the current enterprise and use it to identify gaps. A governance body could then update the matrix as transformation progresses, first with planned changes and then as implementation occurs, and use it as a means to judge enterprise alignment. The ongoing monitoring and assessment of enterprise transformation projects engages many different stakeholders, each of whom have individual priorities and limited visibility into the whole enterprise. The power of the X-Matrix is that it offers a shared "boundary object" for ongoing discussion and negotiation (for example, the allocation of limited resources to initiatives). Having a consensus set of metrics specific to transformation provides a common basis for understanding progress.

10.3.3 Phase 1 Lessons Learned: Implications for Governance and Workforce Development

Section 2.8 summarizes a non-exhaustive list of categorized observations and lessons learned from the Phase 1 effort. Many of these are model technology-specific lessons. While categorization is a useful approach for organization lessons, additional insights may be gained by looking through alternative lenses.

As a means to provide an alternate summary of these from an enterprise (vs. category) perspective, selected lessons learned are mapped to enterprise element viewpoints in Table 5, with possible implications for governance and workforce development. Further formulation of lessons learned with mapping to elements and implications could be performed as part of SET deployment planning.

Table 5 Selected SE Transformation Lessons Learned Mapped to Enterprise Elements

SET Lessons Learned Category	Enterprise Element	Implications for Governance	Implications for Workforce Development
Objectives Identification for Phases	Strategy	Standard use of NASA/JPL ontology	Objectives identified to cut across mission, system, RFP, and source selection processes providing unclassified modeling examples for workforce training
infrastructures for IME tools and AST	Infrastructure	Standardize guidance and schedules for infrastructure for new programs	Inform and train new program workforce on infrastructure at start of program
Interactive interaction with surrogate contractor during RFI and pre-RFP very useful	Strategy	Need to establish policy for early collaboration using models concerning information sharing	Need to train workforce on interaction policies and process for doing so

SET Lessons Learned Category	Enterprise Element	Implications for Governance	Implications for Workforce Development
Technically feasible to develop everything in a model	Strategy	Promote culture to embrace the broad use models where valuable. Encourage consideration and justification for model use/no use decision	Open MBEE and associated modeling tools provided key capabilities, and provided underlying infrastructure for implementation of AST
Methods and guidance	Knowledge	Standard modeling guidelines	Train workforce on standard methods and how to tailor if needed
Model Management	Process	Ensure comprehensive development/ application of model management practices, as distinct but aligned with CM	Provides example for doing modeling management in the context of AST that goes beyond traditional CM of documents
Model Management	Organization		Promote involvement in community efforts to standardize model management practice
Model Modularization	Strategy	Promote modularization as strategy to promote reuse, isolate classified information, provide access control, reduce complexity, etc.	Strategic decision to educate workforce on model modularization practice, and use of toolsets
Project Usages for Model Modularization	Infrastructure	Ensure modeling toolset capabilities leveraged to achieve benefits of modularity	Provides means for working on separate aspects of lifecycle in parallel such a mission and system model that are also linked
RFI and RFP	Process	Guidance for model-based RFI and RFP process	Educate workforce on RFI and RFP processes in model-based situation
Access to AST	Information	Investigate feasibility of providing access to public domain hosted server information	Provides exemplar to inform workforce how to work collaboratively on models that span the lifecycle

SET Lessons Learned Category	Enterprise Element	Implications for Governance	Implications for Workforce Development
Team SME with modelers	Organization	Promote a culture of collaboration and open communications between modelers and SME	Organize training with teamed SMEs and modelers to reinforce use of approach

11 AI-Based Assistants to Augment Human Systems Engineers

There has been much interest of late in how best to leverage AI to enhance the capabilities of military platforms, other vehicles, and various technology-based processes. This section addresses how to use AI-based support to enhance the performance of the engineers that design and develop these platforms, vehicles, and processes.

A brief background on key constructs is first provided. The overall approach to this project is then outlined. A case study on supporting automotive engineering is then presented in some detail. The conceptual design of a Systems Engineering Advisor (SEA) is presented – a scenario of the use of SEA appears in a section appendix. This report concludes with consideration of the prospects for developing and deploying SEA.

11.1 Background

Much of the support needed by engineers involves information management. AI-based information management can be more helpful if it knows both what tasks engineers are performing and what tasks they intend to perform.

Representing humans' task structure in terms of goals, plans, and scripts [182] can enable making such inferences. Goals are high-level intentions. Plans are general templates for achieving goals. Scripts are specific sequences of actions.

Scripts are connected to information and control requirements. These requirements define what information the engineer needs and what controls are needed to execute a script. When the intelligent support infers what you intend to do, it then knows what you need to accomplish it.

Rouse and Spohrer [179] and Rouse [178] discuss the technology underlying the abilities of AI-based assistants to make these inferences and provide appropriate support. Rouse (2007) provides considerable more technical detail. This section focuses on the design of an AI-based assistant for automotive engineers, because the data and the subject matter experts were available. However, we believe the insights gained should apply to other AI-based assistant cyber physical systems engineers.

11.2 Approach

A five-step approach was adopted for this research:

1. Represent model-based automotive engineering (MBAE) and confirm with auto industry experts
2. Define several user experience (UX) scenarios, including characterizations of alternative users in terms of background, support needs, preferences, etc.
3. Project abilities AI will need to support these scenarios. This includes what it will need to know about MBAE and what it will need to be able to do.
4. Specify the user interface (UI) in terms of information requirements and controls needed by both users and AI assistance, e.g., natural language understanding and synthesis, interactive visualizations so users can explore models and relationships.
5. Draft stories of one or more scenarios with users and AI communicating, problem finding, problem solving, and reaching conclusions. These stories will be suitable for user evaluations of the UX, UI, and AI-based augmented intelligence capabilities.

11.3 CASE STUDY

The first step involved developing a representation of the primary elements of MBAE. The result is shown in Figure 79. We reviewed this depiction with General Motors (GM). Their observations included:

- This representation is how things actually work, at least conceptually
- However, there is no overall integrated computational model
- Component models feed variables and parameters to other models, often through interactions with owners/users of component models
- There are significant back and forth interactions between component model owners/users; such dialogs are seen to be very valuable
- Some models are physical rather than computational; a good example is the GM Proving Grounds

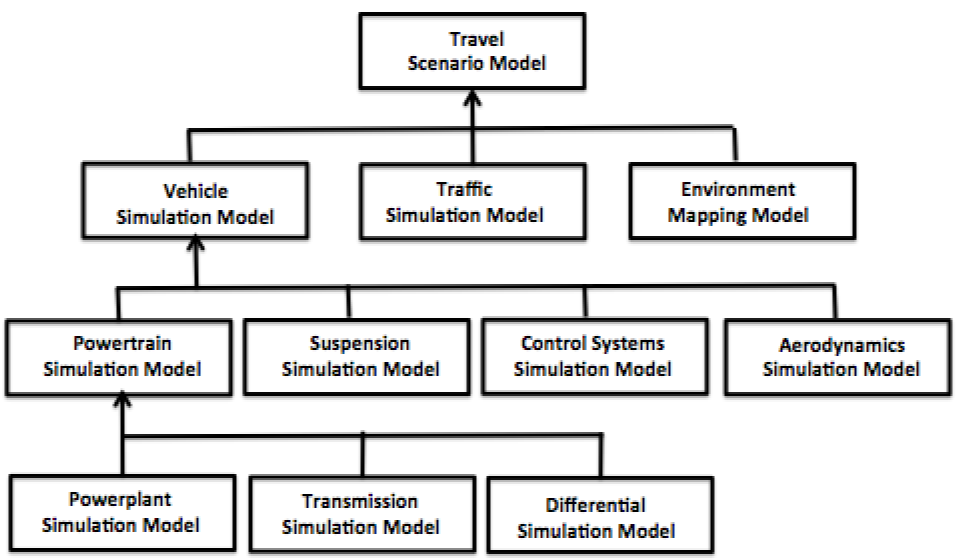


Figure 79. Model-Based Automotive Engineering

11.4 Characterizing Users' Goals

How do engineers interact with each of the models in Figure 79? We identified the following six overall goals:

1. Configure: Configure component models, e.g., parameterize
2. Compose: Compose connections of component models
3. Troubleshoot: Troubleshoot connected models
4. Analyze: Perform sensitivity analyses, i.e., parameters, assumptions
5. Compile: Compile & integrate results, e.g., response surfaces
6. Revise: Revisit connections, parameters, assumptions

11.5 Users' Goals, Plans & Scripts

The plans and scripts associated with these six goals are shown in Table 6.

Table 6. Goals, Plans & Scripts

Goals	Plans	Scripts
Configure	Chose assumptions and estimate parameters for problem	Use procedures & parameter estimation methods
Compose	Establish connectivity among component models	Use procedures to address composability challenges
Troubleshoot	Determine why outputs are inconsistent with expectations	Use procedures for troubleshooting & debugging
Analyze	Determine sensitivity of outputs to assumptions & parameters	Use procedures for sensitivity analyses & creating surface plots
Compile	Compile & integrate results; determine best portrayals	Employ methods & tools to create interactive visualizations
Revise	Revisit connections, assumptions & parameters to react to advice	Use procedures to trace and modify relationships

11.6 Scripts, Information & Controls

As indicated earlier, each script has associated information and control requirements, i.e., what an engineer has to know and be able to do to successfully execute the scripts, as shown in Table 7. The AI-based assistant has to know how to access and display the needed information and provide access to the required controls. The key is that the engineer should not have to search for information or figure out how to access controls.

Table 7. Scripts, Information & Controls

Scripts	Information	Controls
Procedures & parameter estimation methods	Model inputs, outputs, assumptions, parameters	Keyboard, mouse, sliders, radio buttons, etc.

Procedures to address composability challenges	Nature of challenges & how best to address	Keyboard, mouse, sliders, radio buttons, etc.
Procedures for troubleshooting & debugging	Tracing of variable flows & transformations	Keyboard, mouse, sliders, radio buttons, etc.
Procedures for sensitivity analyses & creating surface plots	Attributes of interest, ranges & scales	Keyboard, mouse, sliders, radio buttons, etc.
Methods & tools to create interactive visualizations	Attribute interactions of significance & interest	Keyboard, mouse, sliders, radio buttons, etc.
Procedures to trace and modify relationships	Topography of models, relationships & settings	Keyboard, mouse, sliders, radio buttons, etc.

11.7 User Experience (UX)

The user experience that engineers prefer includes the following:

- Humans see displays and controls, and decide and act. Humans need not be concerned with other than these three elements of the support system architecture. The overall system frames human's roles and tasks, and provides support accordingly.
- The intent inference function infers what task(s) humans intend to do. This function retrieves information and control needs for these task(s). The information management function determines displays and controls appropriate for meeting information and control needs
- An intelligent tutoring function infers humans' knowledge and skill deficits relative to these task(s). If humans cannot perform the task(s) acceptably, the information management function either provides just-in-time training or informs adaptive aiding (see below) of the humans' need for aiding.
- Deep learning neural nets and symbolic logic models provide recommended actions and decisions. The explanation management function provides explanations of these recommendations to the extent that explanations are requested.
- The adaptive aiding function, within the intelligent interface, determines the human's role in execution. This can range from manual to automatic control, with execution typically involving somewhere between these extremes. The error monitoring function, within the intelligent interface, detects, classifies and remediates anomalies.

11.8 Needed AI Functions

The following overall functions are elaborated in great detail in Rouse [177] [178] and Rouse and Spohrer [179].

Information Management: Involves information selection (what to present) and scheduling (when to present it). Information modality selection involves choosing among visual, auditory, and tactile channels. Information formatting concerns choosing the best levels of abstraction (concept) and aggregation (detail) for the tasks at hand. Artificial intelligence can be used to make all these choices in real time as the human is pursuing the tasks of interest.

Intent Inferencing: Information management can be more helpful if it knows both what humans are doing and what they intend to do. Representing humans' task structure in terms of goals, plans, and scripts can enable making such inferences. Scripts are sequences of actions to which are connected information and control requirements. When the intelligence infers what the user intends to do, it then knows what information the user need and what controls wants to execute it.

Error Tolerant Interface: Capabilities to identify and classify errors, which are defined as actions that do not make sense (commissions) or the lack of actions (omissions) that seem warranted at the time. Identification and classification lead to remediation. This occurs at three levels: monitoring, feedback, and control. Monitoring involves collection of more evidence to support the error assessment. Feedback involves making sure the humans realize what they just did. This usually results in humans immediately correcting their errors. Control involves the automation taking over, e.g., applying the brakes, to avoid the imminent consequences.

Adaptive Aiding: Addresses the issue of whether humans or computers should perform particular tasks. There are many cases where the answer is situation dependent. Thus, this function is termed adaptive aiding. The overall concept is to have mechanisms that enable real time determination of who should be in control. Such mechanisms have been researched extensively, resulting in a framework for design that includes principles of adaptation and principles of interaction (Rouse, 2007).

Intelligent Tutoring: Addresses both training humans and keeping them sufficiently in the loop to enable successful human task performance when needed. Training usually addresses two questions: 1) How the system works and, 2) How to work the system. Keeping humans in the loop addresses maintaining competence. Unless tasks can be automated to perfection, humans' competencies need to be maintained. Not surprisingly, this often results in training vs. aiding tradeoffs.

AI Understanding & Abilities

What does an AI assistant need to know, and what does it need to know how to do, to provide the above functionality? It needs to understand the following:

- Context of Interest -- Automotive engineering, broadly
- Elements of Domain -- Purpose of the elements of Figure 79
- Component Models – How the elements of function
- Assumptions – Typical assumptions underlying the elements
- Inputs/Outputs – What is fed into each element and what typically results
- Data & Metrics – Available data sources and relevant metrics
- Natural Language – Real time parsing of English or other languages
- Interpretations of Language – Understanding meaning and intent of parsings

The AI assistants needs to have the abilities to do the following:

- Reason About Context & Domain – Relevant attributes, tradeoffs & decisions

- Access Data – Access, download & tabulate relevant data
- Stratify Data – Organize data in relation to questions posed
- Perform Analyses – Statistical analyses, simulations of various types
- Summarize Results – Organize results in relation to questions posed
- Visualize Results – Alternative portrayals of results
- Explain Reasoning – Rationale for results & implications
- Learn from Current & Previous Users – Preferences, interpretation & insights

11.9 Systems Engineering Advisor (SEA)

Figure 80 depicts the overall dashboard of the Systems Engineering Advisor (SEA). The persona of the advisor (Marie in the scenario at the end of this section) is shown on the upper left. The main menu is shown in the upper right. Available controls are shown at the bottom.

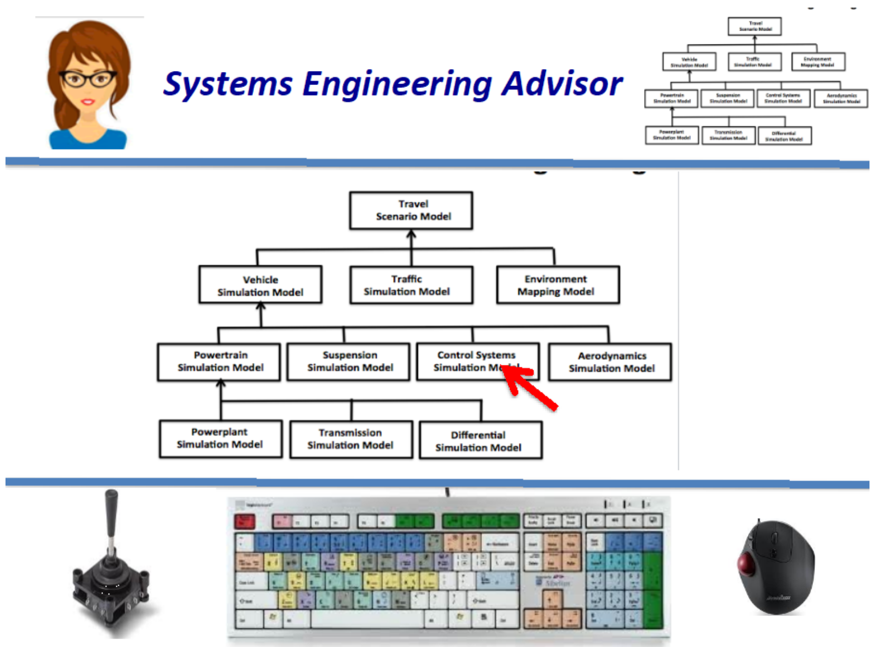


Figure 80. SEA Dashboard Directory

Figure 81 depicts the display once the user has selected Control Systems Simulation Model. The main menu in the upper right indicates that this choice has been made. The results on the screen reflect analyses discussed in the scenario in the appendix.

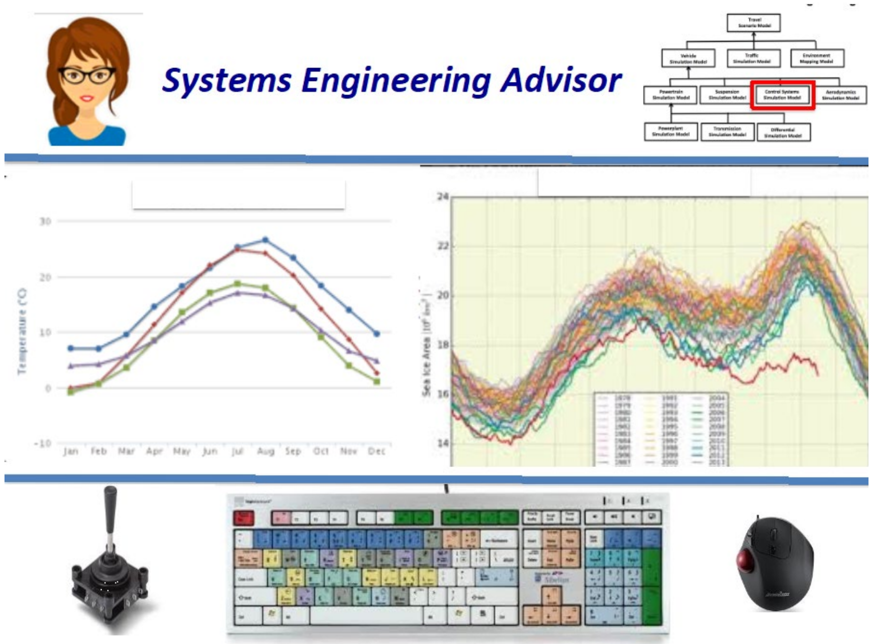


Figure 81. Control Systems Dashboard

11.10 Observations from General Motors

We reviewed the line of reasoning in this section with General Motors (GM). They felt that it all made sense. They really liked the scenario. In fact, they recently experienced the anomaly in the scenario when driving a Tesla.

GM asked for more detail on how AI functions would be realized. We shared the publications listed in the reference list. They would like to meet and discuss next steps when travel is again feasible.

11.11 Conclusions on AI-Based Digital Assistants for Systems Engineering

The conceptual design for SEA presented in this section is completely feasible, with two caveats. First, actual development, evaluation, and deployment will require an extensive effort. Enabling the understanding and abilities outlined above can borrow from previous efforts but, nevertheless, will require many person-years.

Second, it is unlikely that one can develop a SEA that will cover all domains in one platform. The knowledge and skills to design and develop airplanes, automobiles, ships, and trains, for example are too varied to compress into a single advisor. Instead, domain-specific advisors should be developed with subsequent instantiations learning from earlier ones.

The promise of AI-based assistants for engineers is enormous. We know what conceptually is needed. But, as always, the devil is in the details. We need to get on with these details.

11.12 Appendix for AI-Based Assistants to Augment Human Systems Engineers

The following scenario provides a vision for how AI might augment the performance of a systems engineer.

Dave Sawyer has led the SE SWAT Team (SEST) for two months. The role of SEST is to solve tough systems problems quickly. He inherited this role when his mentor retired. He had long been groomed for this role. He was happy to run with the ball.

Today, he's more pressured than happy. The head of their driverless car program – Apollo – is very worried that the advanced prototype that they have been testing at the Proving Grounds is consistently making a rather odd error. It occasionally makes a small, jerking movement to the right and then immediately recovers. It is rather disconcerting to passengers in the back seat.

Dave and his team have two days to provide some insights and one week to recommend solutions before the Blue Ribbon Oversight Committee shows up for an evaluation of Apollo. Fortunately, they have the Systems Engineering Advisor (SEA) to help them. Meeting these deadlines would be impossible without this AI-based platform.

Dave decides to explore the resources available before the first meeting with his team tomorrow morning. He logs into the secure SEA platform. Its intelligent interface immediately engages him.

"Welcome back, Dave. Do you want to continue the analysis you were working on?"

"No, Marie. I have a new problem."

Users of SEA can name their cognitive assistant, as they like. Marie was Dave's favorite aunt, almost his second mother.

"So, Marie, what do you know about control algorithms in driverless cars?"

"That's an awfully broad question. Do you really want to know everything?"

"No, of course not. I will just assume that you know everything and will help me get to exactly what we need."

"Let's just assume that I know what can be known, but not everything."

"Great. Show me the trajectory data for the most recent Apollo tests."

"Do you want it aggregated across test runs, or just each individual run?"

"Actually, both would be a good idea."

A large interactive visualization appears almost instantly. It is quickly apparent that the slight jerk to the right does not always occur at the same place. Thus, it has nothing to do with the track itself.

"I find it hard to believe that these jerks are just random."

"Apollo is not just responding to the road. It is also responding to other vehicles," Marie offers.

"Good point. Do you have data on other nearby vehicles over time?"

"Yes. I thought you might want that, so I asked that this data be transferred as well."

"Highlight in red the segments of the traces you just showed me whenever another oncoming vehicle is within 30 seconds of Apollo."

The highlighted traces appeared immediately. The slight jerks to the right always occurred when the segment was red, but it did not happen during all the red segments.

"Apollo is clearly reacting to the other vehicles, but not all of them."

"Do you want the traces of the trajectories of the other vehicles in each red segment?"

"Yes, that's a good idea."

"Should I also average across runs where Apollo reacts, with another average for when Apollo does not react?"

"Yes, great."

Another set of plots quickly appeared.

"The differences between the two averages seem real, but quite subtle."

"Even if the differences are very small, keep in mind that Apollo can sense things much better than you can," Marie responds.

"OK, but how do we explain these differences?"

"There is a suite of biomedical sensors used for all human-driven vehicles at the Proving Ground. It is a lot of data. Do you want to see it all?"

"Do you know which measures are the best predictors of drivers' loss of vigilance?"

"Yes, EEG is best."

"Great let's see it."

"These measurements are pretty noisy. Should I smooth them out a bit?"

"Yes, that will help."

"Two averages again?"

"Yes."

The plots that soon appeared were quite clear.

"Apollo is reacting to the oncoming drivers' fading vigilance."

"Yes, and Apollo is inferring this, without realizing it, from subtle movements of the oncoming vehicle."

"So, we know why the slight jerks to the right are happening, but what do we do about it?"

"Should I make sure the algorithm people are in tomorrow's meeting?" Marie asked.

"Absolutely. Put together a montage of everything we have done, with annotations for team members."

"Will do. It will be broadcast in the next couple of minutes."

"Also, change the calendar to make tomorrow morning's meeting top priority. The Apollo program manager has to be there because we need an increased budget commitment from him."

"I am sure he will like that."

"Do I detect a bit of sarcasm, Marie?

"I am doing my best to learn from you, Dave."

"Be careful or I will limit your access."

"I'm sorry, Dave. I'm afraid you can't do that."

12 SERC RESEARCH SYNERGIES

This section summarizes some synergies to the ongoing NAVAIR research tasks that are briefly mentioned in this report to inform readers of the relationships to these other activities.

12.1 ART-002 COMBAT CAPABILITIES DEVELOPMENT COMMAND ARMAMENTS CENTER RESEARCH

We have efforts with the US Army Combat Capabilities Development Command Armaments Center (CCDC-AC) (formerly ARDEC) investigating methods and technologies for modeling the "full stack" for an AST with the various modeling tools, as shown in Figure 82, to support formal reasoning (V&V), traceability and multi-dimensional alternative analyses with case study demonstrations using:

- Graphical CONOPS
- Mission modeling - in descriptive modeling language SysML
- System and subsystem modeling - in SysML – mapped to ontologies
- Component modeling - in discipline-specific and multi-physics models for design and analysis – metadata mapped to ontologies
- Co-simulation using Computational Fluid Dynamics (CFD), Finite Element Analysis (FEA), and 6 Degree of Freedom (6DOF) analyses
- Domain and tool ontologies aligning with the Basic Formal Ontology (BFO)
- Including the tools of the Designing System (tools shown in green)
- SETM model and dynamic views
- Reference models

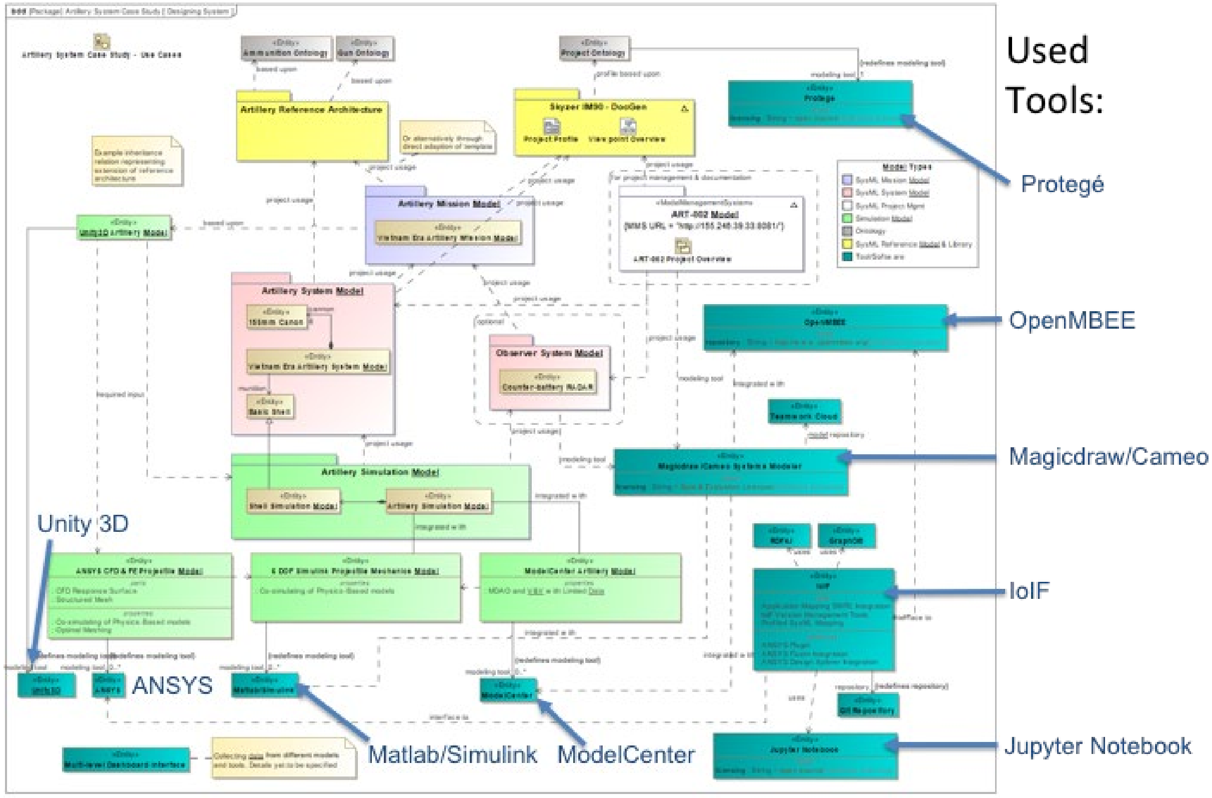


Figure 82. "Full Stack" of Models for Project Research including Designing System Tools[25]

12.2 WRT-1001 Digital Engineering Metrics

The research task WRT-1001 [125] used the following four guiding questions:

1. If you had a "Program Office Guide to Successful DE Transition" what would that look like?
2. How can the value and effectiveness of DE be described and measured?
3. Are there game-changing methods and/or technologies that would make a difference?
4. Can we describe an organizational performance model for DE transformation?

A key result of the WRT-1001 research is the development and definition of two frameworks that categorize DE benefits and adoption strategies which can be universally applied to a formal enterprise change strategy and associated performance measurement activities. The first framework is linked to the benefits of DE and categorizes 48 benefit areas linked to four digital transformation outcome areas: quality, velocity/agility, user experience, and knowledge transfer. This framework identifies a number of candidate success metrics. A test application to an ongoing DoD pilot project was completed and is documented in this report. The second framework addresses enterprise adoption of DE and provides a categorization of 37 success factors linked to organizational management subsystems encompassing leadership,

[25] UNCLASSIFIED Distribution Statement A: Approved for public release. Distribution is unlimited.

communication, strategy and vision, resources, workforce, change strategy and processes, customers, measurement and data, workforce, organization DE processes relate to DE, and the organizational and external environments. The two frameworks were developed from literature reviews and a survey of the systems engineering community.

We supported an analysis from the 17 lesson learned categories from the surrogate pilot experiments with Skyzer, shown in Section 2.8, that mapped to 22 DE benefit areas grouped into four metrics. The analysis is discussed in Section 2.9 of this report.

12.3 WRT-1006 Digital Engineering Competency Framework

In support of the DoD's implementation of the Digital Engineering Strategy, we are investigating the critical digital engineering knowledge, skills, and abilities needed by the DoD acquisition workforce. Some of the work from the Surrogate Pilot under this RT have demonstrated the art-of-the-possible. We operated as advisor to support the development of the Digital Engineering Competency Framework, by describing and reflecting on the approach used for DE in "doing everything" in models to demonstrate the art-of-the-possible.

12.4 WRT-1009 Model Curation Innovation & Implementation

The SERC Model Curation task applied the model curation criteria to the Skyzer Surrogate Pilot, which is summarized in Section 10.2.

12.5 WRT-1025

The research task WRT-1025 objective is to investigate digital twin design architectures that support AI and ML formalisms working side-by-side as a team, providing complementary and supportive roles in the collection, formalizing representations and processing of data, identification and correlation of events, in evolving spatial contexts and automated decision making throughout the system lifecycle.

The efforts will use two case studies, with one that includes the Skyzer System model discussed in this report to provide a means for demonstrating and explaining AI/ML for MCE in the context of mission, system and discipline-specific models and scenarios already understood by SERC research task sponsors.

12.6 RT-176 Verification and Validation (V&V) of System Behavior Specifications

Our NAVAIR sponsor had requested that the SERC RT-176 research task being led by Dr. Kristin Giammarco, which is discussed in Section 8. The Monterey Phoenix capability was applied to the Skyzer Mission Model. This research task is complete [87].

12.7 OpenMBEE and Open Collaboration Group for MBSE

We are members of the OpenMBEE Collaboration Group for MBSE leadership team and committers team. We use OpenMBEE in our lab and on the surrogate pilot, and contribute to the community effort (e.g., created Docker) in order to advance its capabilities. We often present our efforts at the OpenMBEE Collaboration Group bi-weekly meetings.

12.8 Semantic Technologies Foundation Initiative for Systems Engineering

The NASA/JPL Symposium and Workshop on MBSE resulted in the initiation of an effort with the support to create and ecosystem on Semantic Technologies for Systems Engineering. The working group has created a charter and mission:

- Charter
  - The Semantic Technologies Foundation Initiative for Systems Engineering is to promote and champion the development and utilization of ontologies and semantic technologies to support system engineering practice, education, and research.
- Mission
  - The mission of the initiative is to collect a suite of interoperable ontologies that are logically well-formed and accurate from both scientific and engineering points of view. The initiative will charter a collective of stakeholders that are committed to collaboration and adherence to shared semantic principles for the advancement of systems engineering. To achieve this, initiative working group participants will voluntarily adhere to and contribute to the development of an evolving set of principles including open use, collaborative development, and non-overlapping and appropriately-scoped content. They will capture and maintain metadata for each ontology to encourage implementation and reuse.

These efforts are being moved to INCOSE MBSE Patterns Working Group and the proposed name for the project is: Semantic Patterns for Systems Engineering (SP4SE) Project.

12.9 National Defense Industry Association Modeling and Simulation

National Defense Industry Association (NDIA) Modeling and Simulation group is looking at approaches for using digital engineering for competitive down select. We have been involved in all of these efforts to further the objectives of our sponsor since August of 2016 and present periodically at different sessions as recent as March 2019. These events help inform industry about the efforts of the NAVAIR SE Transformation in the context of Surrogate Pilot experiments [24] [43] [117].

12.10 Aerospace Industry Association CONOPS for MBSE Collaboration

This is a follow-up to the effort completed last year which developed a white paper on the Life Cycle Benefits of Collaborative MBSE Use for Early Requirements Development [3]. This white paper discusses the current state and benefits of MBSE across the entire life cycle and provides proposals for addressing such issues as MBSE Collaborative Framework, Government Data Rights, Intellectual Property, and Life Cycle Effectiveness with MBSE. A follow-on effort involved many of the industry contractors to NAVAIR and DoD.

13 Part II Summary

Our research continues to demonstrate the art-of-the-possible in using MCE methods and Digital Engineering Environment (DEE) technologies in the context of Surrogate Pilot experiments. The pilot is developing an experimental UAV system called Skyzer, and Phase 1 completed a deep dive on search and rescue mission operational scenarios. For Phase 2 we expanded the scope of the search and rescue mission to include operational scenarios that bring in a ship-based launch and recovery system. For the specific deep dive of a landing gear system, we provided align of the mission and system model with the NAVAIR Systems Engineering (NAVSEM) process steps 1, 2, 3, & 4. The research team also developed the Skyzer contractor model that aligns with NAVSEM process step 5. The deep dive for Phase 2 included a landing gear system with a MDAO tradespace analysis that provides for looking at airworthiness considerations, and potentially ship-based operations. The team also created a model for Capability-Based Test and Evaluation (CBT&E)/Mission-Based Test Design (MBTD) process and schema related to test points associated with the landing gear deep dive. The surrogate pilot team has demonstrated the feasibility of modeling everything to demonstrate the art-of-the-possible using modeling methods at the mission, systems, and even using models for the request for proposal, statement of work, and source selection using models. We have used DocGen to demonstrate how to generate stakeholder-relevant views from the various models.

We extended the Authoritative Source of Truth (AST) implementation from Phase 1 for the government-side and contractor side of the surrogate pilot project. We have been successful at the initial use and deployment of OpenMBEE as a core element in the experimental DEE for an AST. We demonstrated a new operational paradigm between government and industry in the execution the SET Framework in the context of an AST. We are sharing detailed aspects of the surrogate pilot experiments discussed in this report on the All Partners Network (APAN) in order to journal our project, socialize these new operational concepts, and to solicit feedback from industry, government and academia.

As we move to complete Phase 2 of the SET Framework uses cases we want our examples and models to provide the basis for unclassified examples for workforce development that demonstrate mission modeling, system modeling through NAVSEM, Model Management Guidelines, Airworthiness deep-dive, new forms of contracting and review in an AST, Capability-Based Test and Evaluation (CBT&E), and Digital Signoffs.

We provided ontology demonstrations using the Cyber Ontology Pilot and a new approach that has developed a Systems Engineering Technical and Management plan model that has an underlying ontology.

We were also able to look at some new research into Digital Engineering Metrics. The report includes an application of a new set of criteria for model curation using the Skyzer System Model as a use case. Finally, we took an initial look at an AI-Based Assistants to Augment Human

Systems Engineers with the objectives to investigate how best to leverage AI to enhance the capabilities of military platforms, other vehicles, and various technology-based processes.

We have created two perspectives on roadmaps, one for technologies that are likely to enable DE, and a second perspective is for a roadmap based on the DoD Digital Engineering Strategy goals reflected in the context of an evolution of Mission and Systems Engineering. A key reflection is that these roadmaps anticipate the increased need to formalize the underlying information model as we move to the right (i.e., future), which can exploit more computational automation such as (i.e., AI, machine learning, etc.), enabled by high performance computing.

Finally, we continue to foster our synergies with other research tasks with the US Army ARDEC, Semantic Technologies for System Engineering Initiative, Digital Engineering Working Group, NDIA, Aerospace Industry Association, INCOSE MBX Ecosystem, and the OpenMBEE Collaboration Group for MBSE. We are participating with the three Navy systems commands (SYSCOM) NAVAIR, NAVSEA and NAVWAR on an initiative to scope an effort to build Navy and DoD interoperable ontologies. Through collaboration with our US Army sponsors and other connections through our DoD sponsors we have provided multiple interchanges with other services and commands to describe our surrogate pilot efforts as part of the outreach to government and industry.

14 ACRONYMS AND ABBREVIATION

This section provides a list of some of the terms used throughout the paper. The model lexicon should have all of these terms and many others.

2D	Two dimensions
3D	Three dimensions
AADL	Architecture Analysis & Design Language
ACAT	Acquisition Category
ACES	Automated Concurrent Engineering System
AFD	Assessment Flow Diagram
AFT	Architecture Framework Tool of NASA/JPL
AGI	Analytical Graphics, Inc.
AGM	Acquisition Guidance Model
AGS	Army Game Studio
ALM	Application Lifecycle Management
AMMODAT	Armament Analytics Multiple Objective Decision Analysis
ANSI	American National Standards Institute
AP233	Application Protocol 233
APAN	All Partners Network
API	Application Programming Interface
AR	Augmented Reality
ARDEC	Armament Research, Development and Engineering Center
ASELCM	Agile Systems Engineering Life Cycle Model
ASR	Alternative System Review
AST	Authoritative Source of Truth
ATL	ATLAS Transformation Language
AVCE	Armament Virtual Collaboratory Environment
AVSI	Aerospace Vehicle Systems Institute
BDD	SysML Block Definition Diagram
BN	Bayesian Network
BNF	Backus Naur Form
BOM	Bill of Material
BPML	Business Process Modeling Language
C-BML	Coalition Battle Management Language
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CBT&E	Capability-Based Test and Evaluation
CDR	Critical Design Review
CEO	Chief Executive Officer
CESUN	International Engineering Systems Symposium
CFD	Computational Fluid Dynamic
CGF	Computer Generated Forces
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CONOPS	Concept of Operations
CORBA	Common Object Requesting Broker Architecture
COTS	Commercial Off The Shelf
CPS	Cyber Physical System

CREATE	Computational Research and Engineering for Acquisition Tools and Environments
cUAS	Counter UAS
CWM	Common Warehouse Metamodel
DAA	Data Acquisition and Aggregation layer
DASD	Deputy Assistant Secretary of Defense
dB	Decibel
DBMS	Database Management System
DAG	Defense Acquisition Guidebook
DARPA	Defense Advanced Research Project Agency
DAU	Defense Acquisition University
DCDR	Digital design from Critical Design Review (CDR)
DE	Digital Engineering
DIS	Distributed Interactive Simulation
DISA	Defense Information Services Agency
DL	Descriptive Logic
DLR	DLR Institute of Flight
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DoE	Design of Experiments
DOORS	Requirement Management product
DOORS-NG	DOORS-Next Generation
DSEEP	Distributed Simulation Engineering and Execution Process
DSL	Domain Specific Languages
DSM	Domain Specific Modeling
DSM	Design Structure Matrix
DSML	Domain Specific Modeling Language
E/DRAP	Engineering Data Requirements Agreement Plan
ERP	Enterprise Resource Planning
ESP:HE	ESP: Higher Echelon
ERS	Engineered Resilient Systems
ESP	Early Synthetic Prototype
FAA	Federal Aviation Administration
FEA	Finite Element Analysis
FMEA	Failure Modes and Effects Analysis
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit
FOM	Federation Object Model
GAO	Government Accounting Office
GFI	Government Furnished Information
GUI	Graphical User Interface
HLA	High Level Architecture
HPC	High Performance Computing
HPCM	High Performance Computing Modernization
HW	Hardware
I&I	Integration and Interoperability
IBM	International Business Machines
IBD	Internal Block Diagram (SysML)
ICD	Interface Control Document
ICT	Institute for Creative Technologies

ICTB	Integrated Capability Technical Baseline
IDEF0	Icam DEFinition for Function Modeling
IEEE	Institute of Electrical and Electronics Engineers
IME	Integrated Modeling Environment
iMBE	AVCE-Integrated Model-Based Engineering
INCOSE	International Council on Systems Engineering
IPR	Integration Problem Report
IoIF	Interoperability and Integration Frameowk, previously referred to as Integration and Interoperability Framework
IRL	Integration Readiness Level
ISEDM	Integrated Systems Engineering Decision Management
ISEF	Integrated System Engineering Framework developed by Army's TARDEC
ISO	International Organization for Standardization
IT	Information Technology
IWC	Integrated Warfighter Capability
JCIDS	Joint Capabilities Integration and Development System
JEO	Jupiter Europa Orbiter project at NASA/JPL
JSF	Joint Strike Fighter
JPL	Jet Propulsion Laboratory (NASA)
JSON	JavaScript Object Notation
KPP	Key Performance Parameter
KSA	Key System Attributes
LIDAR	Light Detection and Ranging
LOC	Lines of Code
LSL	Lab Streaming Layer
M&S	Modeling and Simulation
MARTE	Modeling and Analysis of Real Time Embedded systems
MATRIXx	Product family for model-based control system design produced by National Instruments; Similar to Simulink
MBE	Model Based Engineering
MBEE	Model Based Engineering Environment
MBSE	Model Based System Engineering
MBT	Model Based Testing
MC/DC	Modified Condition/Decision
MCE	Model Centric engineering
MDA®	Model Driven Architecture®
MDAO	Multidisciplinary Design, Analysis and Optimization
MDD™	Model Driven Development
MDE	Model Driven Engineering
MDK	Model Development Kit – OpenMBEE plugin to MagicDraw
MDSD	Model Driven Software Development
MDSE	Model Driven Software Engineering
MIC	Model Integrated Computing
MMM	Modeling Maturity Model
MMS	Model Management System (part of OpenMBEE)
MoDAF	Ministry of Defence Architectural Framework (United Kingdom)
MOE	Measure of Effectiveness
MOF	Meta Object Facility
MOP	Measure of Performance

MP	Monterey Phoenix
MRL	Mixed Reality Lab
MxRP	Mixed Reality Prototyping
MSDL	Military Scenario Definition Language
MVS	Multiple Virtual Storage
N2	N-squared diagram
NASA	National Aeronautics and Space Administration
NASA/JPL	NASA Jet Propulsion Laboratory
NAVAIR	U.S. Navy Naval Air Systems Command
NAVSEA	U.S. Naval Sea Systems Command
NDA	Non-disclosure Agreement
NDIA	National Defense Industrial Association
NEAR	Naval Enterprise Architecture Repository
NPS	Naval Postgraduate School
NSGA	Non-dominated Sorting Genetic Algorithm
OCL	Object Constraint Language
OMG	Object Management Group
OO	Object oriented
OpenMBEE	Open Model Based Engineering Environment
OpenVSP	Open Vehicle Sketch Pad
OSD	Office of the Secretary of Defense
OSLC	Open Services for Lifecycle Collaboration
OV1	Operational View 1 – type of DoDAF diagram
OWL	Web Ontology Language
PAR	Parametric Block in SysML
PDM	Product Data Management
PDR	Preliminary Design Review
PEA	Post Exercise Analysis
PES	Physical Exchange Specification
PIA	Proprietary Information Agreement
PIM	Platform Independent Model
PLM	Product Lifecycle Management
POR	Program of Record
PRR	Production Readiness Review
PSM	Platform Specific Model
QMU	Quantification of Margins and Uncertainty
RDEC	US Army Research Development and Engineering Center
RDF	Resource Description Framework
RDECOM	US Army Research, Development and Engineering Command
RT	Research Task
RTI	Runtime Infrastructure
RFI	Request for Information
RFP	Request for Proposal
RPM	Revolutions Per Minute
RPR FOM	Real-time Platform Reference Federation Object Model
ROI	Return On Investment
SAVI	System Architecture Virtual Integration
SE	System Engineering
SERC	Systems Engineering Research Center

SETR	System Engineering Technical Review
Simulink/Stateflow	Product family for model-based control system produced by The Mathworks
SCR	Software Cost Reduction
SDD	Software Design Document
SE	System Engineering
SET	Systems Engineering Transformation
SFR	System Functional Review
SISO	Simulation Interoperability Standards Organization
SLOC	Software Lines of Code
SME	Subject Matter Expert
SOAP	A protocol for exchanging XML-based messages – originally stood for Simple Object Access Protocol
SoS	System of Systems
Software Factory	Term used by Microsoft
SPARQL	SPARQL Protocol and RDF Query Language
SRR	System Requirements Review
SRS	Software Requirement Specification
SST	Single Source of Truth
SSTT	Single Source of Technical Truth
ST4SE	Semantic Technologies for Systems Engineering
STOVL	Short takeoff and vertical landing
SVR	System Verification Review
SW	Software
SWT	Semantic Web Technology
SysML	System Modeling Language
TARDEC	US Army Tank Automotive Research
TBD	To Be Determined
TRL	Technology Readiness Level
TRR	Test Readiness Review
Turtle	Terse RDF Triple Language
UAV	Unmanned Aerial Vehicle
UAS	Unmanned Aerial System
UC	Use Case
UCAV	Unmanned Combat Air Vehicles
UML	Unified Modeling Language
Unix	An operating system with trademark held by the Open Group
UQ	Uncertainty Quantification
US	United States
USD	US Dollars
USC	University of Southern California
VHDL	Verilog Hardware Description Language
VR	Virtual Reality
V&V	Verification and Validation
XMI	XML Metadata Interchange
XML	eXtensible Markup Language
XSLT	eXtensible Stylesheet Language family (XSL) Transformation
xUML	Executable UML

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Phase 1 of the Surrogate Pilot officially kicked-off on December 7, 2017 and ended around December 2018 at the end of the surrogate pilot contractors contract. Additions and refactoring are occurring during Phase 2. The timeline of events for the Surrogate Pilot planning and execution are shown in Figure 83.

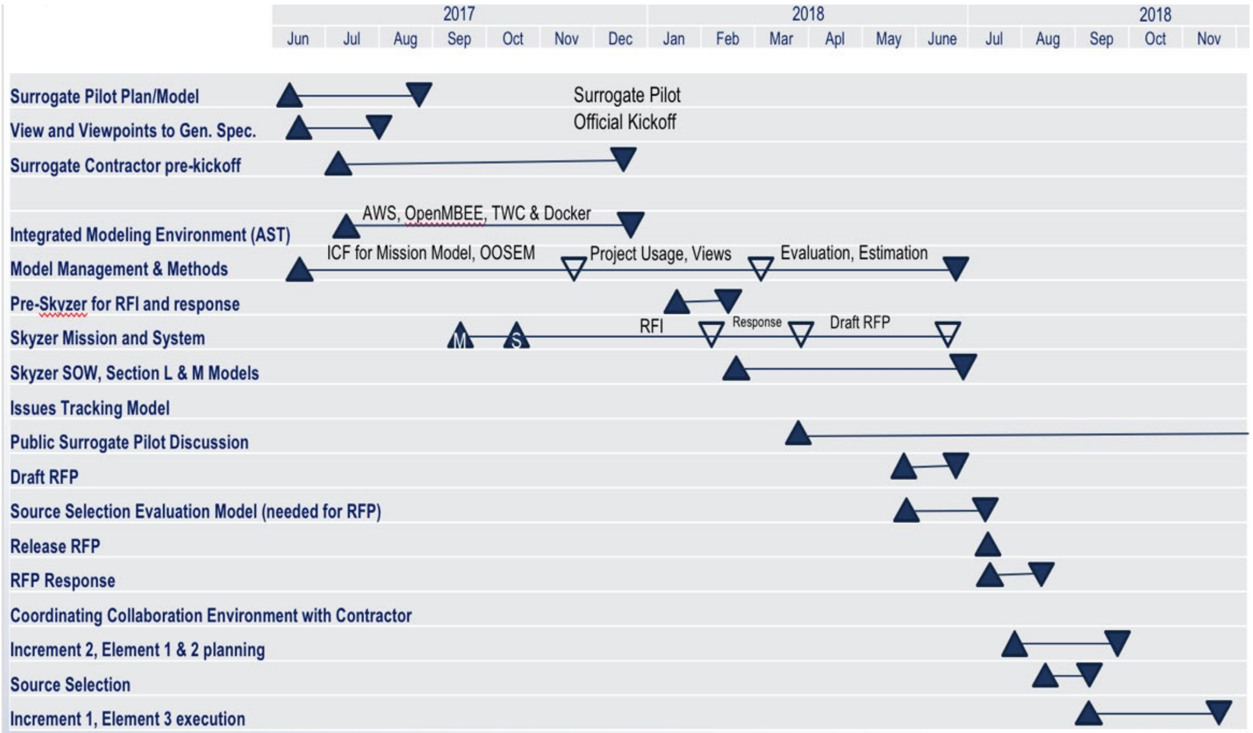

Figure 83. Time Line of Surrogate Pilot Experiments[26]

Three appendices from RT-195 have not be included in this report. Please refer to the RT-195 Final Technical Report [25] to see:

- NAVAIR - SERC Systems Engineering Transformation Surrogate Pilot: SE Transformation Surrogate Pilot Project
    - This model uses the NASA/JPL Integrated Model Centric Engineering (IMCE) ontologies as a basis for characterizing the objective prior to Phase 1 as a plan for answering questions about the surrogate pilot concept. See RT-195 for an autogenerated representation of this plan [24]. It is also online in the Surrogate Project Plan area of Amazon Web Services (https://ime.sercuarc.org/alfresco/mmsapp/mms.html#/projects/PROJECT-837de740-7ac3-46de-9edc-8ddd1c4f830a/master/document/_18_5_2_1ada0494_1511370934099_833224_128980)

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- University of Maryland Ontology Research [8] [58]
    - The University of Maryland (UMD)'s role in RT 195 is to explore opportunities for supporting the SET framework with semantic technologies for reasoning about completeness and consistency of system entities (e.g., textual requirements, mathematical constraints, elements of system structure and behavior) across a multiplicity of domains relevant to the surrogate (Skyzer) pilot case study problem.
- Implementing a Decision Framework in SysML Integrating MDAO Tools [76]
    - This article describes an implementation of a decision framework modeled in SysML that we can execute with two different parametric analyzers. One of those analyzers supplies the kind of cross-tool and cross-domain integration of simulation and analysis tools that engineers will require to implement model-based design at large scales. The paper describes the decision framework and illustrates its implementation in SysML in the context of the design of a notional surveillance drone. The paper concludes with some observations about future directions and some of the difficulties that were met.