Transforming Systems Engineering through Model-Centric Engineering

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Acknowledgments

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Executive Summary

This is the final technical report of the Systems Engineering Research Center (SERC) research task RT-157. This research task (RT) addresses research needs extending prior efforts under RT-48/118/141 that informed us that model-centric engineering (MCE) is in use and adoption seems to be accelerating. Model-centric engineering[1] can be characterized as an overarching digital engineering approach that integrates different model types with simulations, surrogates, systems and components at different levels of abstraction and fidelity across disciplines throughout the lifecycle. Industry is trending towards more integration of computational capabilities, models, software, hardware, platforms, and humans-in-the-loop. 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 tradespace decisions in the face of changing mission needs.

NAVAIR senior leadership confirmed in late 2015 that the research findings and analysis validated their vision hypothesis stated at the System Engineering Transformation kickoff meeting of RT-48. They concluded that NAVAIR must move quickly to keep pace with the other organizations that have adopted MCE and who continue to evolve at an accelerating pace enabled by the advances in computational and modeling technologies, and improved methods.

In March of 2016, there was a Change of Command at AIR 4.0 (Research and Engineering). NAVAIR decided to accelerate the Systems Engineering Transformation (SET). The “roll out” strategy is a layered approach where evolving research needs are provided by SERC research, as shown in Figure 1. This research provides analyses into NAVAIR enterprise capability, and builds on efforts for cross-domain model integration and model integrity (per RT-157). NAVAIR also extended the RT-157 research under RT-170 to address the evolving SET needs and priorities.

The path forward has challenges but also many opportunities, both technical and sociotechnical. It must include a modeling framework with high performance computing (HPC) that enables single source of truth (SST), integration of multi-domain and multi-physics models, and provides for a method for model integrity. The modeling and infrastructure for a digital engineering environment is a critical step to enable a SST. While there are literally thousands of tools[2], they are often federated and there is no one single solution that can be purchased. Every organization providing inputs to this research has had to architect and engineer their MCE environment. Most organization use commercial tools, but also have developed the integrating fabric between the different tools, models, simulations and data. Some organizations have encoded historical knowledge in reference models, model patterns to embed methodological guidance to support continuous orchestration of analysis through new modeling metrics, and automated workflows. NAVAIR is making strides to develop an *Integrated Modeling Environment* (IME) that captures requirements to link artifacts and evidence in support of decision-making addressing all required checks

[1] DASD has increased the emphasis on using the term Digital Engineering. A draft definition provided by the Defense Acquisition University (DAU) for DE is: **An integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support lifecycle activities from concept through disposal.** This definition is similar to working definition used throughout our prior research task RT-48/118/141 for Model Centric Engineering (MCE).

[2] Certain commercial software products are identified in this material. These products were used only for demonstration purposes. This use does not imply approval or endorsement by Stevens, SERC, or NAVIAR, nor does it imply these products are necessarily the best available for the purpose. Other product names, company names, images, or names of platforms referenced herein may be trademarks or registered trademarks of their respective companies, and they are used for identification purposes only.

and risks. Key questions remain as to how to do that in the context of a new operational paradigm between government and industry using a new framework described herein.

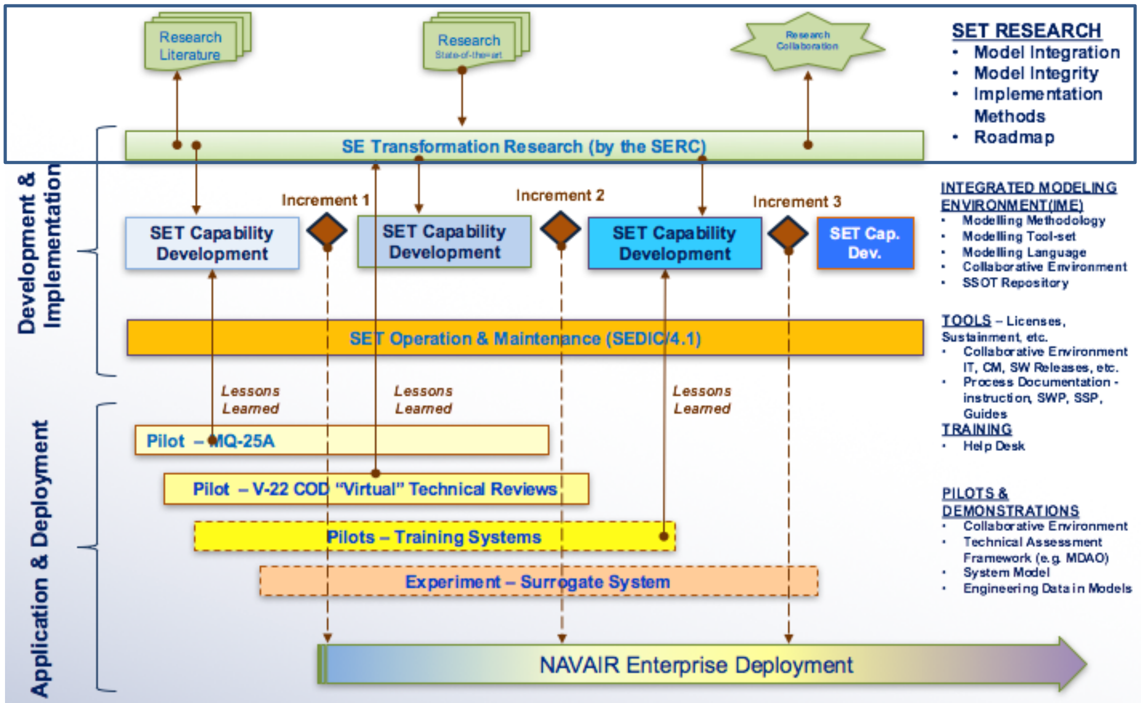


Figure 1. SE Transformation "Roll out" Strategy

The kickoff of RT-157 in January 2016 defined a research plan to investigate challenge areas including, but not limited to:

- Cross-domain integration of models to address the heterogeneity of the various tools and environments
- Model integrity to ensure trust in the model predictions by understanding and quantifying margins and uncertainty
- Modeling methodologies that can embed demonstrated best practices and provide computational technologies for real-time training within digital engineering environments
- Multidisciplinary System Engineering transformation roadmap that looks across:
  - Technologies and their evolution
  - How people interact through digitally enabled technologies and new needed competencies
  - How methodologies enabled by technologies change and subsume processes
  - How acquisition organizations and industry operate in a digital engineering environment throughout the phases of the lifecycle (including operations and sustainment)
  - Governance within this new digital and continually adapting environment

The strategic plans of SET and overarching goals of this research have been expanded through RT-170. RT-170 has support from new research collaborators from Georgia Tech and University of Maryland. This report does blend RT-170-related accomplishments into this report to document the ongoing progress in support of the NAVAIR SET. Finally, we are also working collaboratively with US Army RDECOM-ARDEC in Picatinny, NJ under RT-168, and some of the plans for synergies between these efforts are documented in this report.

1 INTRODUCTION

In 2013, 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 is achieved today for large-scale air vehicle systems. The research need included the evaluation of emerging system design through computer (i.e., digital) models.

Through Systems Engineering Research Center (SERC) research tasks (RT-48, 118, 141) there was considerable emphasis on understanding the state-of-the-art through discussions with industry, government and academia [21] [31]. The team comprised of both NAVAIR and SERC researchers 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 by the enabling technologies. NAVAIR made the decision to press forward with a Systems Engineering Transformation (SET). That effort was started in January of 2016 under RT-157 and had four tasks as shown in Figure 2:

- Task 1 – Model Cross-Domain Integration with underlying Single Source of Technical Truth (SST)
- Task 2 – Model Integrity – developing and accessing trust in model and simulation predictions
- Task 3 – Modeling Methodologies aligning with the roll out of technologies defined under Task 4
- Task 4 – Define System Engineering Transformation Roadmap

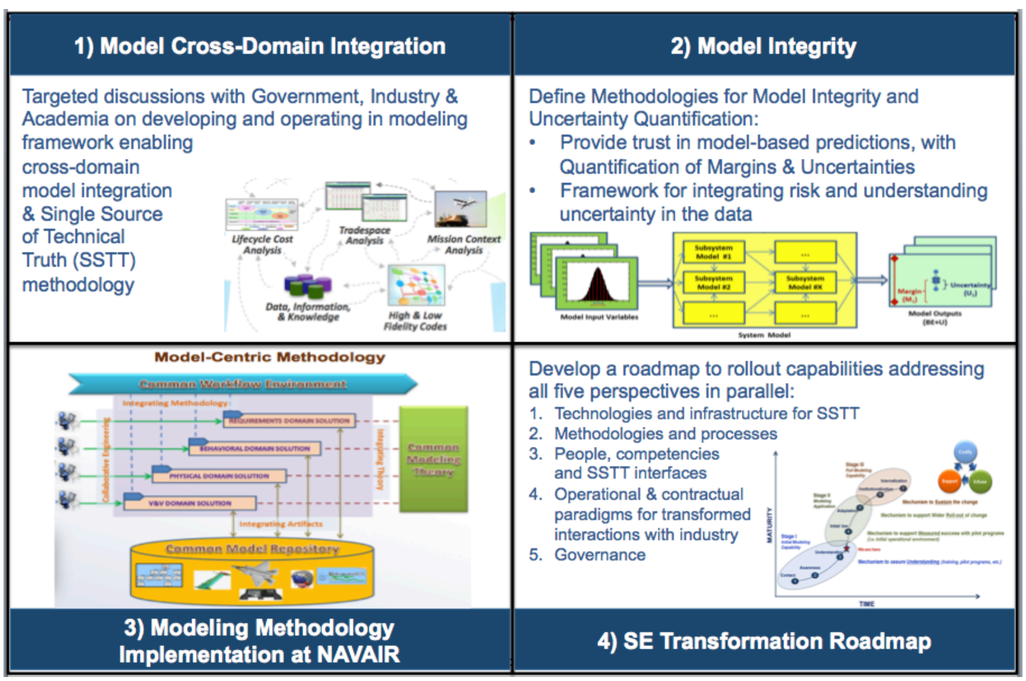


Figure 2. SE Transformation Phase II

In March of 2016, there was a Change of Command at AIR 4.0 (Research and Engineering). NAVAIR decided to accelerate the SET. Notionally as shown in Figure 1, the SET has a layered approach where the needed research provides analyses into NAVAIR enterprise capability, but builds on efforts for cross-domain model integration and model integrity (per RT-157). While the SERC research was directed to focus on the Program of Record (POR)/systems level, a new NAVAIR strategy for accelerating capability delivery to the warfighter is looking to better assess the value and risks of system and system of systems (SoS) capabilities, potentially distributed across platforms to mission and campaign needs in a more dynamically changing environment. Therefore, NAVAIR believes that the following areas are candidates for SERC research as characterized in RT-170, which are a layer on top of the other dimensions of the research, as shown in Figure 3:

- Prioritization and Trade-off Analysis
- Concept Engineering
- Architecture & Design Analysis
- Design & Test Reuse and Synthesis
- Active System Characterization
- Human-System Integration

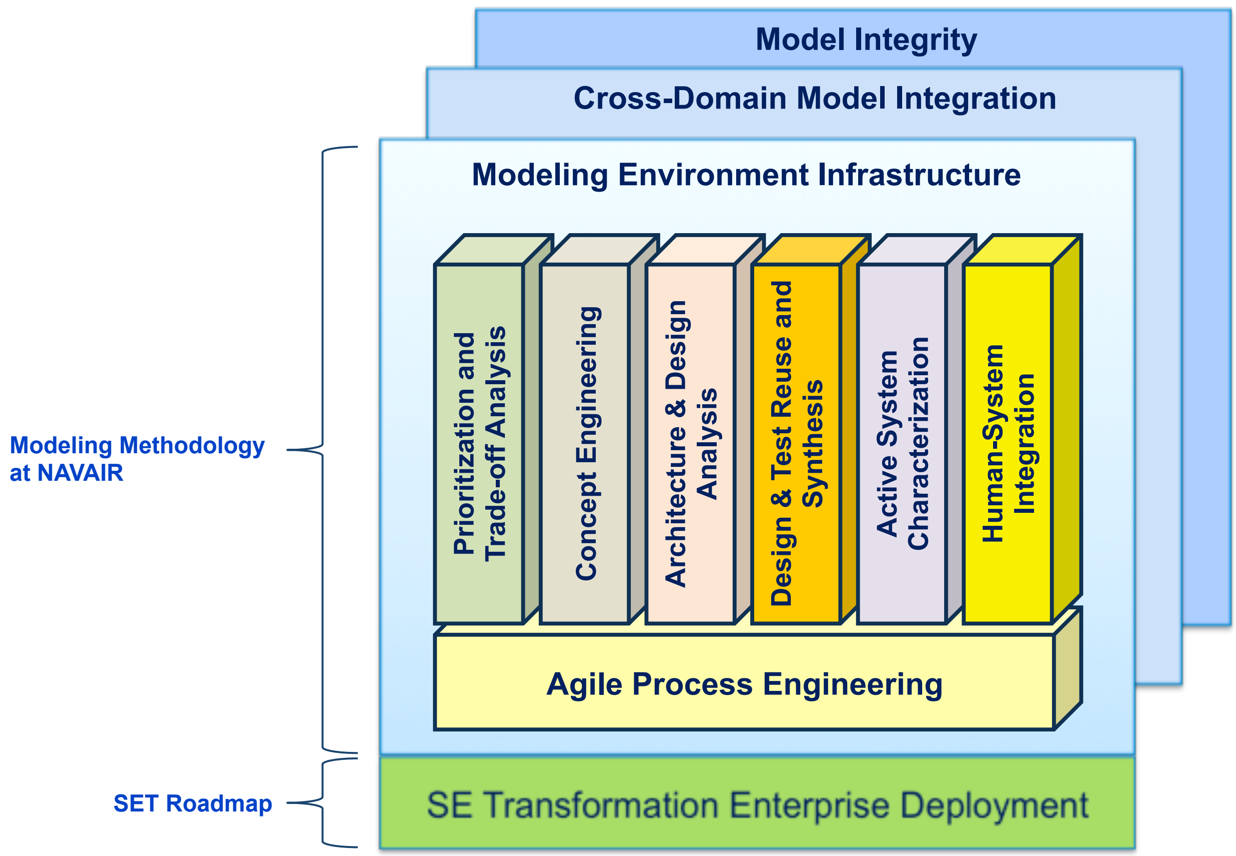


Figure 3. SE Transformation Research Areas (SERC)

During the execution of RT-157, our sponsor Dave Cohen proposed a new operational framework, which is shown in Figure 4. This evolving framework is being assessed and refined in order to support a new operational paradigm to mission engineering, analysis and acquisition, which would be led by NAVAIR with a collaborative design effort led by industry. We are also involved in industry meetings with our sponsor to assist in understanding concepts for a new type of collaboration, and to assess the impacts on the NAVAIR enterprise, from both a technical and socio-technical perspective.

Briefly 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 tradespace analyses of the mission capabilities using approaches such as Multidisciplinary Design, Analysis and Optimization (MDAO) as a 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 System Attributes (KSAs)[3], 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 tradespace analyses of the solution/system for the program of record (POR) cannot achieve mission-level objectives
  - All requirements are tradeable if they don't add value to the mission-level KSAs
  - These are asynchronous activities in creating an Initial Balanced Design
  - Government and Industry must work together to assess "digital evidence" and "production feasibility"

[3] We have been informed that Key System Attributes are being substituted for Key Performance Parameters in the Joint Capabilities Integration and Development System (JCIDS).

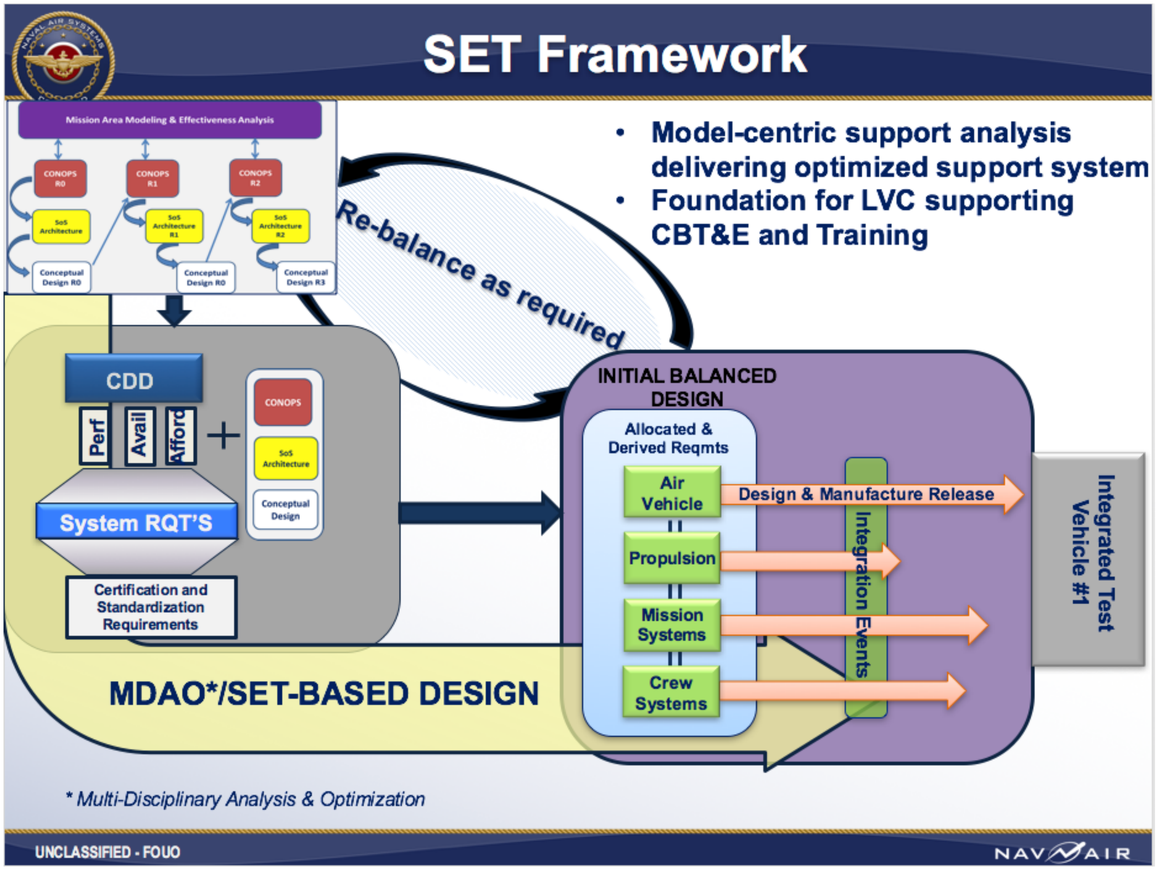


Figure 4. Proposed Framework for New Operational Paradigm for Acquisition and Design

Another objective under consideration in the context of the operational model 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 evaluation based on model-centric information. NAVAIR needs some type of objective decision framework to assess evolving design maturity with considerations of value to the KSAs, risk and uncertainty. This framework's operational concept has produced some specific research questions such as:

- How does/can government participate in these continual event-driven and objective evaluation steps?
- How to judge evolving maturity of design?
- How can government interact to provide value without impedance?

These efforts for improving the collaboration between government and industry are also underway to develop a new CONOPS of operations with organizations involved in the Aerospace Industry Association (AIA) working group [3], and the National Defense Industry Association (NDIA) Modeling and Simulation group which is looking at approaches for using digital engineering for competitive down select. We are involved in all of these efforts to further the objectives of our sponsor.

This report covers both the research performed against the RT-157 objectives, and the request of our sponsor that has expanded to address the needs of the SET under RT-170, specifically in the context of the new framework (Figure 4).

1.1 Objectives

As shown in Figure 3, the scope of these research task areas has expanded and are continually being realigned to the prioritizes of the SET. Demonstrations and NAVAIR-relevant example models are important to support workforce needs. Therefore, we are supporting the research using a case study based on a conceptual Unmanned Air Vehicle (UAV). This case study serves as a surrogate for the pilot project identified in Figure 1. This example directly supports some of the needs for Task 3 (Modeling Methods), Task 4 and addresses some questions related to the new framework.

We are using publically available information [85] to construct examples and reference models, including SysML, MDAO system examples, and mission-level CONOPS scenarios such as:

- Surveillance
- Refueling
- On-board UAV refueling

This approach supports a research objective to inform competencies (Task 4) with reference models and modeling methods. The examples can be "reference models" of modeling patterns or surrogate. This case study supports the three cross-cutting critical items from RT-157, but extends it to the mission/SoS level:

- Cross-domain and multi-physics model integration, and the associated methodologies
- Technologies to establish and quantify model integrity
- High Performance Computing (HPC), which enables the previous two bullet points

As reflected in Figure 4 there are four elements of research that relate to the critical enablers that extend the RT-157 task as defined in the RT-170 that include:

- Mission Engineering and Analysis using MDAO methods and applicable operational, capability, and system models
- Decision framework related to cross-domain integration through the single source of technical truth (SST)
  - Provides a basis for an objective approach to assess design maturity based on an ontological representation of the system using open semantic web technologies
- Integrated digital/collaboration environment capabilities and operational models both within NAVAIR and industry
  - This includes the development of methods and reference models to enrich workforce understanding of MCE methods, models and tools
- Update the SET Roadmap to address the prioritized SET needs, such as:
  - New workforce skills
  - Integration of re-engineered processes, competency management and cultural alignment
  - Communications with industry, and stakeholder management
  - Environment evolution, more analytic-based decision making and planning
  - Leadership, governance and prioritization
  - Needs to address iterations (currently three planned) as reflected in Figure 1

1.2 Scope

Given the objectives, we aligned the RT-157 efforts with sponsor priorities relevant to SET, which included research to:

- Assess the new framework and identify challenges and focus areas to develop a prioritization for the research
  - Identify key research given gaps and challenges of new concept
  - Support meeting with NAVAIR sponsors and industry on new approaches to collaboration
- Understand how requirements can be represented as models
  - Use the case study to help show, in the various ways, how models can be used to support requirements, constraints, validation, and verification planning
  - We have developed example models for addressing this question and are looking to use in upcoming pilots
- Understand approaches to completeness and consistency of formal requirements
- Support development of pilot projects

We believe we have provided insights into these objectives, which are discussed in more detail in this report. Some of the results of the research and contributions are reflected in the December 2016 sponsor briefing. The latest briefing articulates the need for formalizing the use of models, including: level of models, types of models, and the conceptual boundary between government models as shown in Figure 5. This concept reflects on a draft "System Model" that is part of "requirement" for a request for proposal that would be elaborated by contractors during source selection into a "Final System Model." We want to simulate this concept during the pilots if at all possible. We believe we can use our evolving UAV model as the "Draft System Model" for the upcoming surrogate pilot.

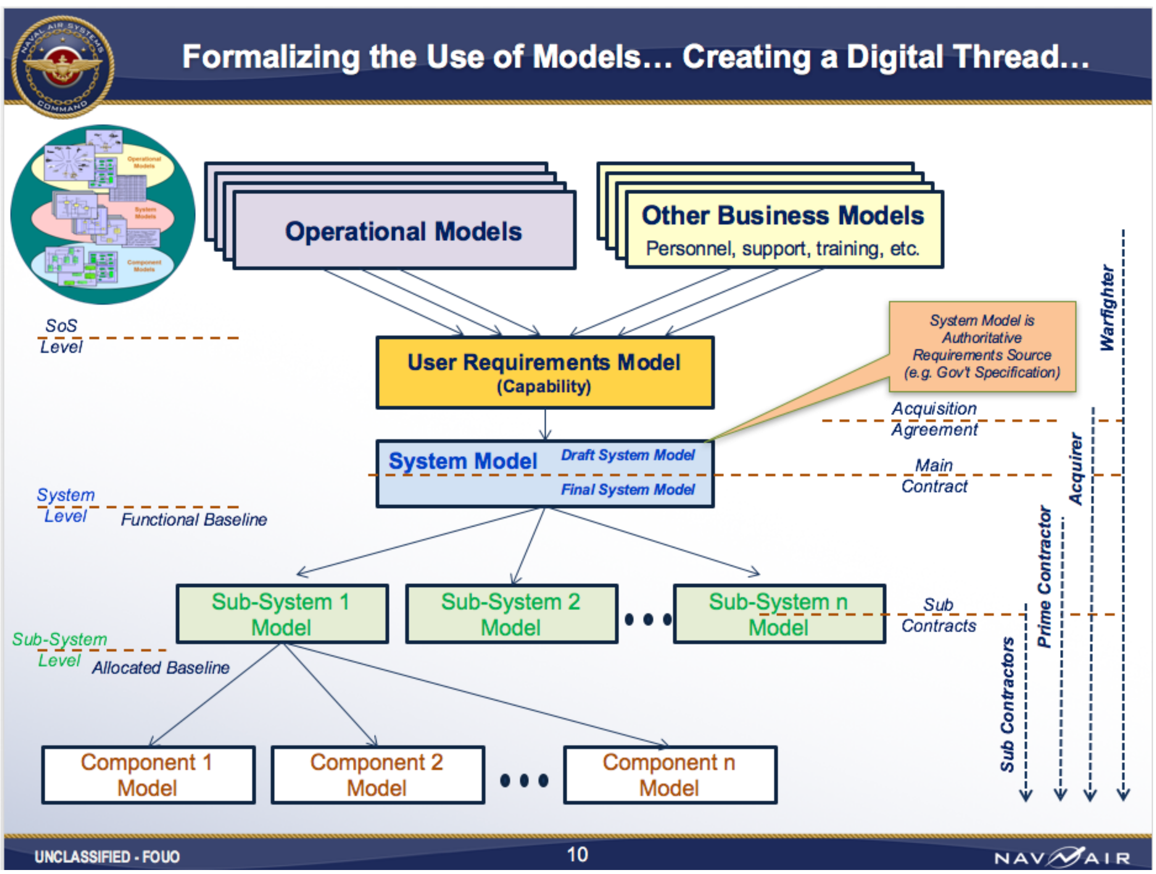


Figure 5. Characterizes the Boundary of Models between Government and Industry

The ongoing SERC research should support the NAVAIR strategies that include plans for:

- Formal use of models as a standard practice for specifying, analyzing, designing, and verifying systems
- System models adapted to the application domain that include a broad spectrum of digital models for representing all aspects of systems
- The use of internet-driven knowledge representation and immersive technologies enable highly efficient and shared human understanding of systems in a virtual environment that span the full life cycle from concept through development, manufacturing, operations, and support

Figure 6 provides another perspective reflecting in information provided under RT-157 on the SST that must include various types of cross-discipline models (e.g., mechanical, electrical, software, testing, etc.) for the different aspects of the system model. It must trace to mission-level models. MDAO will play a role at the mission, system and subsystem level. It must support cross-domain analysis. A key question is what is captured in the SST that provides insight into the evolving/maturing design in order to provide effective oversight. This will be worked under RT-170, and may be supported by:

- Pilot/Demonstration Coordination with Program Executive Officer (PEO)/Program Manager Air (PMA) on pilot candidates
  - Determination of ideal pilot programs
  - SET Pilot execution planning
- Collaboration with Competencies to consider:
  - Moving from Contract Data Requirements Lists (CDRLs) to Models
  - Appropriate “new” Contract Language
  - System Modeling
  - Pilots/Demonstration
- Collaboration with Industry (potential collaborators removed)
- Workforce Development
  - Modeling Methodology Definition – SERC/Naval Postgraduate School (NPS)
  - Modeling Training
- SERC Modeling Research presented through working sessions and reports
- Office of Secretary of Defense (OSD) Digital Engineering coordination
- SERC research synergies through RT-168 with US Army and RT-176 with NPS

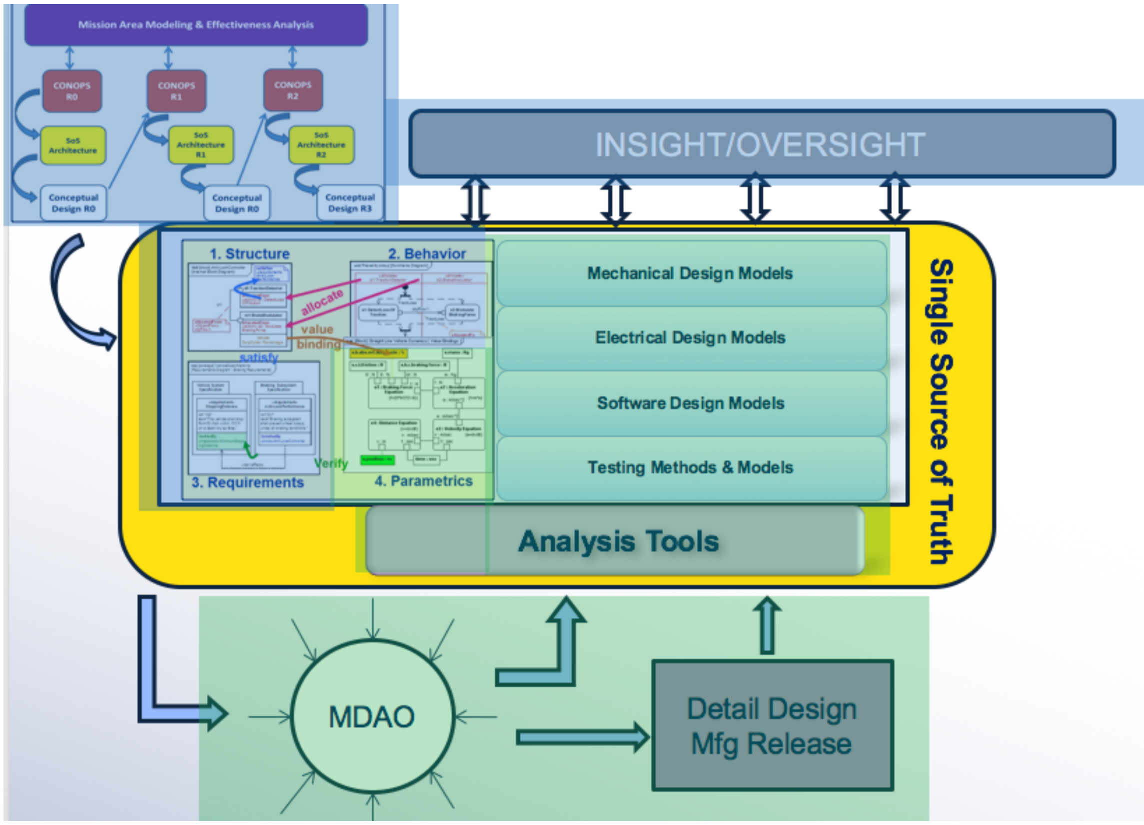


Figure 6. SET Activity Views

1.3 Organization of Document

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

Section 2 provides the summary of our efforts, findings, analyses and recommendations including key aspects from RT-48/118/141. This section also briefly summarizes the expanded scope of our current research under the newly awarded RT-170.

Section 3 describes approach and results of developing information models underlying the single source of truth, and a requirement ontology and requirement manager prototype.

Section 4 describes the need for and approaches to Model Integrity – developing and accessing trust in model and simulation predictions.

Section 5 describes the modeling methodologies, including examples and demonstrations created to illustrate mission, system, enterprise and reference models, including example and methods for Multidisciplinary Design, Analysis and Optimization.

Section 6 discusses the SET roadmap.

Section 7 discusses 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.

Section 8 provides conclusions with a brief summary of the planned next steps.

2 RESEARCH SUMMARY

This section provides some context into the concerns of the NAVAIR leadership in moving forward with a SET. Similar to the approach used in RT-48/118/141, this section provides a high-level summary of the research, plans, results and deliverables. Part II of this report provides additional details on each task.

2.1 BACKGROUND: CHARACTERIZING PROBLEM AND VISION

The RT-141 final report [21] generalized the types of capabilities many organizations use in MCE [8] [9] [10] [38] [51] [71] [77] [111]. The report characterizes a canonical reference architecture of an Integrated MCE Environment, as shown in Figure 7. The following provides some perspectives and capabilities of this vision:

- Provides appropriate views for the various stakeholders
- Stakeholders have views into the Single Source of Truth (SST)
  - Using rich modeling interfaces for those with expertise in modeling
  - Using rich "web" interfaces, which today provides support for graphics, integrated with structure inputs, generated textual views and 3D model viewing [115]
- MDAO layer provides for problem and design space exploration of
  - Physics-based models
  - Integrity-based models
  - Cost and scheduling models
  - Risk models
  - Various "illities" models
- Includes surrogates and components
- Enabled by High Performance Computing (HPC)
- Semantically rich linkages between data and information in the SST provides for continuous workflow orchestration – enabled by HPC
- Document generation is enabled by
  - Semantically rich links to information in the SST
  - Templates that formalize patterns for requirements, contracts, etc.
- Enabling technologies such as machine learning provides a virtual knowledge librarian that assist users guided by embedding knowledge and training
- Contractor and collaborators have a secure means to plugin to view or share digital information, as a new paradigm for interactions
- This view of the Designing System provides links downstream to fully link Product Lifecycle Management (PLM)

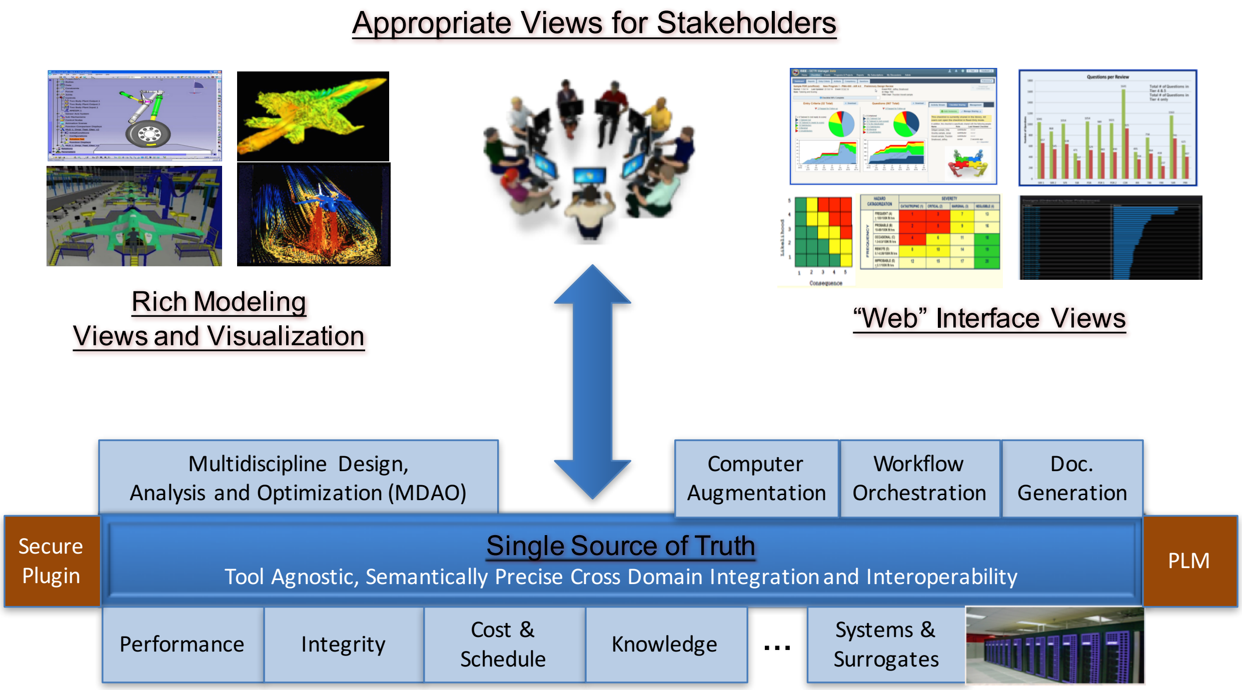


Figure 7. Integrated Environment for Iterative Tradespace Analysis of Problem and Design Space

Through our 27 working sessions, as summarized in Section 2.4, we continue to initiate discussions about what the SET is and its implications moving forward, along with benefits and challenges. We have used the following scenarios to supplement our characterization of a future vision state shown in Figure 7. It has helped provide additional perspectives moving from a mission-perspective to several systems-perspectives down to specific design disciplines. It also provides a means to identify some of the challenges associated with the four tasks of RT-157, but also other needs defined in RT-170.

As shown in Figure 8, we have seen the use of the Net-Centric Evaluation Capability Module (NECM) that uses modeling and simulation and a Study Views method to structure the development of needed mission capabilities. These capabilities support some aspects of the Joint Capabilities Integration and Development System (JCIDS) to analyze joint mission threads in near real-time and automate net-ready Key Performance Parameter (KPP) analysis**.** Currently this information (and others) are used as input to develop Department of Defense Architectural Framework (DoDAF) models, which are focused primarily on the net-ready capabilities. However, there are more concerns in developing a weapon system than just the net-ready capabilities. Therefore, if we want to support the vision of the NAVAIR sponsor to have a deeper system and component-level analysis as it relates to the value to key KSA/KPPs relative to the mission, we need better integration to higher-level fidelity models at the system levels as described in the scenarios below. We believe there are opportunities and benefits to better link the NECM capabilities into dynamic simulations of both mission and system capabilities to create more dynamic operational representations of the concepts of operation (CONOPS).

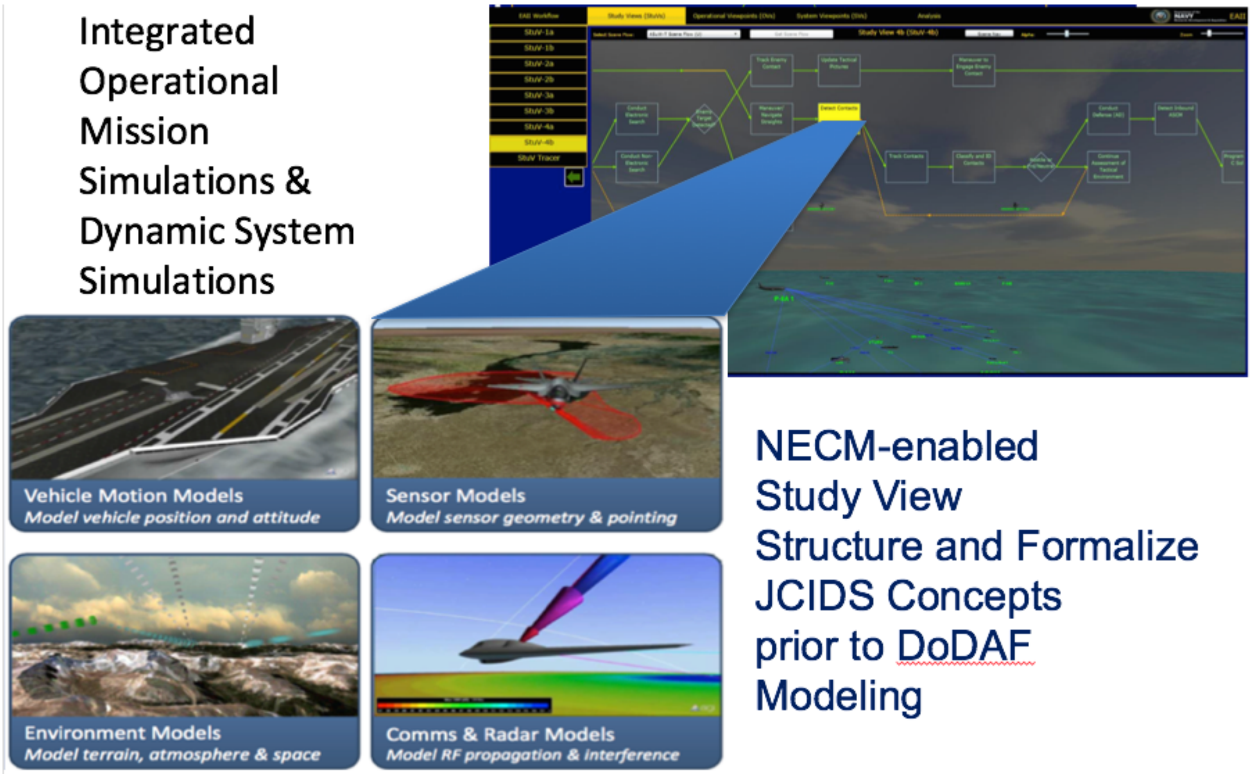


Figure 8. Dynamic CONOPS Integrated with Mission Simulations[4]

Those dynamic capabilities reflected in Figure 8 that are linked into the study views map to higher-level fidelity views related to specific design disciplines as shown in Figure 9. At this level, we want to improve the tradespace by using MDAO. Most organizations that develop aircraft systems have been using MDAO for over 10 years, more focused at the system level. Such capabilities allow for 1000x the number of design excursions [59] as has been done with traditional approaches in the past. These types of MDAO approaches provide for some amount of cross-domain analysis. However, we want to develop more comprehensive approaches and be systematic about covering the tradespace at the mission and system levels, at least for the critical KSAs. All of the main contractors to NAVAIR use these capabilities, and we shared publically known information with attendees about such usage at our working sessions [110]. MDAO can also be used at the mission level as reflected in Figure 4. There are opportunities in research for developing and improving MDAO methods [86].

[4] Image credit: Phoenix Integration

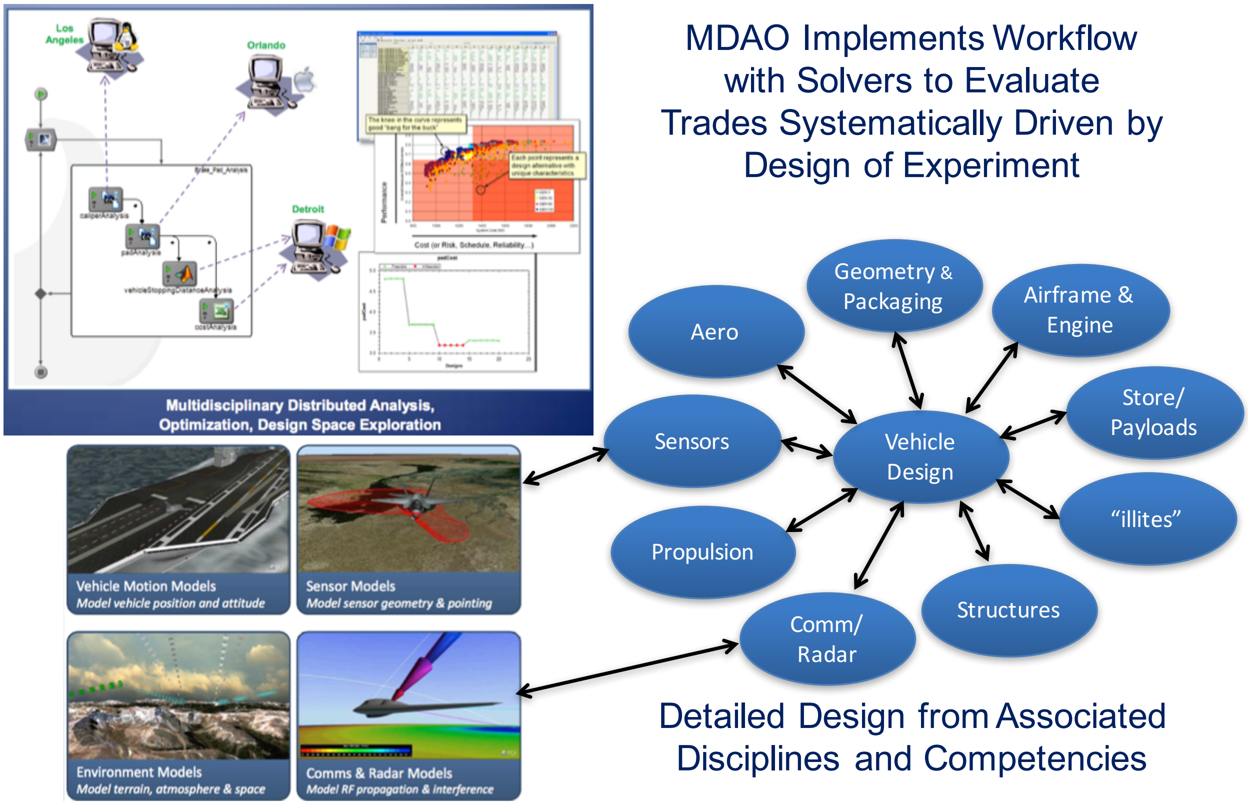


Figure 9. Multidisciplinary Design, Analysis and Optimization Supports Tradespace Analysis Across Disciplines

Another area of opportunity is to improve the integration of architectural, system and component models across the domains, and better link with other modeling and simulation capabilities targeted to specific disciplines. These "architectural" models may be developed using DoDAF to characterize mission capabilities and operational views. At the system level they may be developed using Model Based System Engineering (MBSE) methods and be represented in standard modeling languages such as SysML [104]. The linkages between the MBSE and design disciplines is often not precisely represented, with a few exceptions. When it is done using tool-to-tool integration, such integrations can be rather susceptible to updates to the tools [34]. We believe there are opportunities to address this need in more tool agnostic ways using semantic web technologies [27] [126]; this is one area of research supporting cross-domain model integration (Task 1).

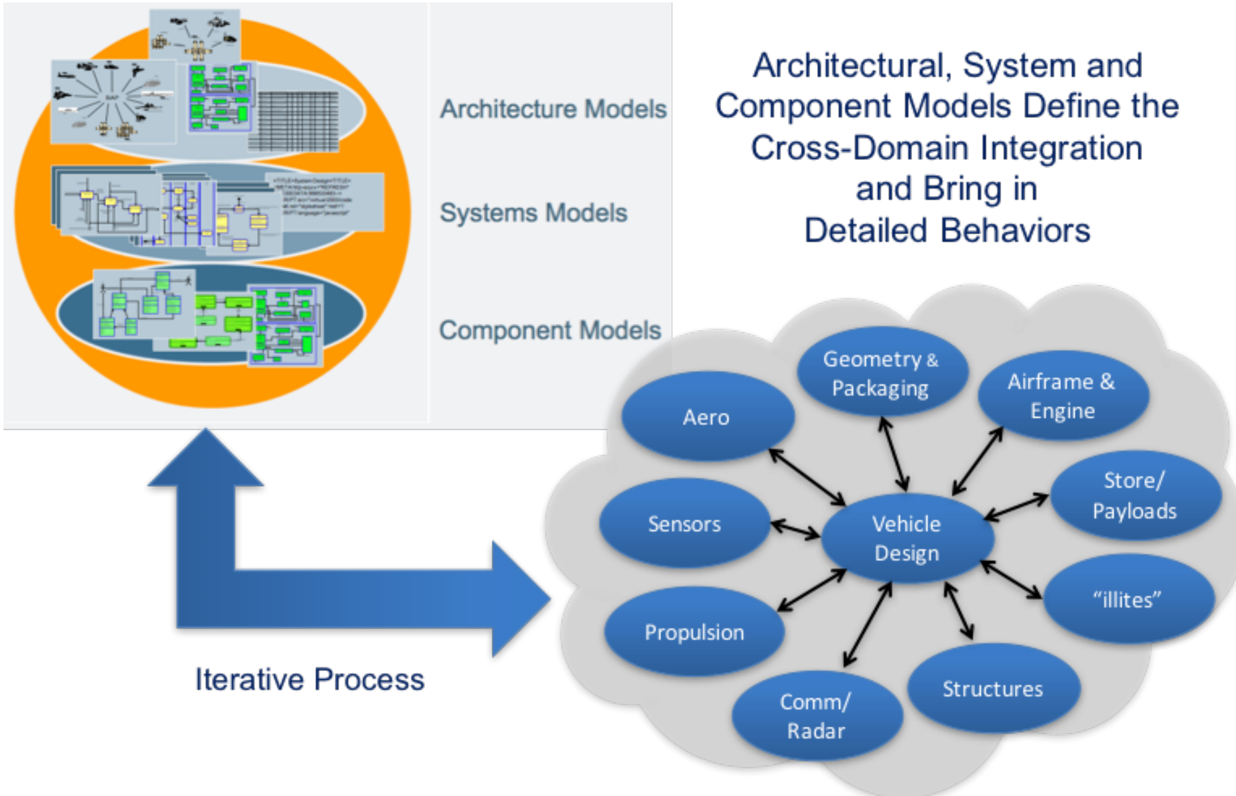


Figure 10. Integrate Multiple Levels of System Models with Discipline-Specific Designs

The key reason for the need for cross-domain model integration (Task 1) is the underlying complexity needed to accomplish the scenarios associated with Figure 9 and Figure 10. In addition, our research as illustrated by the DARPA META project [9] has shown that methods are needed to ensure that the tools provide the expected automation, efficiencies, and produce the desired information. This points to the need for both methods (Task 3) and because many of the modeling and simulation capabilities that may be integrated into an MDAO workflow can be modeling and simulation capabilities, they require some type of assessment to ensure the integrity of the predictions (Task 2).

We believe there are research challenges to better quantify design margins, parameter uncertainties, and system performance sensitivities associated with physics-based digital models. There are opportunities and challenges in integration of relevant multi-physics modeling and simulation, need for earlier high-fidelity models, and means to assess reduced-order models. In addition, there are needs for determining optimal risk/cost tradeoff for continual Verification, Validation and Accreditation (VV&A) [55] or alternative means for assessing trust in model and simulation predictions [120].

As shown in Figure 11 [45], there can be a very large set of tools that can be used to develop the needed data and information across all of the domains[5]. 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 leading edge approach by NASA/JPL is to ensure models are created that comply with established modeling patterns; their approach transforms the model information into a tool-neutral SST based on ontologies, and then uses standard semantic web technologies to apply checks to ensure completeness and consistency [77]. Some of our deliverables are providing the building blocks to

[5] For example, in an inventory analysis of modeling and simulation tools used at NAVAIR, there was more than 300, and we were told that the list was incomplete.

accomplish these types of checks and are planned to be integrated into the NAVAIR Integrated Systems Engineering Environment (ISEE) as discussed below.

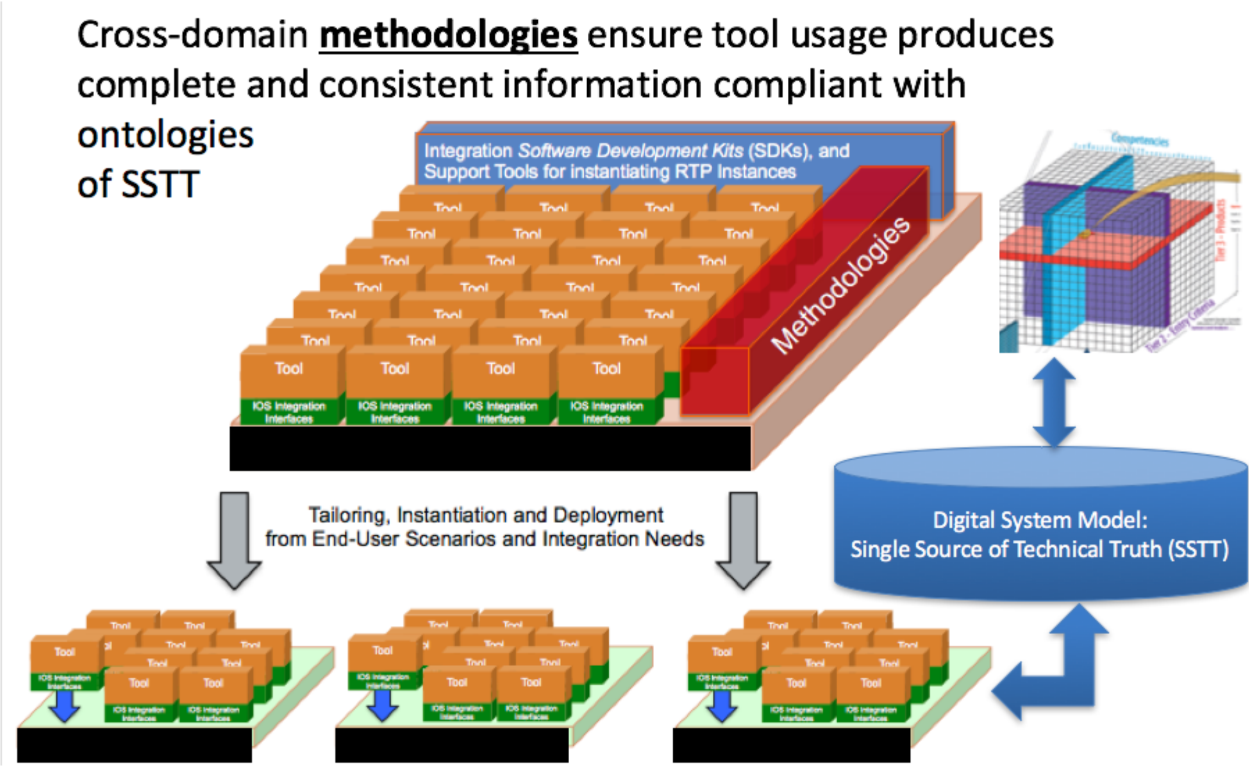


Figure 11. Appropriate Methods Needed Across Domains

Another challenge underlying the reason for the need for cross-domain model integration (Task 1), as rendered notionally in Figure 12, is that the current competencies may support one or more domains and may often "buy all the data," often referred to as Contract Data Requirements List (CDRLs); this practice is aimed at reducing the potential future risks. Currently, there are limited ways of understanding the value of that data to the mission or the implication of design decisions across the domains. Models, modeling, and computationally enabled concepts such as the use of precise models that are linked across domains in the SST should provide a means to begin to understand the value, risk and uncertainty of information relative to the mission. This is a specific objective articulated by the sponsor. However, this also leads to another new need in how digital engineering impacts the language and information that is put on contract in a statement of work (SOW) or requests for proposal (RFP). Therefore, we too are looking at potential approaches this need as that relates to the information that flows across the contractual boundary (Figure 5). We have an effort to look at approaches to formalize contractual language, and may need to define how a proposal response will be evaluated using more dynamic modeling and simulations, and digital engineering information.

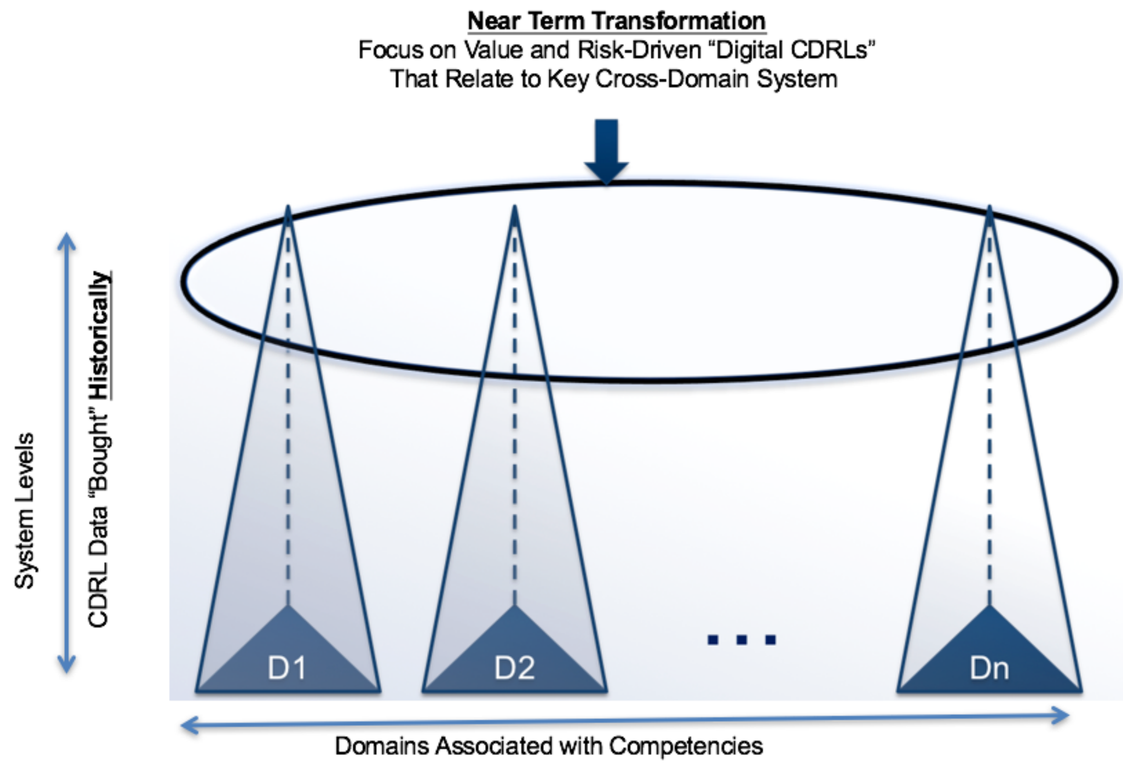


Figure 12. Need for Obtaining Digital Information Across the Domains

2.2 System Engineering Transformation (SET) – Perspectives on Clarifying the Focus

We were also requested to contribute to an effort to create an executive level message that can be used by senior leadership to describe the SET. Like most complex enterprise there are many stakeholders and they all have different concerns and views on the solution and/or vision. We share some perspectives from some of the leaders of the SE transformation:

- Senior Executive for Research and Engineering - Emphasizes Digitalization and Virtualization
    - Also discussed in terms of Better, Faster, Cheaper
- Mission modeling director emphasizes the ability for models to represent a higher level of abstraction of the system including the multi-physics aspects in order to get to an Integrated Test Vehicle (per SET Framework)
    - We also know based on the framework is concerned with continuous collaboration between Government and Industry and event-driven decision making
- Systems engineering director emphasizes the underlying "data" (Information Model) of the integrated information that represents "all" aspects of the system, mission, users and environment in the SST
    - This perspective is about ***Systems Engineering***, including principles and methods carried out in terms of more precise models and standard languages
    - Integrated views across all of the domains including risk, uncertainty, and new metrics for understanding "design maturity" (recognizing that some and maybe most competencies still like to think in their stove pipes)
    - Leveraging computational capabilities to let the computer do work that in a document-centric world is done primarily by humans

The digitalization in terms of precise models allows computers to help find defects to make the system "Better." Computers also provide the means to analyze 1000x number of trades [59], again based on precise models and the associated simulations leading to a "Better" design, both in terms of multi-physics, but also in terms of other cost and "ilities" models.

The digitalization in terms of precise models also allows computers to do work that has in the past been done by humans, allowing work to be done "Faster."

The precise digitalization including the increased emphasis on representing the cross-domain relationships and dependencies associated with the competencies and disciplines provides for a SST where work is event-driven ("Faster"), allowing for the continuous Virtualization of meetings ("Faster") to eliminate the monolithic and costly reviews ("Cheaper").

As a community, perhaps we should create a Systems Engineering Transformation Manifesto (e.g., Manifesto for Agile Software Development is quite well known). A manifesto is a written statement where one (or a group) publicly declares their:

- Intentions (what you/we intend to do)
    - Change the operational paradigm for acquisition of system and system of systems
- Opinions (what you/we believe; stance on a particular topic)
    - We can operate in a more collaborative paradigm
    - Computationally enabled Systems Engineer allows us to deal with complexities not possible through traditional document-centric processes ("Better")
    - Process of models provides for early Validation of Requirements ("Better")
    - Resulting models produces Verification threads to support Verification planning that can serve as a basis of estimate earlier ("Better")
    - Models are reusable from program-to-program ("Faster, Cheaper")
- Vision (the type of world that you dream about and wish to create)
    - See Figure 7 and associated characterization

There are many organizations in DoD that might benefit from coming together with a unified vision on Systems Engineering Transformations.

2.3 Goal-Driven Plan

RT-157 started in February using a goal-oriented method to develop a Plan Objectives, Action and Milestones (POA&M) for the 2016 research, with a mapping to the roadmap categories: (T) Technologies, (M) Methods, (C) Competencies (see Table 1). This plan was developed before SET acceleration plan was started, as discussed in Section 1. This plan was based on the goal to establish a rigorous foundation for a semantically precise and tool agnostic framework for the SST (Task 1). These detailed tasks are contributing to the extension of the Integrated System Engineering Environment (ISEE) as shown in Figure 13. There was also the assumption that there would be an evolutionary adoption of modeling tools and methods at NAVAIR, and the focus would start with improved formalization of requirements that would trace to models, risks, and evidence. Note also that there is a roadmap tag mapping to technology (T), methods (M), competencies (C). We had no specific tasks that address interactions with contracting organizations or a new approach to governance. However, the new framework does bring in plans for a new operational model between government and industry. In addition, the change of command altered this plan implies some changes in governance as reflected by the framework (Figure 4).

Table 1. 2016 RT-157 Plan Objectives, Actions and Milestones

ID	What	Why	Roadmap Tag
0	See Goals Tab	List general goals, priorities and dependencies	T,M,C
1	Requirements Engineering Method	There are multiple capabilities involved in requirements engineering, including ontology-driven requirement engineering to ensure consistency and completeness of information captured; another goal that might take longer to implement is to embed the methodological guidance in the Requirement manager implementation	M
1a	Requirements Ontology	Characterizes in a tool agnostic way the information that must be captured, in addition to representing the attributes of consistency and completeness	T
1b	Requirements Manager Tool Trade	Determine the tools that can perform multiple activities of requirements engineering from elicitation, traceability, through version control, role-based access, security	T, M
1c	Requirement Manager	Implementation and integration into the SSE and single source of technical truth	T, M
2	Risk Method	The risk method will leverage the formality defined in a risk ontology that integrates both with requirements and evidence to support a rigor risk approach that is based on evidence of work, including the incorporation of evidence provided as models	M
2a	Risk Ontology	The key classes from the existing process are already defined, but will be formalized into an ontology that links to both requirements and evidence that will be stored in the SST	T
2b	Evidence Ontology	This is information that is related to the information from the checklist; this will be formalized to link to both requirements and risk. This will formalize the risk process(e.g., low evidence implies high risk)	T
2c	Requirements to Risk Mapping	Relate risk to requirements	T
2d	Risk Manager	Implementation and integration of risk viewpoints and functions into the SST	T, M
2e	Requirements to Evidence Mapping	Relate evidence to requirements	T
2f	Risk to Evidence Mapping	Relate risk to evidence	T
3	Knowledge	This involves the integration of embedded training, examples, modeling patterns, reference models, tradespace analyses; engineers work well with examples. There is currently not much available, and implementation of this concept needs to attempt to embed the methodologies into different tools, as is the currently the case with SETR manager	T. M, C
4	Multidisciplinary Design, Analysis and Optimization	MDAO is a systematic approach to tradespace analysis. This task in 2016 involves informing people about the concept, methods and tools options.	C, M

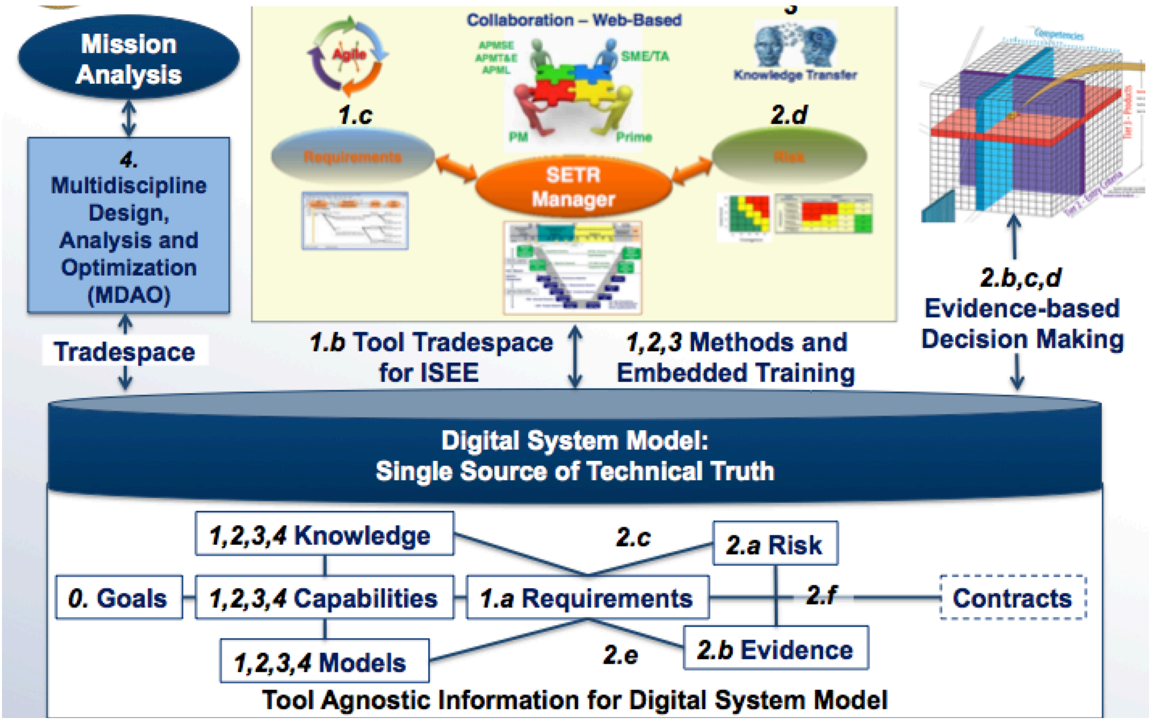


Figure 13. Conceptual POAM Related to ISEE, SST, and MDAO

2.4 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 session also inform the team about relevant information and feedback to scope the deliverables in the context appropriate for NAVAIR; this has been especially important given the recent changes under SET. We also use bi-weekly drumbeats to share status and updates. Each working session has a defined agenda, and detailed meeting notes are provided to our sponsor. The following provides a summary of the working sessions and other events, and a brief description of the contributions to the tasks and deliverables.

- Working session #18: 2/4/2016
  - Developed the goal-driven prioritization plan for RT-157 and confirmed the priorities with the NAVAIR team and sponsors
  - Discussed the concept for developing the ontology underlying the requirement manager (top-level priority)
- Working session #19: 3/3/2016
  - Presented a session on methods for Multidisciplinary Design, Analysis and Optimization methods and tools
  - Presented evidence and example for a concept based on Controlled Natural Language Requirements that will likely be necessary as a supplement for models
- Working session #20: 4/7/2016
  - Discussed the new plan of the SE Transformation acceleration
  - Discussed POA&M for the RT-157-specific discussed in Section 2.3
  - Discussed the importance of modeling methods before tool selection

  - Discussed use of reference models as curated knowledge that may alter the way training is conducted, and must be considered in the creation of the ISEE
  - Discussed the approach for developing the underlying Information Model for the SST
  - Presented a working demonstration of the requirement ontology and requirement manager prototype and provided software prototype and ontology to NAVAIR (a bonus deliverable)
- Working session #21: 5/4/2016
  - Discussed concepts and implications associated with the SE transformation and framework (see Figure 4)
- Working session# 22: 6/7/2016
  - Discussed first version of the new framework and implications of developing a POA&M for planning next few years of the SET that included all of NAVAIR and pilot projects as shown in Figure 1
  - Initiated the discussion for follow-on research task now in RT-170, which was awarded on 1-Sep-2016
- Working session #23: 7/14/2016
  - Discussed underlying meaning of the SET (see Section 2.2)
  - Discussed of framework needs and challenges
    - Implications on specification and contracting
  - Presented conceptual UAV as example case study with models for presenting modeling methods
  - Change in needs such as modeling examples
  - Change in collaborator from Wayne State to University of University of Maryland to better support the new priorities of the SET
- Working session #24: 8/8/2016
  - Presented modeling method examples and demonstrations
    - SysML at mission, system, and enterprise
    - Reference models
    - MDAO example of a UAV performance workflow
    - MDAO webinars discussing usages by industry confirming use of MDAO by organization that contract to NAVAIR
- Working session #25: 9/15/2016
  - Col. Tim West (PhD Student of Mark Blackburn) presented – "A Digital Thread Framework for Dynamically Integrating Experimental and Computational Results with Quantified Margins and Uncertainties"
    - Topic is highly relevant to the NAVAIR System Engineering Transformation, and specifically to the challenge of Model Integrity
  - Provide examples and updates on UAV mission and system modeling examples and guidelines using SysML
  - Presented MDAO examples, webinars and demonstration
  - Discussed concepts on "Synthesis of Contract" Request for Proposal (RFP) and statement of work (SOW) as new MCE approach to source selection in a new paradigm
- Working session #26: 11/9/2016
  - First session with Georgia Tech (Dr. Russell Peak) Research Modeling UAV
  - First session with University of Maryland (Drs. Mark Austin and Leonard Petnga) Research – Ontologies
  - Information Model/Artifacts/Ontology effort for Integrated Systems Engineering Environment

- Discussed other related SERC Updates, RT-176 Naval Postgraduate School (NPS), RT-168 Armament Research, Development and Engineering Center (ARDEC)
- Working session #27: 12/15/2016
  - Update on SysML Modeling of UAV
  - Use of Natural Language Processing experiment (by NPS) and ontologies on Standard Work Packages (SWP)
  - Capability Based Test Base and Evaluation
  - Air Force Source Selection using Modeling and Simulation
  - MBSE 101: Three 1-hour modules from NASA Academy Online
  - Information Model/Artifacts/Ontology effort for Integrated Systems Engineering Environment (ISEE)
- Industry and Government Forum on Model Centric Engineering: 5/26/2016
  - Dave Cohen presented information that was pre-framework
  - See white paper [40] on SERC website (http://www.sercuarc.org/wp-content/uploads/2014/05/MCE-Forum-Final-Report.pdf)
- SERC Executive Advisory Board: 6/29/2016
  - Presented results of NAVAIR research results and impacts
  - Dave Cohen was able to present early version of his framework
- Special session with NAVAIR sponsors at Altair Engineering in Detroit MI: 9/29/2016
  - This meeting was requested specifically by Dave Cohen
  - Key topics included:
    - Understanding Altair's views on the advances in computational capabilities for increasing the speed of design, analysis and optimization through modeling and simulation
    - Understanding of the accuracy of multi-physics modeling and simulation predictions (Dave refers to this a 'Model Integrity'), based on their commercial offerings and expertise in usage of those offerings (e.g., tools)
    - Altair's views on advancement of their offering especially in the past four years, because Department of Defense (DoD) organizations are using the DoD Computational Research and Engineering Acquisition Tools and Environments (CREATE) Air Vehicle (AV) family of computational tools and have discussed significant advances
    - Identify areas where there are challenges, and to discuss strategies that can overcome such challenge areas
- Presented NAVAIR research at SERC Sponsor Review to Office of the Deputy Assistant Secretary of Defense for Systems Engineering: 11/17/2016

2.5 OTHER DELIVERABLES

We have been producing models and examples. The following provides a list of models that have been produced and supplied to NAVAIR:

- Requirement ontology and associated Requirement Editor that includes integrations with the requirement ontology
- System Engineering Technical Report (SETR) ontology derived from SETR Process Handbook Version 1.0 Dated 06 February 2015
- SysML one-day course that is provided by Stevens Institute of Technology for the SYS-671,672,673,674 Cyber Physical Systems course
- Demonstration of MDAO workflow for UAV performance scenario

- Stevens supplied UAV SysML models to Georgia Tech and Naval Postgraduate School researchers
- Demonstration of SysML models for simulation and requirement verification
- Plan for using Natural Language Processing and ontologies to re-structure Standard Work Packages

2.6 Expanded Scope Under RT-170

It is acknowledged that there are many possible hurdles beyond technical feasibility (e.g., organizational adoption, training, usability, etc.), and we have had to adjust our plans and work to align with the new priorities to align with the accelerated SET. The path forward includes adjustments to the roadmap to factor in some of these other considerations. The concept proposed by the framework (Figure 4) has changed some of our assumptions about the SST.

The actual statement of work identified research needs relating to the cross-cutting concerns of the lifecycle and modeling environment and infrastructure such as:

- Prioritization & Tradeoff Analysis
- Concept Engineering
- Architecture & Design Analysis
- Design & Test Reuse & Synthesis
- Active System Characterization
- Human-System Integration
- Agile Process Engineering (new)

As shown in Figure 14 (columns to the right), these lifecycle perspectives were in the RT-141 final technical report, and as shown by the traceability, these needs cross many MCE relevant topics. All of these may be reasonable research needs, but we aligned the proposed tasks with the available level of funding to the key needs defined in the framework (Figure 4). These align the proposed tasks with our understanding of the sponsors priorities. We briefly summarize the new proposed RT-170 tasks.

Discussion Topics (not exhaustive)	Instances where discussed (not exhaustive)												Characteristics						From Kickoff Briefing					
	NASA/JPL	A	B	C	Altair	GE	Sandia	DARPA META (VB)	DARPA META (BAE)	Model Center	Automotive	CREATE	Performance	Integrity	Affordability	Risk	Methodology	Single Source of Tech Truth	Prioritization & Tradeoff Analysis	Concept Engineering	Architecture & Design Analysis	Design & Test Reuse & Synthesis	Active System Characterization	Human-System Integration
Modeling CONOPS	x															x	x	x	x	x			x	
Modeling Patterns	x								x					x		x	x	x		x	x	x		
Multi-Physics Modeling and Simulation		x	x	x	x			x	x		x	x	x	x					x	x	x	x	x	
Multi-Discpline/Domain Analysis and Optimization	x	x	x	x	x	x	x	x	x	x			x	x	x	x		x	x		x	x	x	
Mission-to-System-level Simulation Integration	x	x	x													x		x	x	x	x	x	x	x
Affordability Analysis			x				x						x	x	x	x			x		x	x	x	
Quantification of Margins			x				x						x	x	x	x	x		x		x	x	x	
Requirement Generation (from Models)	x		x					x									x	x	x		x	x		
Tool agnostic digital representation	x	x			x				x								x	x	x		x	x	x	x
Model measures (thru formal checks)	x		x			x		x	x							x	x	x			x	x		
Modeling and Sim for Manufacturability			x			x		x					x	x	x	x	x	x	x	x	x	x	x	
Process Automation (workflows)	x				x				x	x							x	x			x			
Iterative/Agile use of MCE	x	x	x							x							x				x	x		
High Performance Computing	x	x	x		x		x	x			x	x	x	x	x				x	x	x		x	
Platform-based and Surrogates	x	x	x								x									x	x	x	x	
3D Environments and Visualization	x	x	x	x	x	x	x	x			x		x	x					x	x		x	x	x
Immersive Environments		x	x								x									x			x	x
Domain-specific modeling languages	x	x	x	x	x	x	x	x	x		x		x	x			x			x	x	x		
Set-based design		x				x							x	x	x	x			x	x	x			
Model validation/qualification/trust							x					x		x		x	x		x		x	x		
Modeling Environment and Infrastructure	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Figure 14. Traceability and Scope of Data Collection of MCE Relevant Topics

2.6.1 RT-170 Task 1: Mission Engineering and Analysis using MDAO Methods

This task investigates factors relating to the relative value and priority of high-level capabilities of the system under development (some of which might be assessed under RT 170 Task 2). It investigates dynamic representations of mission and campaign analysis and defines methods for mapping to MCE-relevant capability representations in contrast to the traditional Capability Development Document (CDD). This should include modeling different viewpoints for capability views, operational views that map to system views.

In the context of the proposed framework shown in Figure 4 and Figure 6, the concept of MDAO are being consider from at least three points of view, such as:

- Support validation of the model-based specification
  - Ensure completeness by tracing from the workflows to the capability threads
  - Ensure an understanding of the boundary conditions against the KSAs to bound, quantify risk and surface potential anomalies
  - Provide a means to look at the constraints imposed across domains
  - Provides means for simulating dynamic behaviors, spanning multiple engineering domains to be able to balance the tradeoffs of performance, availability, affordability and airworthiness across domains
  - Perform sensitivity analyses to assess the value or risk of different capabilities across domain/disciplines
  - Support data-driven decisions with engineering technical data and information that is produced, not just documents (supporting RT-170 Task 2)
- Capture and organize prior analysis of tradespace
  - Support reuse of data and analysis to perform regressions for the inevitable situations of evolving specifications
  - Trace to capability threads associated with specification

- Provide means to integrate different resources (e.g., simulations, surrogates) from different sources (government and/or contractor)

2.6.2 RT-170 Task 2: Decision Framework related to Cross-Domain Integration

The SST provides a basis for an objective approach to assess design maturity based on an ontological representation of the system using standards-based semantic web technologies. This will provide the means for assessing completeness and consistency across different models, developed using different languages and methodologies (as reflected in Task 3). This task will leverage semantic web technologies for creating an information model to demonstrate concepts for reasoning about conceptual models and design model maturity, which is tool neutral.

This task will extend the work with the requirements ontology and information model derived from the CORE model of Tier 3 artifacts developed under RT-141/157.

2.6.3 RT-170 Task 3: Methods for Integrated Digital/Collaboration Environment

This task focuses on the methodology transition from document-centric to model-centric in part to enhance of our understanding/analysis capability of the increasing complexity in tactical systems. This specifically relates to, but is not limited to the methods used to support RT-170 Task 1 and RT-170 Task 2. We are also interested in model-based alternatives to specification representation and the ability to "generate requirements" that would lead to a digital representation of contractor input leading into Step 5 of the framework. This includes but is not limited to:

- MDAO workflows
- Model Based System Engineering (MBSE): Operational, Capability, Systems views
- Model Based Engineering (MBE): Discipline-specific, mechanical, electrical, controls, etc.
- Model Based "illities" (MBX): Fault-trees, Bayesian, etc.
- Risk/Cost models

Finally, we also want to plan for the use and development of model patterns, model references within their environment to embedded knowledge, and methodological guidance to support continuous orchestration of analysis through modeling metrics, and automated workflow into the integrated environment. The case study should produce example models, methods, and reference models to enrich workforce understanding of MCE methods, models and tools. These efforts should support the evolution and experimentation with the Integrated System Engineering Environment (ISEE), and define goals and requirements for the ISEE.

2.6.4 RT-170 Task 4 - Update System Engineering Transformation Roadmap – Task 4

The RT-157 roadmap task will be continued under RT-170.

Part II: Task Detail Summary

The material in Part II provides a summary of some of the task details, including information shared during some of the working sessions. An extensive amount of material covered in Part II of the RT-141 final report [21] still provides relevant information to this research, but has not been included in this report.

3 Task 1 – Model Cross-Domain Integration with underlying Single Source of Truth (SST)

As discussed in Section 2, understanding the impacts related to cross-domain integration is a key need and challenge; these concerns can impact decisions made by different disciplines and competencies, and can be a critical risk, especially as systems increase in complexity. Traditionally the cross-domain implications surface during integration and test, which is typically late in the life cycle, and where changes can be costly. Today, this is an acknowledged problem and challenge. The solutions are often believed to be better standards for tool integration, but as discussed earlier tools continually change and the integrations become brittle [34]. Newer approaches based on data interoperability as a means of sharing information using standards and tool neutral approaches are emerging as being a better approach, and this is the approach we are pursuing [27] [126].

3.1 Information Model for a Single Source of Technical Truth

The concept for developing a SST is directly related to identifying the NAVAIR relevant information within the domains of the competencies and their relationships within and across the domains. We selected information from several sources in RT-141 final report to explain the evolving approach used by NASA/JPL. Crain [44] provided a process to explain how to approach the problem of understanding the underlying "data" for the producing systems. Start by identifying the objects (classes in an ontology), object properties, and object relationships. Figure 15 provides a perspective on some of the "data objects" and their associated relationships that are relevant to the enterprise at NASA/JSC; similar objects are relevant to NAVAIR too. We have identified about 300 "objects" that are needed to define a NAVAIR-relevant Information Model that underlies the SST. This information was collected by analyzing the artifacts collected as part of the Tier 3 products from the "As Is" effort of RT-48/118/141, and created in a CORE (Vitech) model.

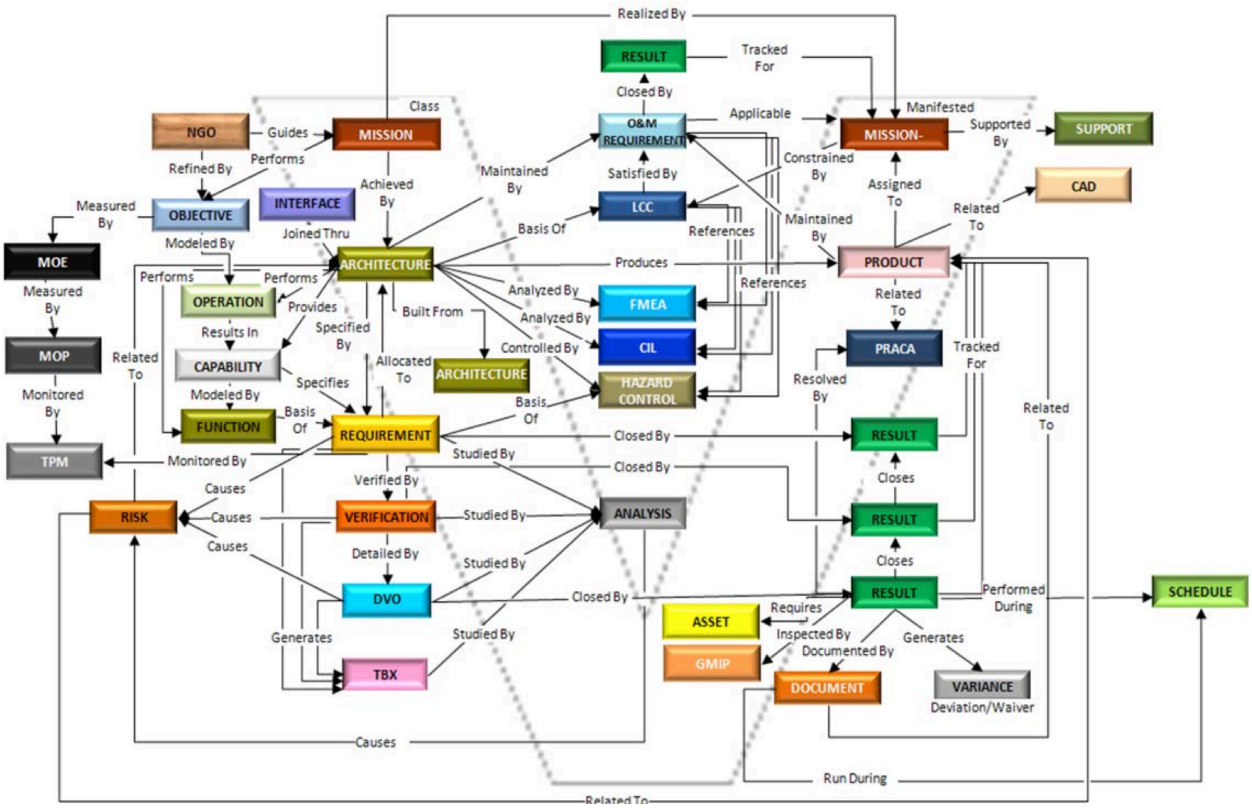


Figure 15. Integrated Data Objects Partial Entity Relational Diagram

We have discussed ontologies as a means of creating a tool-neutral information model. An ontology is a conceptualization for a domain with the associated relationships as shown in Figure 15. What is at least as important is that an ontology can be represented in the standard language OWL (Web Ontology Language, actually OWL2) [143] where open and standard Semantic Web Technologies (tools) can be used to store, update, delete, query, and reason about consistency and completeness; such information is stored in a type of database called a triple store. An ontology can be thought about as a schema in the database for the data related to an ontology. In addition, we can relate different domain ontologies, which reflect on the cross-domain dependencies. This approach is what we call tool agnostic (i.e., tool neutral), but can map to any tool that stores models/data [27].

A recommended approach for us to obtain this information across the competencies of NAVAIR is to:

1. Identify the "objects" for each competency and/or aircraft domain
2. Define the associations, as shown for requirements in Figure 16
3. Define the integrated data model in the form of an ontology, so that we can leverage Semantic Web Technologies, which provide the tool agnostic approach for analysis of dependencies, assessing measures of consistency and completeness

With the new proposed framework, there needs to be some type of decision framework for assessing maturity. We plan to address this using the Information Model (as a means of collecting relevant information, and using completeness and consistency checks much like NASA/JPL [77]).

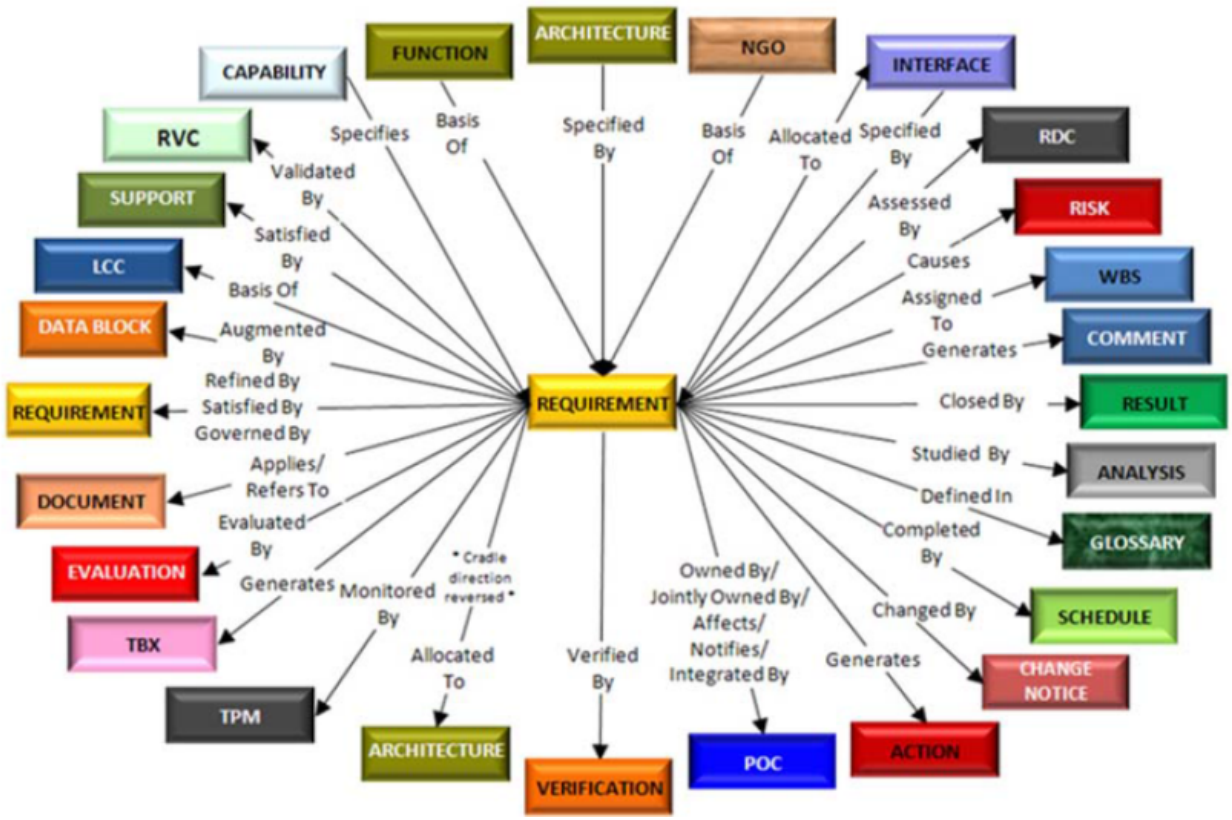


Figure 16. Association to Requirements

3.2 Requirement Ontology Status

Figure 16 provides a perspective on some of our 2016 deliverables. We have a requirement ontology, and developed and associated requirement manager prototype, which uses semantic web technology for checking requirement consistency and completeness, as shown in Figure 17. This capability was a high priority as part of the draft POA&M, but has moved lower in priority as described earlier. On the left side of Figure 17 is the requirement ontology that we're evolving, and on the right side is a simple GUI that we have used to enter requirements, which are associated with a Telepresence Robot system that we use in a course at Stevens. It is simple, but it has many facets of interest:

- Hardware: mechanical, electrical components
- Software
- System of system (distributed)
- Sensors
- Multiple processors
- Communication, uses Wi-Fi and internet
- Humans-in-the-loop
- Mobile
- Semi-autonomous
- Needs to address availability, data integrity, safety and security

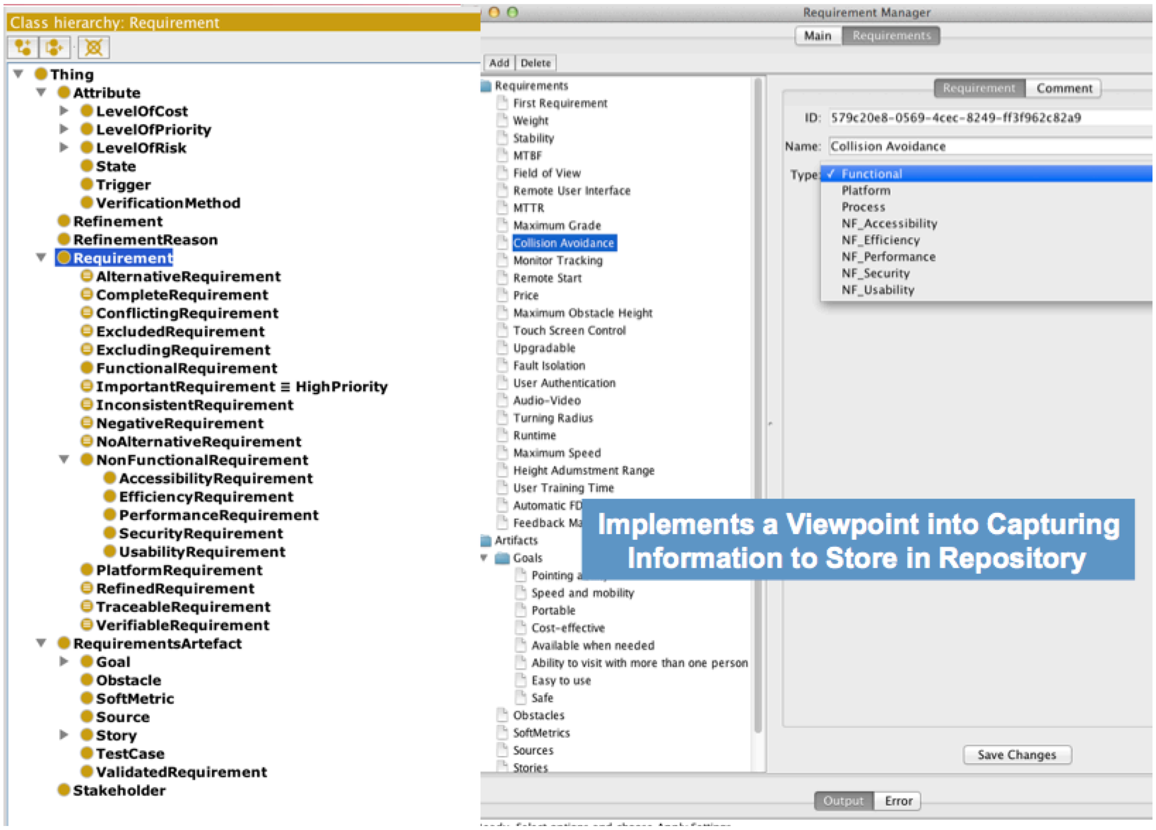


Figure 17. Ontology and Requirement Manager Engine Prototype

The next steps are to develop completeness and consistency checks for requirements [127], and evolve that to support risk assessment per the plan shown in Table 1.

4 Task 2 – Model Integrity – Developing and Accessing Trust in Model and Simulation Predictions

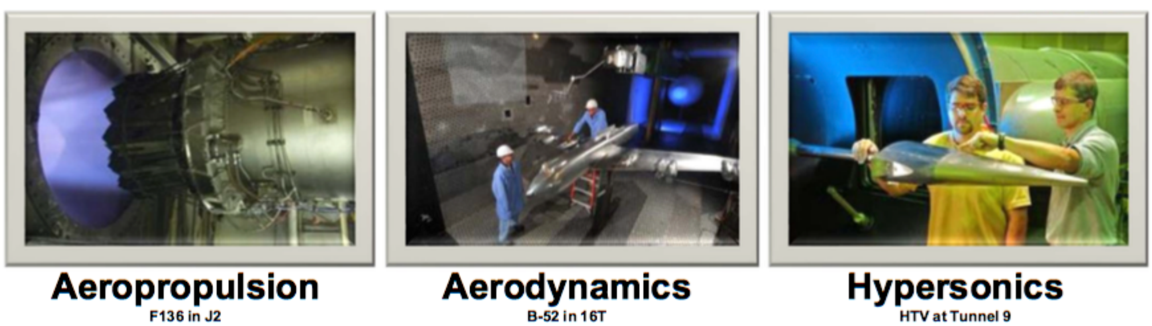
Model integrity, from our sponsor's perspective, is a means to understand margins and uncertainty in what models and associated simulations "predict" or in other words when/how do we trust the models. The objectives characterized by the sponsor are to ensure that the research covered the key objectives; those objectives 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
  - 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

Sandia National Laboratory discussed advanced approaches for supporting uncertainty quantification (UQ) to enable risk-informed decision-making [98]. 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 [123], and the need and challenge of Model Validation and Simulation Qualification [120]. 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.

All of these approaches remain in scope of our research, but they have been pushed out in time to address the priorities of SET. However, research advised under Mark Blackburn by PhD Col. Timothy West [139] at Stevens Institute of Technologies involves a proposed methodology to use the Sandia National Laboratory (SNL) DAKOTA Toolkit [123] with the Department of Defense (DoD) Computational Research and Engineering Acquisition Tools and Environments (CREATE) Air Vehicle (AV) [111] family of computational tools (e.g., CFD), in order to develop an optimized wind tunnel campaign for two different aerodynamic shapes to assess the process.

Col. Timothy West was a guest speaker at the working session. He gave a briefing on his PhD research related to the Model Integrity Task, which involves the assessment of modeling and simulation for reducing or guiding the efforts in wind tunnel testing conducted at Arnold Engineering Development Complex (AEDC). Col. West runs the Test Operations Division at AEDC, which involves the management of all wind tunnel testing. His talk briefly discussed the historical perspectives setting the context of AEDC and the challenge in running these wind tunnels.



Col. West's research is titled ("A Digital Thread Framework for Dynamically Integrating Experimental and Computational Results with Quantified Margins and Uncertainties") involves a proposed methodology to use the DAKOTA Toolkit with CREATE Air Vehicle (AV) family of computational tools (e.g., CFD, FEA), in order to develop an optimized wind tunnel campaign for two different aerodynamic shapes to assess the process. This topic is highly relevant to the NAVAIR SET, and specifically to the challenge of Model Integrity (how to trust the predictive capabilities of multi-physics modeling and simulations).

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 [55]. The word tool qualification [56] and simulation qualification [120] have also been used by organizations regarding the trust in models and simulations capabilities.

See also Section 5.7 for more details on Modeling and Methods for Uncertainty Quantification.

5 TASK 3 – MODELING METHODOLOGIES

Task 1 and the SST is a study about what information/data is needed to understand both the problem and design space. Task 2 is about understanding the “trust” in the information/data that is produced by various types of models and tools. Task 3 is about best methods to systematically produce that information. Often there is a symbiotic approach to assess the methods and select supporting tools. There have been extensive discussions about a broad spectrum of tools documented in the RT-141 final report [21]. However, there have been numerous meetings, research papers, even presentations by representatives of companies that sell modeling tools that all describe that it is critical to do several things before “buying tools.” For example, Matthew Hause who works for a company that sells MBSE modeling tools and other related products provides a list of things not to do when adopting MBSE. A key point from the list involves the need for organizations to: 1) understand what they need to produce (with models), and 2) the method for using the tools. Therefore, this section discusses the needs for methods as discussed in Section 2.1.

Our team is aligned with many of these “better practices,” towards MCE adoption:

- Identifying information that is needed (by NAVAIR) that is produced or analyzed through models to support decision making, see Section 3
- Methods that need to be used to enable the modeling tools to work in a more efficient manner
    - One such failing of utilizing a proper method was pointed out by the DARPA META project program manager [9]
- We need to increase focus on cross-domain methodologies to ensure tool usage produces complete and consistent information compliant with information captured in the SST
- We also want to embed methodological guidance in the new tooling, such as: design patterns, reference models, etc.
    - Methods could be represented as an SysML Activity Diagram (type of flow chart) that shows the process flow, and data flow (both in and out) to the SST
    - NASA/JPL provides a good example [10]

5.1 MODELING EXAMPLES OVERVIEW

Our sponsor requested that we develop some example reference models, MDAO models, and mission and system level models to improve the knowledge of the NAVAIR team. Per their recommendation we started with SysML characterizing capability, operational, structural, and behavioral views. The need is for people to be able to read and have discussions about the models (not necessarily be able to create the models – at least at this point). We selected some UAV scenarios and created models showing a few different types of modeling views. The following is an overview of some of the information shared; more details are provided in Section 5.1:

- Activity diagrams to describe different process models
    - Pre-modeling guidelines
    - Example CONOPS
    - Simple MBSE process, including MDAO relationship
    - Functional Requirements Decomposition
- Package hierarchy for structuring and organizing model information
    - For example, we organized this model to include:
        - Enterprise models
        - Reference models
        - Mission models

        - System models
        - Aircraft system hierarchy
- Mission level models
    - Created these model views to set the context for the system (best practice guideline)
    - Use Case diagram for mission using (Observe, Orient, Decide, Act) in context of Find, Fix, Finish
    - Activity diagram of Mission Activity relating a Sensor Platform (UAV) and its interactions with Communication Platform(s)
- System level models
    - Illustrate the system context using a Block Definition Diagram (BDD), which shows the element (systems, actors, environment) in the Mission Domain
    - Top-level Use Case for a UAV (fly, surveillance, refuel, on-ship refueling)
    - State machine diagram of the states of a UAV, from off, taxi, takeoff, cruise, loiter, descend, hold, land, etc.
- Activity diagram of Dave Cohen's framework process
    - We expect that modeling the framework will help in supporting analysis of the challenges and gaps matrix
    - This forced use into the need to model KSA as a BDD
- Illustrated how SysML models can relate to other models using MDAO parameters and constraints to model a workflow to reflect some cross-domain analysis related to Weight, Aerodynamics, Propulsion, and Performance (e.g., vehicle range) as shown in Figure 18. This example allowed us to discuss the notional steps in MDAO (For additional details see Section 8.7):
    - A MDAO analysis is defined as a sequence of workflows (scenarios)
    - After identifying a set of inputs and outputs (parameters)
    - Define a Design of Experiments (DoE) and use analyses such as sensitivity analysis and visualizations to understand the key parameter (this scopes the problem)
    - Use Optimization using solvers with the 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
    - NOTE: Any node on an Architectural (SysML) model could map to some Physics-based model
    - Some of these architectural views from SysML models can be workflows of analysis through MDAO (using Magic Draw, and Rhapsody)
- We showed some MDAO webinars during a lunch of a working session and discussed:
    - "Part III: MDAO for Conceptual Aircraft Design at Northrup Grumman"
    - Provided links to other relevant Webinars from different contracting organization to NAVAIR
        - System Trade Studies & Design Optimization, presented by Lockheed Martin
        - Phoenix Integration (ModelCenter) & the Skunk Works presented by Boeing
        - The Role of Multi-Domain Dynamic Models for Functional Verification in MBSE
    - Link is here to more webinars [110]: http://www.phoenix-int.com/resources/webinars/on-demand-webinars.php

5.2 Multi-disciplinary Design Analysis & Optimization

Multi-disciplinary Design Analysis & Optimization (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 a 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.

More specific objectives include:

- 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 requests for proposals (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 multi-disciplinary models of a UAV, including analyses of the geometry, structure, aerodynamics, propulsion, and performance capabilities, to be used as an example case
- Explore using systems representations (e.g., SysML) to map inputs (parameters and variables) and outputs (objectives, constraints, intermediate parameters) among the individual models
- Conduct trade studies on the UAV 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
- Work with NAVAIR project leads 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 (1) requirements setting for RFP or CONOPS, and (2) value-driven design

Further, while the initial research exams the use of MDAO at the systems level, it is applicable to use at the mission and subsystem levels.

5.2.1 MDAO Methods

One of the objectives of this project is to leverage the most powerful tools that are often used by industry as well as government organization. There a number of tools that support MDAO, including both open source and commercial (non-exhaustive):

- DAKOTA [123], OpenMDAO, iSight, ModelCenter [110], modeFRONTIER, FIDO, IMAGE, CONSOL-OPTCAD
- Sometimes referred to as Process Integration and Design Optimization (PIDO)
- Modeling and simulation inventory analysis identified 348, most of these were for mission-level simulation, but it was believed that there are many more used by the competencies; these tools may also be wrapped within and MDAO workflow

We have secured academic licenses to Phoenix Integration's ModelCenter [110]. We then want to investigate the methods for apply such tools, and also identify the 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 scope that will be used in set 1.d
- 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

A number of methods can be applied to formulate multi-disciplinary 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.

5.2.2 INTEGRATIONS WITH RELATED TASKS

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 from easily assessing how changing one design variable affects the outputs from different models or simulations. Through this project, and the creation of an MCE architecture that follows a SST and a consistent ontology, we will be able to leverage MDAO techniques in the design decision-making process. From an academic perspective, the major contributions will be to build a roadmap for integrating MDAO practices into complex existing and new organizational structures.

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.

5.2.3 MDAO UAV Example

NAVAIR sponsors were present at a demonstration of a MDAO workflow shown in Figure 18 that was developed using ModelCenter. The demonstration covered several aspects of the objectives discussed in this section, including:

- Describe and execute a workflow analysis of UAV 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

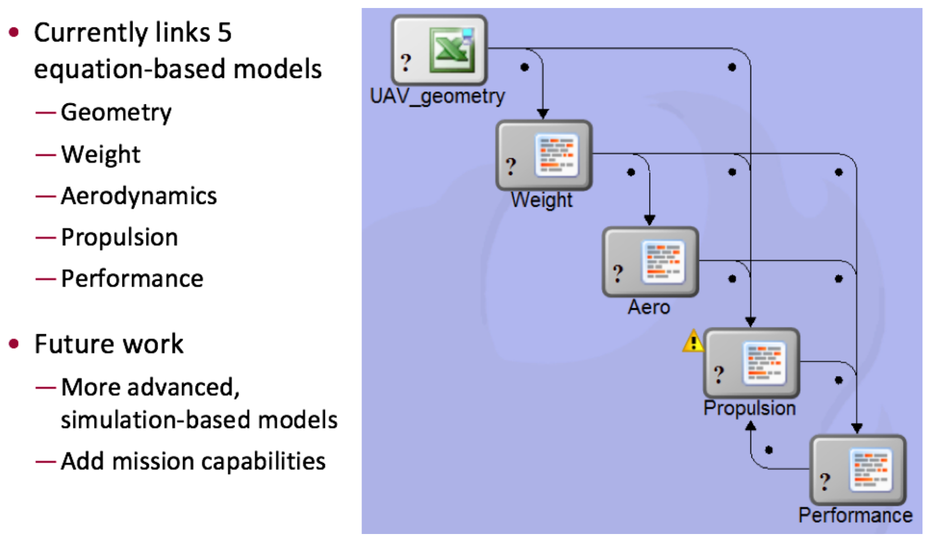


Figure 18. MDAO Example Workflow

As shown in Figure 19, 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 20 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.

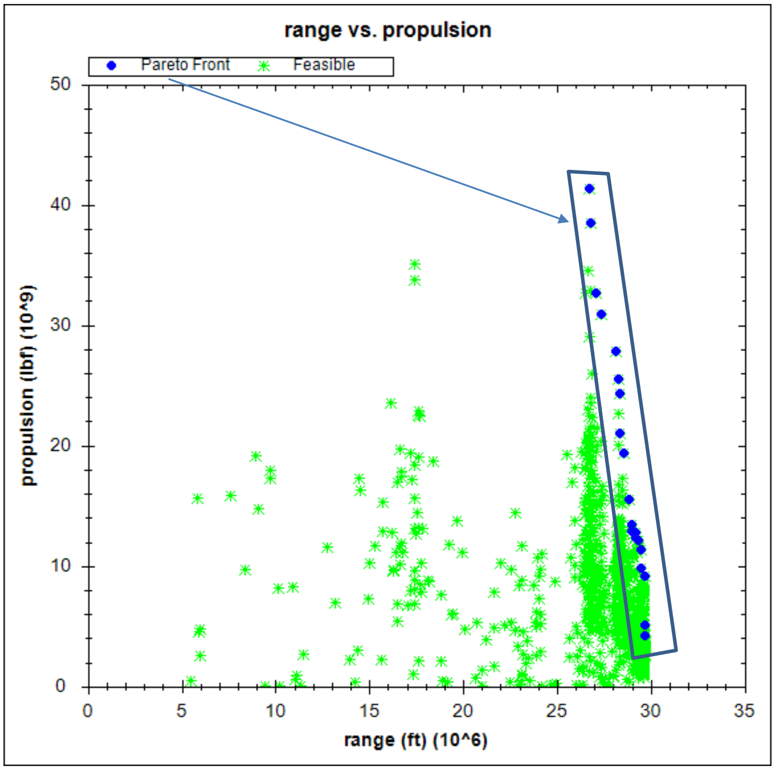


Figure 19. Pareto frontier (Pareto optimal set) Shows Trade-off Between Range and Propulsion

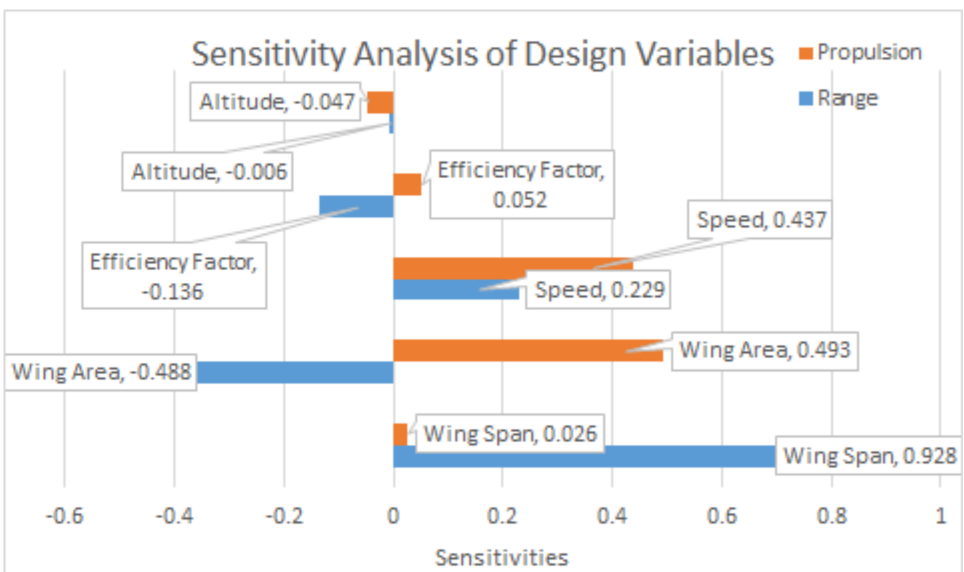


Figure 20. Sensitivity of Objectives to Design Variables

5.3 MODELING EXAMPLES USING SYSML

This section provides some examples of SysML models shown during a number of different working sessions. SysML models can be used to describe both mission, system and process models.

5.3.1 TABLE OF CONTENTS

We created a Content Diagram as a type of table of contents where we put hyperlinks to the different diagrams. This section shows some of the diagrams in each of these groups.

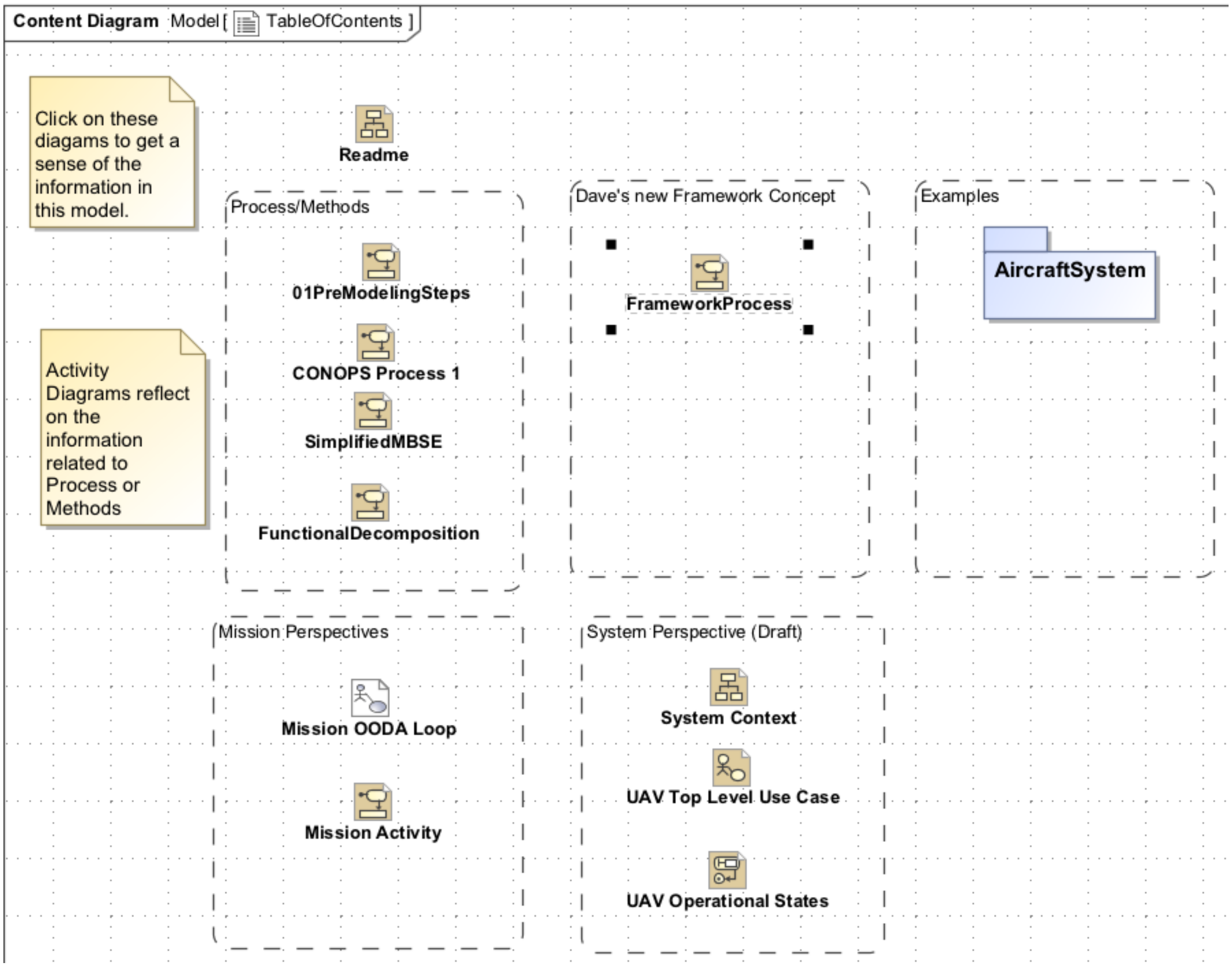


Figure 21. Table of Contents to Models and Diagrams

5.3.2 PROCESS/METHODS

We created a few SysML activity diagrams to describe different process/methods models. Ideally, these types of models would be reference models that establish a best practice approach for starting different types of models. These guidelines are shown in an activity diagram called pre-modeling guidelines. Such guidelines as shown in Figure 22, include defining the structure of the overall project, naming conventions, colors. This picture also shows the different types of SysML diagrams. In the remainder of this section we will show a few diagram types. The pre-modeling guidelines are defined in an activity diagram, which shows the actions, control flows, and can show data flows. The dark bar can represent a fork (to distribute asynchronous processes) or a join to synchronize distributed processes. One of the first things a team needs to decide is on the structure of the overarching model. An example is shown in the Containment view as shown in Figure 23. We used the MagicDraw tool, but SysML is a standard modeling language supported by many different tools.

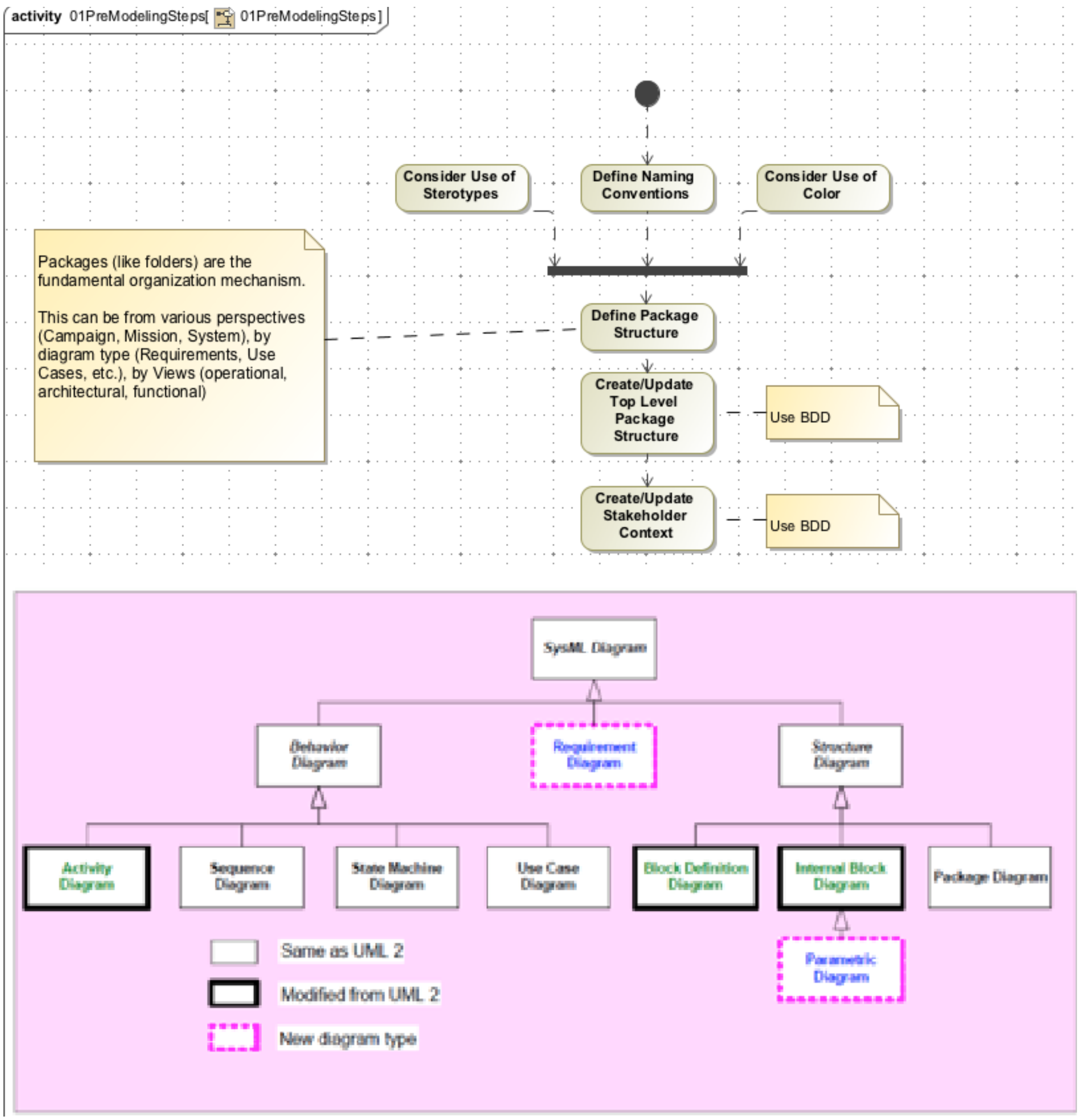


Figure 22. Pre-modeling Guidelines

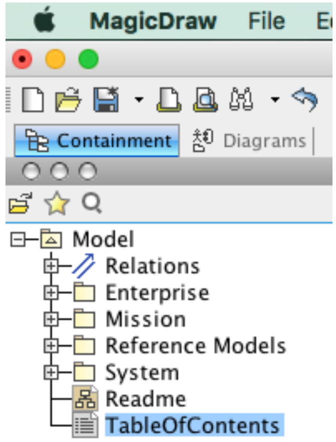


Figure 23. Containment Structure

Figure 24 shows an activity diagram that was developed under the Stevens Institute of Technology SYS-750 Advanced Architecture Course. This activity diagram illustrates an overarching, but simplified MBSE process. This activity diagram shows the control flow (without feedback), but also the data flow to the objects colored in blue. These objects highlight the types of diagrams that might be used to capture the information in the various steps of the process. These activities can be further decomposed to describe additional details of the process steps and other information that is used or produced.

Note also that there is a Perform MDAO activity, colored orange Figure 24. This type of analysis is performed by other types of modeling tools such as ModelCenter as discussed in Section 5.2. These types of activity diagrams that represent processes or methods are not representing the target system, but can be characterized as reference models used as part of the Enterprise that includes what we have referred to in our prior technical reports as the “Designing System” [21].

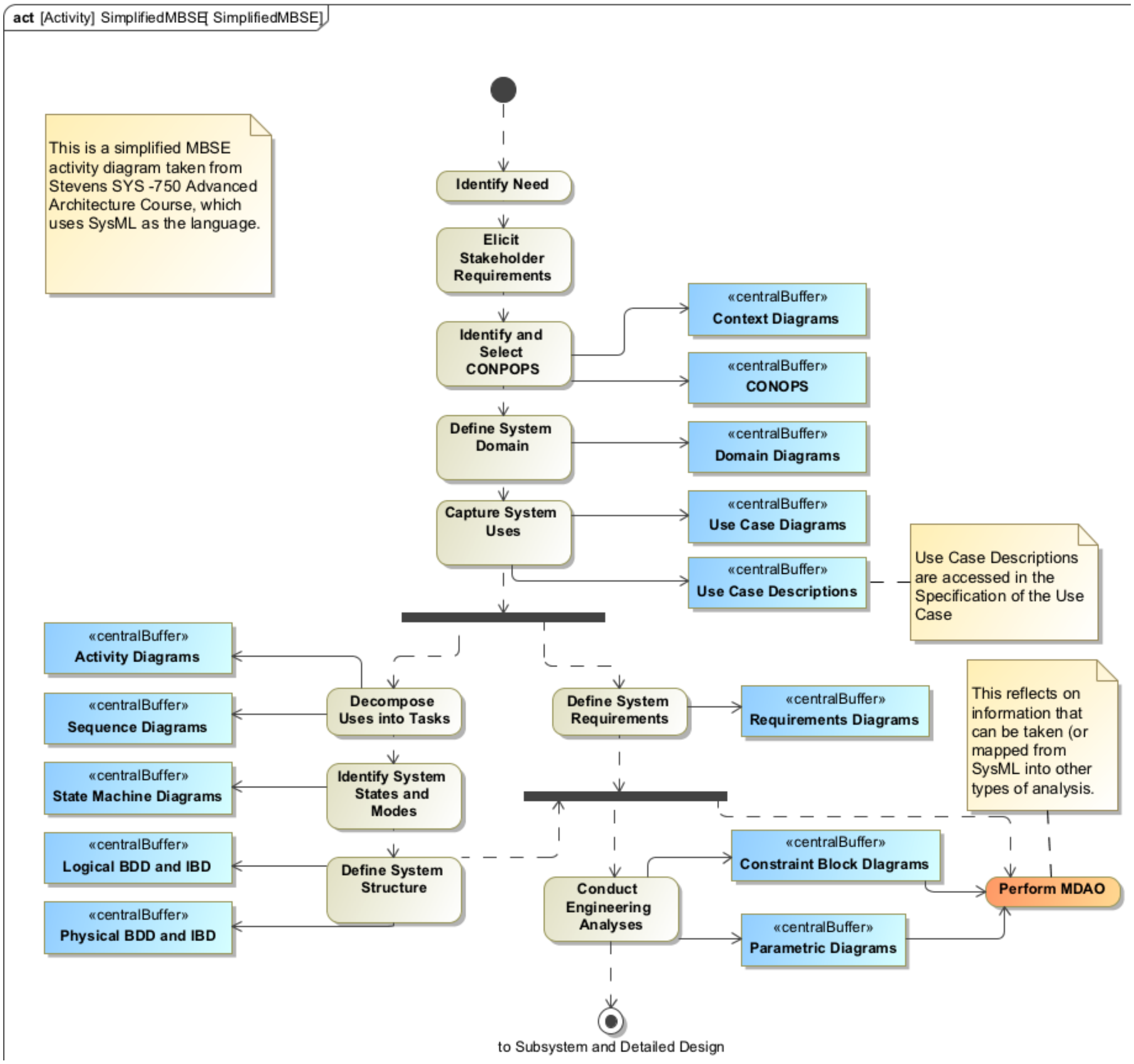


Figure 24. Simple MBSE Activity Diagram with Link to MDAO

5.3.3 Package Hierarchy for Structuring and Organizing Model Information

We showed an example of a package structure for organizing the different perspective (enterprise, mission, system), but we can also use a similar concept to organize the actual system structure, from either a logical or physical perspective, see Figure 25. This is a good decision to make by the team as early as possible.

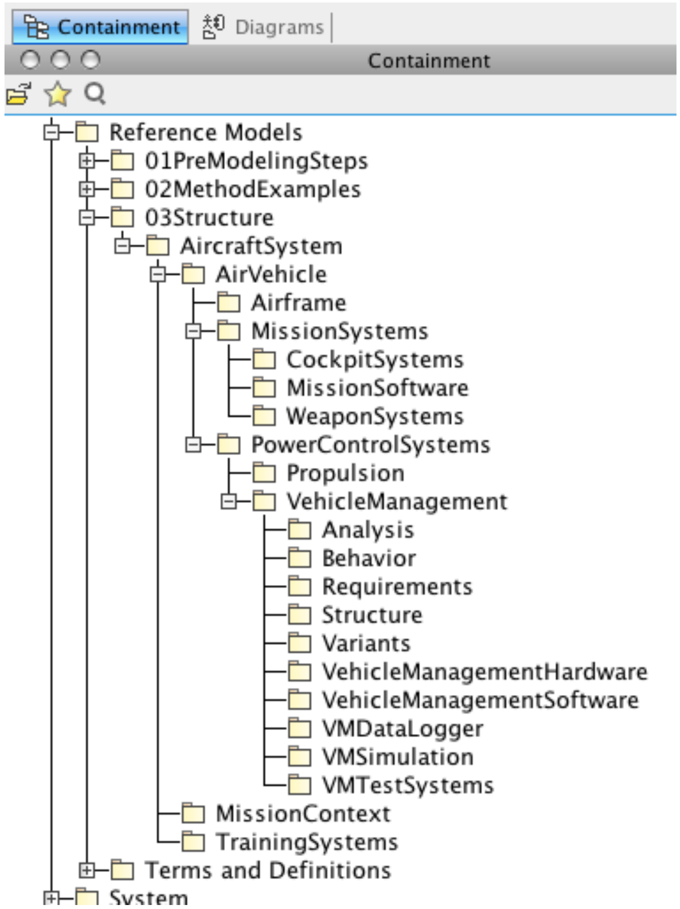


Figure 25. Model Organization

5.3.4 MISSION LEVEL MODELS

Mission-level models set the context for the "system of interest," which is a typical best practice. From a military perspective, we included a Use Case diagram for mission using (Observe, Orient, Decide, Act) in context of Find, Fix, Finish. This could be a reusable Use Case, or reference model where the specific textual elements of the use case could be tailored to a specific mission as shown in Figure 27.

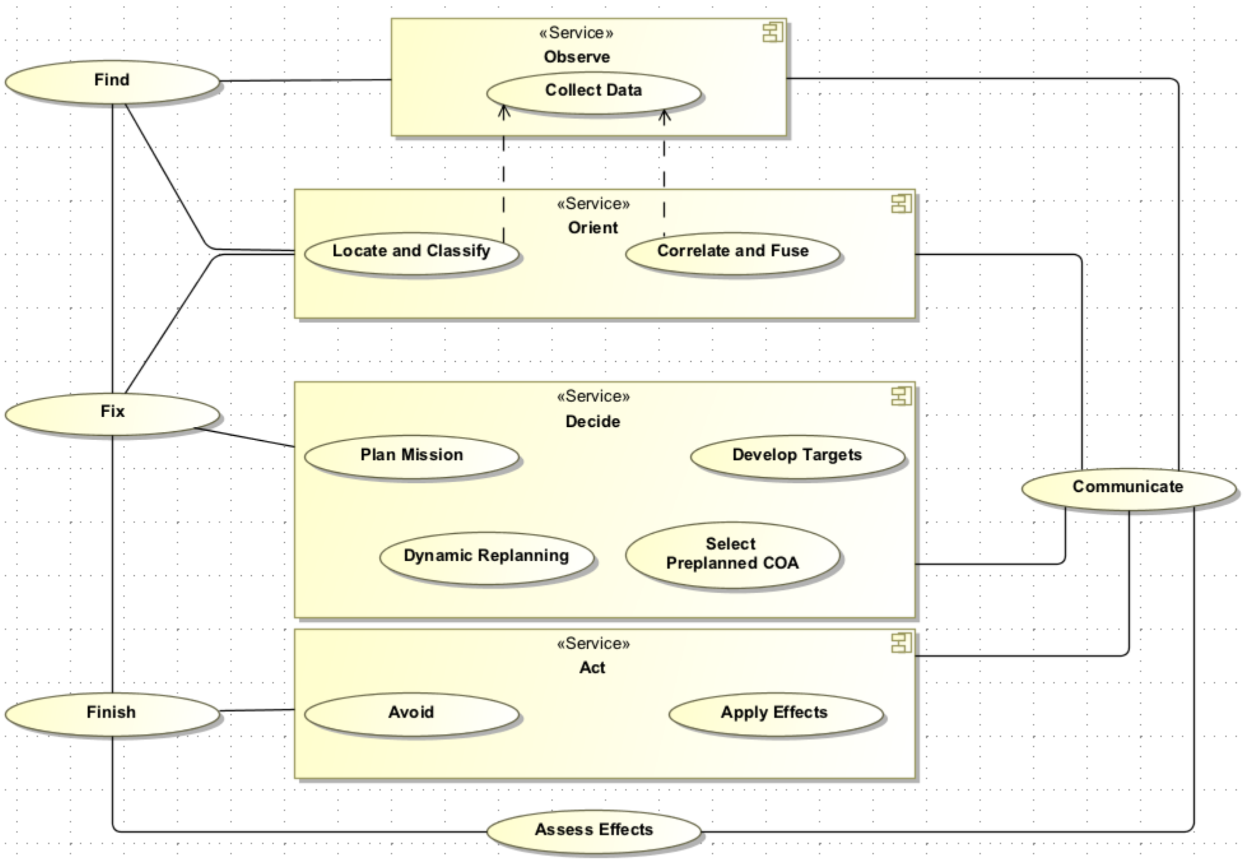


Figure 26. High-Level Mission Use Case

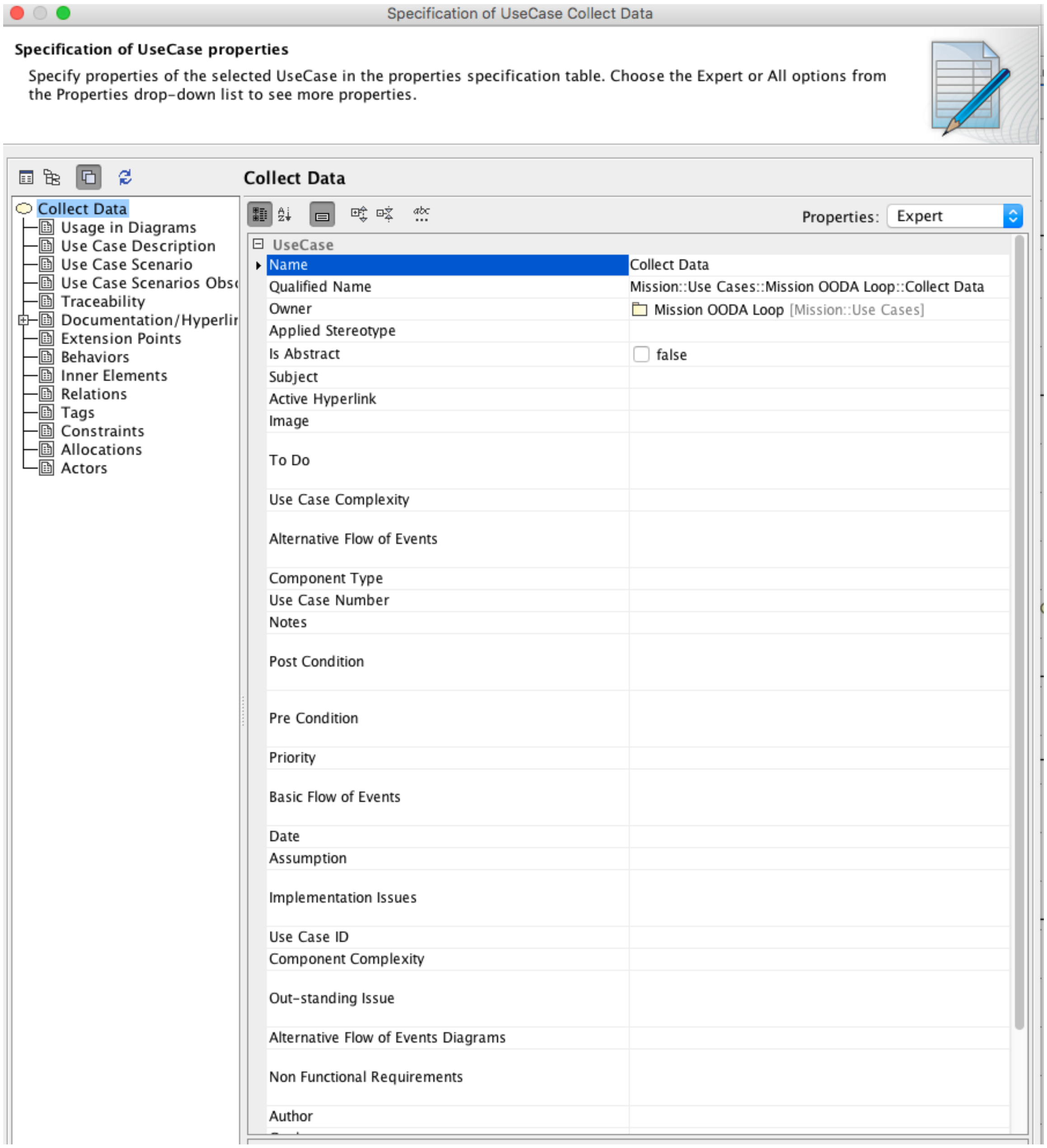


Figure 27. Textual Element of the Use Case

The system domain shows the various elements associated with surveillance using a Block Definition Diagram (BDD), as shown in Figure 28,. This shows the context of the higher-level system of system, of which the UAV is one system.

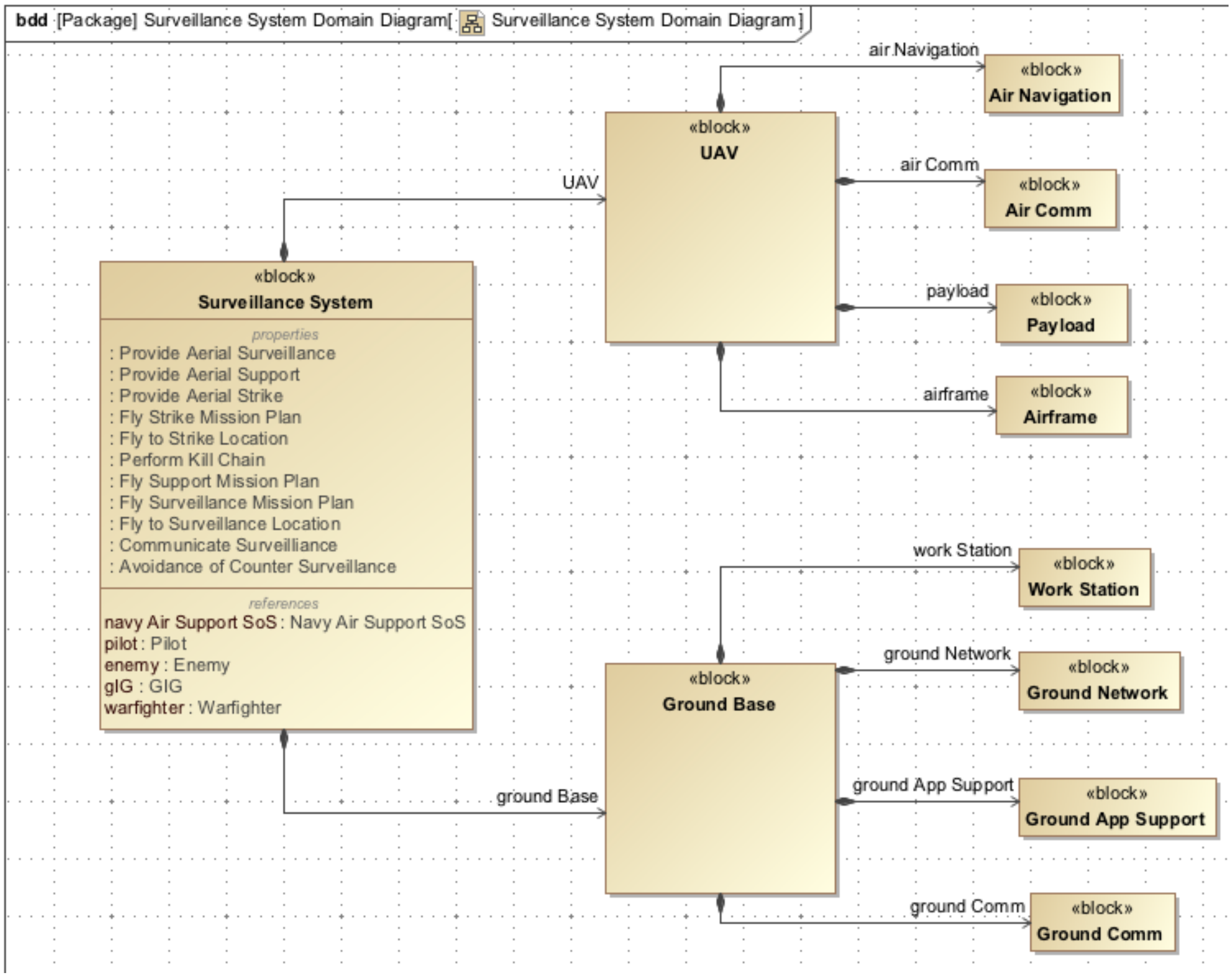


Figure 28. Surveillance System Domain Diagram

We also provided an example of Activity diagram of Mission Activity relating a Sensor Platform (UAV) and its interactions with Communication Platform(s) as shown in Figure 29 [134]. This concept is presented from a logical perspective and shows both control flow (dash lines), and data flow (solid lines); this activity diagram also shows swim lanes that illustrate the different partitioning of the activities.

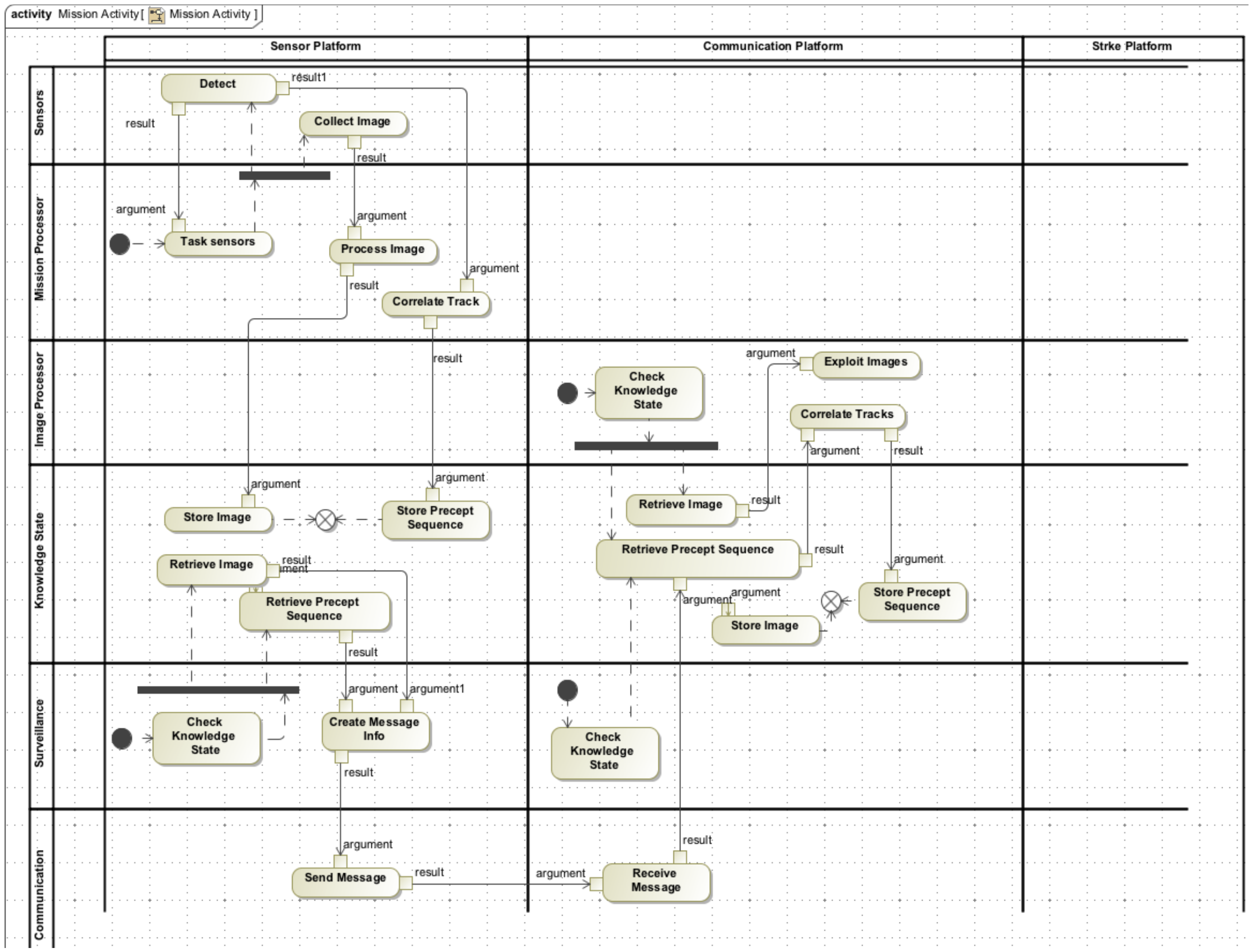


Figure 29. Mission-level Activity Diagram with Swim Lane Partitions

5.3.5 System level models

Use Cases are also a common starting point for system level operational scenarios. An example top-level Use Case for a UAV (fly, surveillance, refuel, on-ship refueling) is shown in Figure 30. Each of the use cases would typically have a structured narrative created using a template similar to Figure 27. Therefore, when we discuss using models, we do not imply that there is no textual narrative, rather the narrative is often structured and embedded within some type of modeling element.

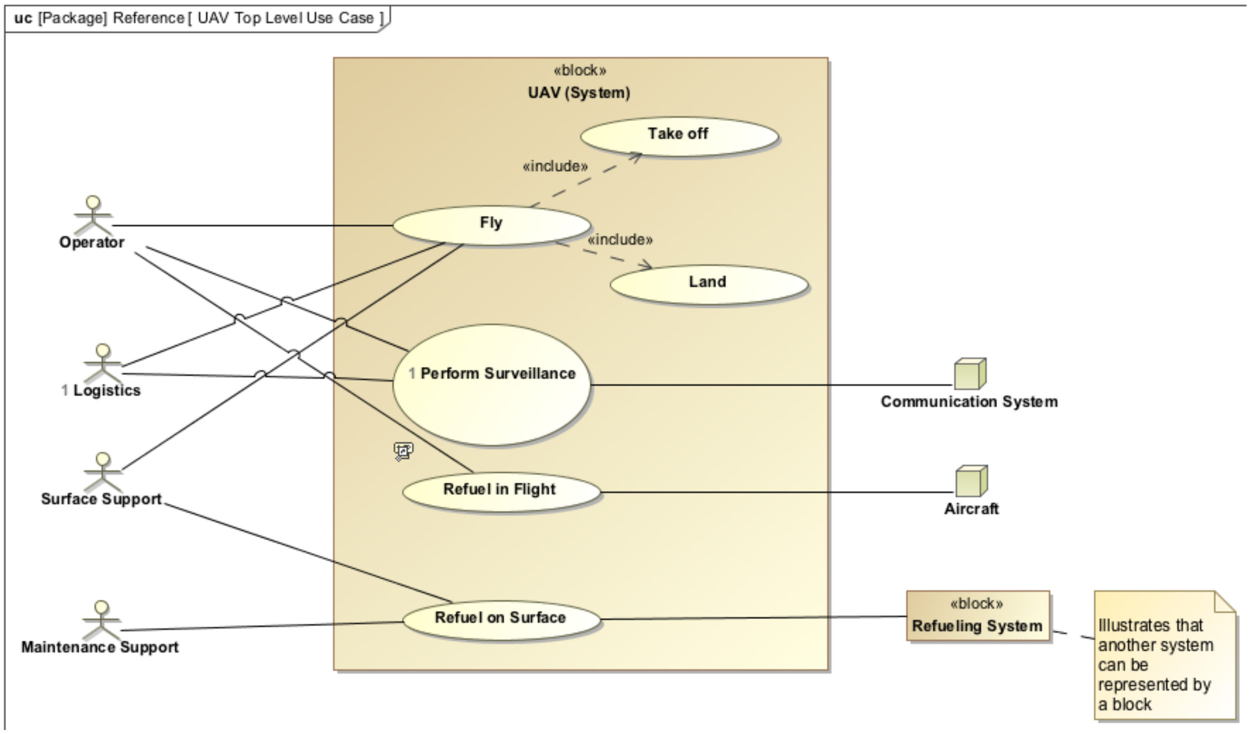


Figure 30. Generic UAV Use Case Diagram with Actors

To illustrate another type of behavioral perspective, we showed an incomplete state machine diagram of the states of a UAV, from off, parked, taxi, takeoff, cruise, loiter, descend, hold, land, etc. as shown in Figure 31.

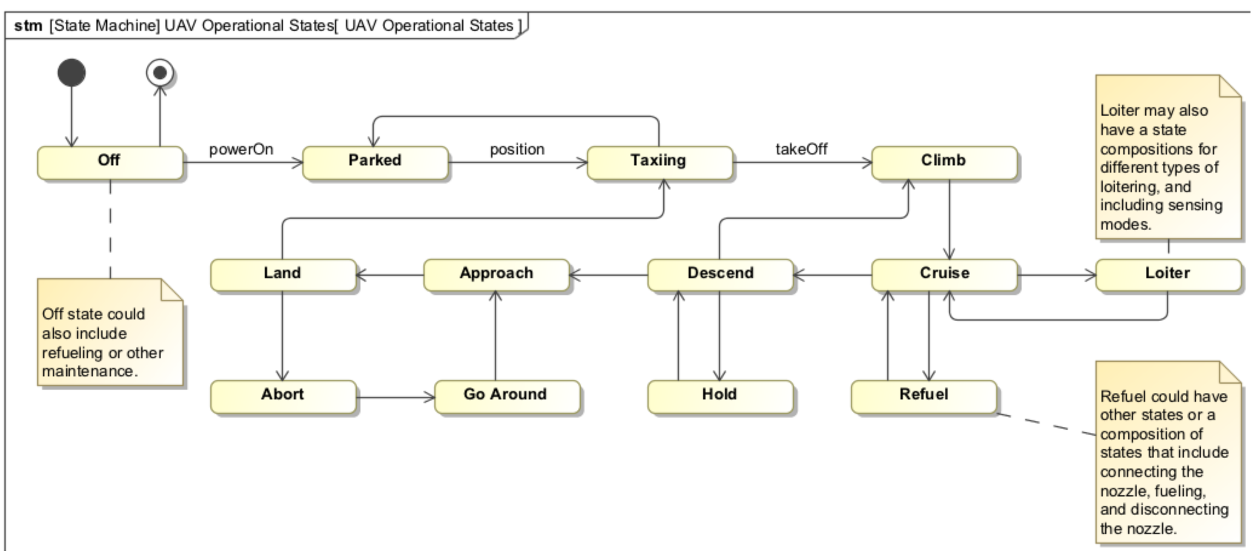


Figure 31. State Machine Diagram of Top-Level UAV Operational States.

We also have examples that are based on a product family of UAV being developed by our research collaborator Dr. Russell Peak under RT-170 that include:

- Rotor UAV 2.1 portfolio effectively completed
  - Includes optical camera option to original package delivery UAV squadron

- Includes physics calculations via SysML parametrics (par)
- Includes behavior simulation via SysML state machine (stm) / activity (act) / parametrics (par)

- Fixed-wing UAV 0.1 portfolio initiated (WIP)
  - Inspired by fixed wing surveillance.
  - Applying ~same approach as for rotor UAV portfolio

Some of the Work in Progress (WIP) elements include the system model for the Fixed-Wing Refueling UAV. These are shown below in a SysML BDD, which includes some of the subsystems of the UAV such as: propulsion, fuel, and refueling subsystems.

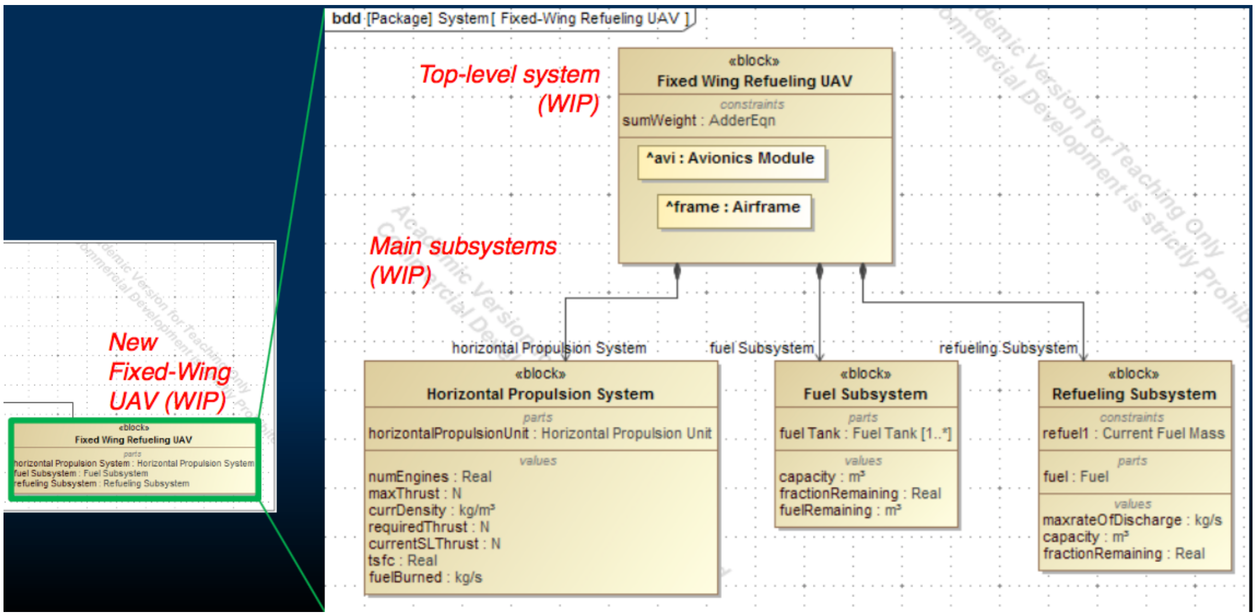


Figure 32. Fixed-Wing Refueling UAV Extension to UAV Portfolio

There are elaboration on some parameters of the fuel system as shown in Figure 33 to do some analysis on the First-Order Physics using SysML Parametrics. A parametrics diagram provides a way to describe constraints between parameters. Add-on analysis tools can then be used to verify that the constraints are satisfiable (i.e., not contradictory). This model is developed in MagicDraw and uses some automation provided by a MagicDraw plugin called the Cameo Simulation Toolkit for requirement verification as shown in Figure 34. For example, the result of pass/fail on a constraint can be traced directly back to specific requirement object in the model.

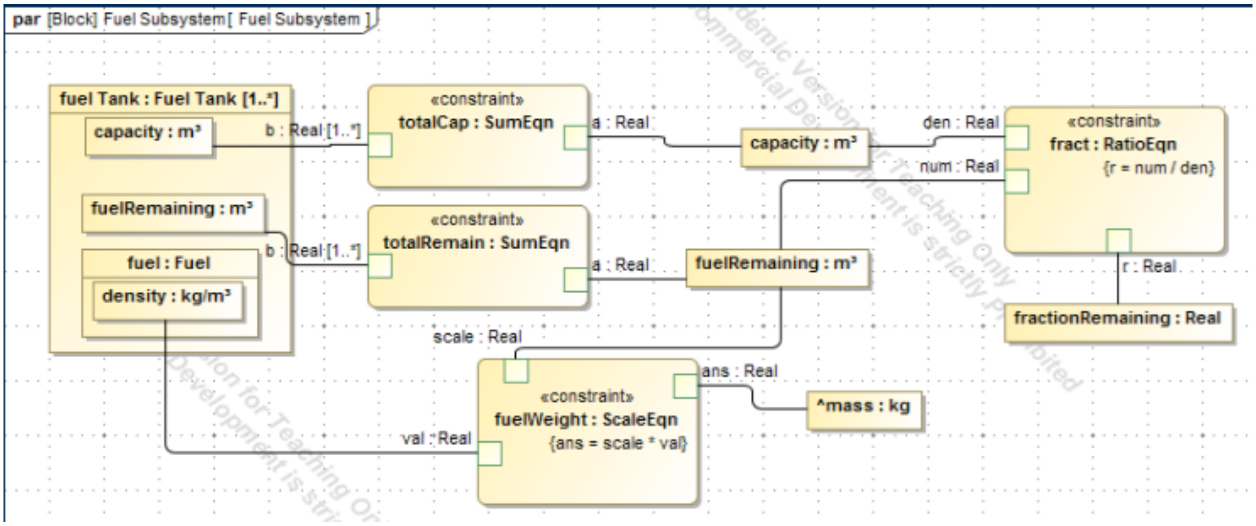


Figure 33. Parametric Diagram of Fuel System

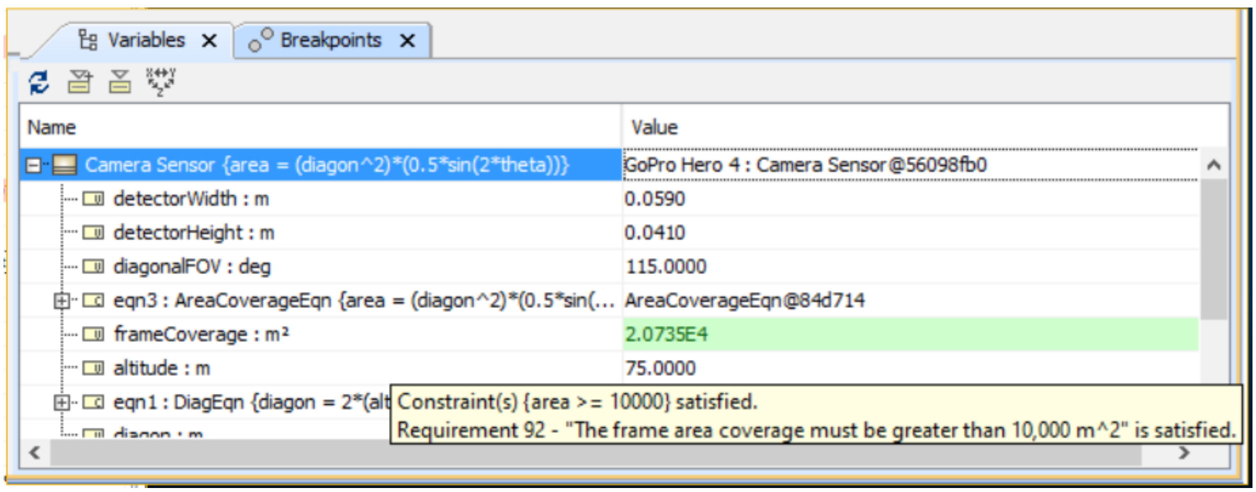


Figure 34. Cameo Simulation Toolkit Verifies Constraints Representing Numeric Requirements

There were other models presented in the various working session and the briefing material was provided to our NAVAIR sponsor.

5.3.6 Activity Diagram of Dave Cohen's Framework Process

We illustrate the generality of the SysML modeling approach by creating a model for the framework (shown in Figure 4). We expect that modeling the framework, as shown in Figure 35, will help in supporting analysis of the challenges and gaps. This forced us into the need to model KPP/KSA as a SysML Block Definition Diagram (BDD).

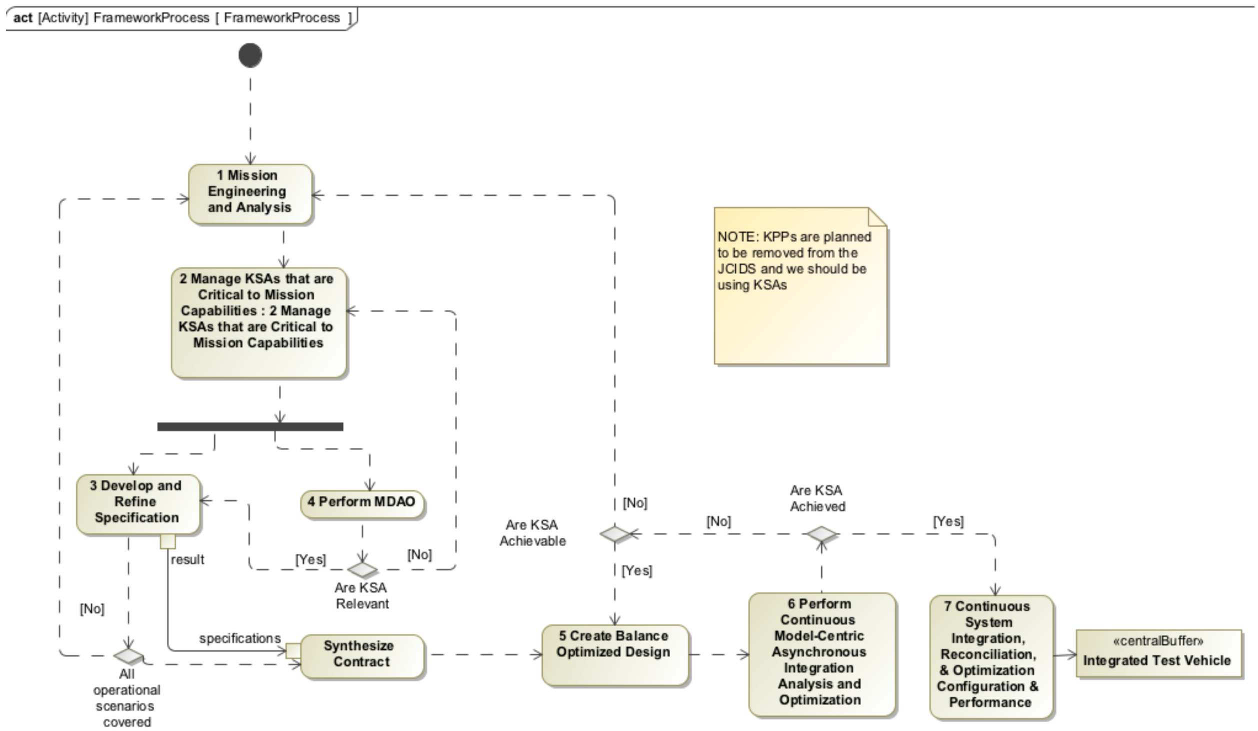


Figure 35. Draft Activity Diagram of SE Transformation Framework

5.4 VIEWS AND VIEWPOINTS

The working session had a section on explaining various different methods for doing system engineering modeling. This also relates to the concept of View and Viewpoints in the SST [51]. Each Viewpoint, as shown in Figure 36, is a specification of conventions and rules for constructing and using a View for purposes of addressing a set of stakeholder concerns, which is based on a standard that relates to:

- Purpose of the viewpoint
- Stakeholder that are likely to use the viewpoint
- Concern of the stakeholder
- Method to develop a Model using a Modeling Language
- Analysis that can be performed with the models

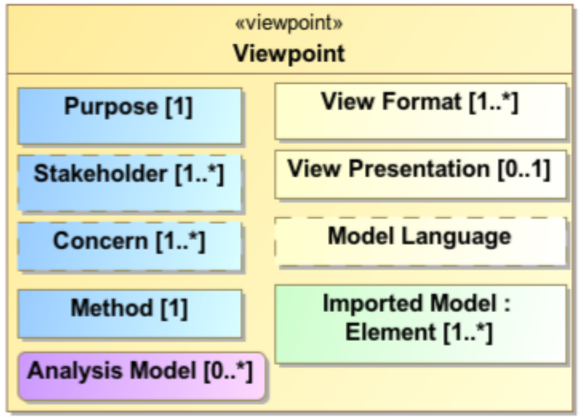


Figure 36. Viewpoint

5.5 CAPABILITY AND OPERATIONAL-LEVEL MODELING GUIDELINES

NAVAIR has an architecture group that constructs models associated with the Capability Description Document. They have defined guideline to provide some methodological guidance in constructing DoDAF models. Notionally, the guidelines cover: capabilities view, operational views and system views. These are generalized as architecture models.

- The "architectural modelers" who create DoDAF based on these guidelines use the UML Integrated Architecture (UPIA) profile; they have some notional "ontologies"
  - Integrated Operational Model Ontology
    - Capability Ontology (WP 1010-0000-01)
    - Operational Ontology (WP 1020-0000-01)
  - Integrated System Interface Model Ontology
  - System Interface Ontology (WP 1030-0000-02)
  - Diagram Ontology (WP 1060-0000-01)
  - Operational Diagram Ontology
    - OV-5a Use Case
    - OV-5b Activity Diagram
    - OV-6c Event Trace
  - System Diagram Ontology
    - SV-4a Use Case
    - SV-4b Activity Diagram
    - SV-10c Event Trace

Currently, these efforts are fundamentally limited to the net-ready aspects of capabilities, governing communications and interoperability. It is acknowledged that extending this to logical and functional views is desirable for the SET.

5.6 NAVAIR STUDY VIEWS

Study views were created to address a number of challenges at the Program of Record (POR) level and in creating DoDAF requirements, however there does not appear to be extensive knowledge about their use. The study view concept builds on lessons learned from creating early DoDAF models; analyses have uncovered that interoperating at the lowest (data) levels is insufficient for scenarios, and scenarios require behaviors, which is missing at the data level. DoDAF does not accommodate other scenario requirements (e.g., conditions, assumptions) very well, and is insufficient to fully characterize the dynamics needed for analysis.

A mission-level SoS analysis begins with formalization using Study Views, as reflected in Figure 37 [133], which has modeling and simulation dynamic views and visualization. Study views provide structure and a common context that acts as a basis for framing and bounding the functional decomposition of DoDAF products. Study views formalize the need and intent, provide a situational context and influencing factors to frame and bound the functions and activities of the mission and scenarios that ultimately lead into corresponding representations of the Mission and System Capabilities (i.e., the capabilities for the POR). These capability representations are further analyzed using modeling and simulation and corresponding analysis capabilities. The outputs of which are then formalized in terms of DoDAF artifacts by the NAVAIR Architecture group (see Section 5.5). This information forms the analysis boundaries for the System Capabilities information needed to define requirements for the POR.

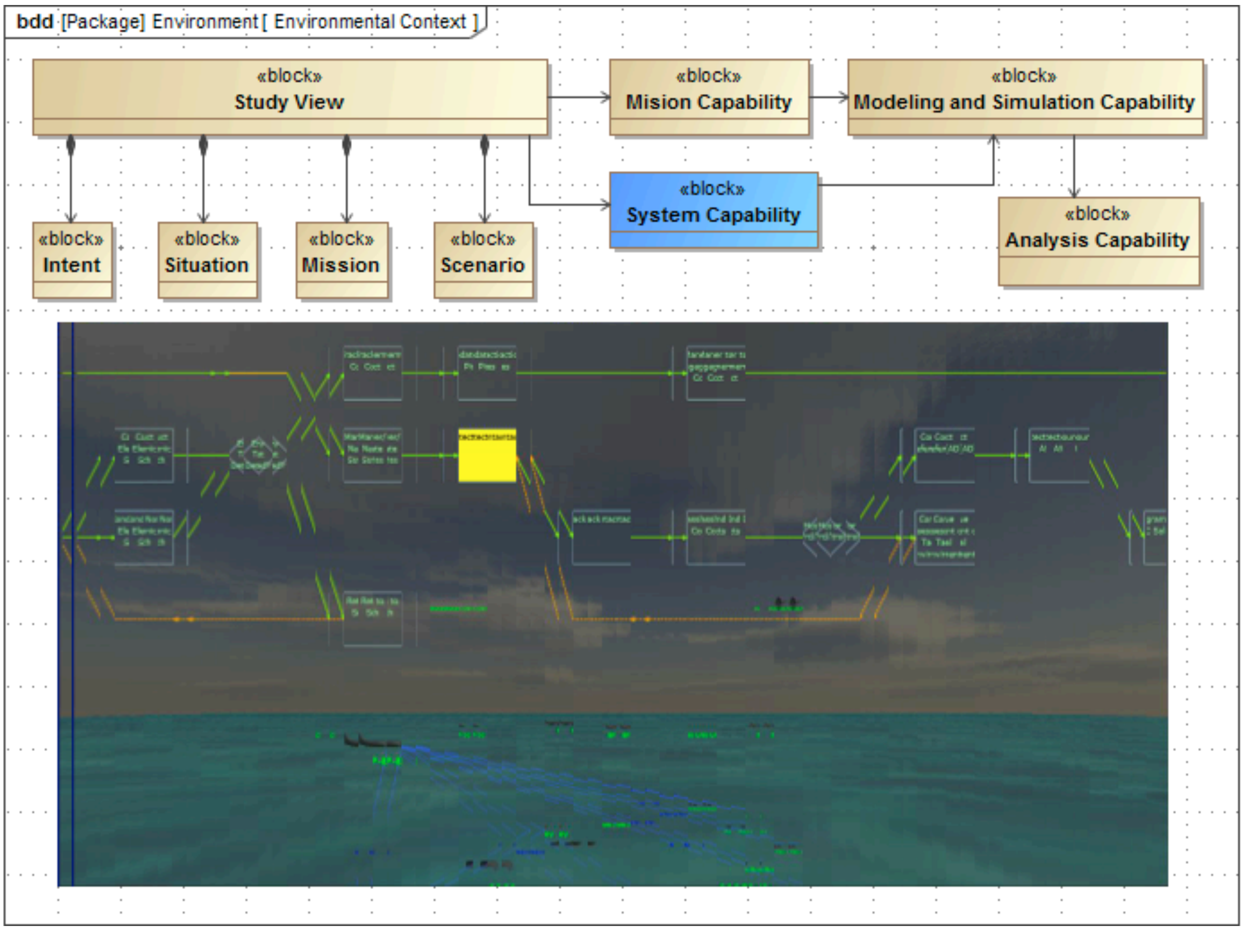


Figure 37. Mission Context for System Capability

5.7 Modeling and Methods for Uncertainty Quantification

As discussed in Section 4, Sandia National Laboratory discussed some advanced methods for supporting uncertainty quantification (UQ) to enable risk-informed decision-making [98]. 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 Dakota, and the need and challenge of Model Validation and Simulation Qualification [120]. 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.

5.7.1 Dakota Sensitivity Analysis and Uncertainty Quantification (UQ)

The Dakota framework supports optimization and uncertainty analysis [123]. There is significant demand at Sandia for risk-informed decision-making using credible modeling and simulation:

- Predictive simulations: verified, validated for application domain of interest
- Quantified margins and uncertainties: random variability effect is understood, best estimate with uncertainty prediction for decision-making
- Especially important to respond to **shift from test-based** to modeling and simulation-based design and certification
  - This gets to an important point about how to use models as opposed to testing, which is critical for NAVAIR's objective to rapidly and continuously "cross the virtual V"

The HPC capabilities comes into play as they are built to take advantage of the HPC environment and can be combined with predictive computational models, enabled by environment and culture that focuses on theory and experimentation to help:

- Predict, analyze scenarios, including in **untestable regimes**
- Assess risk and suitability
- Design through virtual prototyping
- Generate or test theories
- Guide physical experiments

Dakota is referred to as a framework, because it is a collection of algorithms supporting various types of integration through programmatic (scripting) interfaces; this is representative of the concept of model-centric engineering, see Figure 38. It automates typical "parameter variation" studies to support various advanced methods and a generic interface to simulations/code, enabling QMU and design with simulations in a manner analogous to experiment-based physical design/test cycles to:

- Enhances understanding of risk by quantifying margins and uncertainties
- Improves products through simulation-based design
- Assesses simulation credibility through verification and validation
- Answer questions:
  - Which are crucial factors/parameters, how do they affect key metrics? (sensitivity)
  - How safe, reliable, robust, or variable is my system?
    (quantification of margins and uncertainty: QMU, UQ)
  - What is the best performing design or control? (optimization)
  - What models and parameters best match experimental data? (calibration)

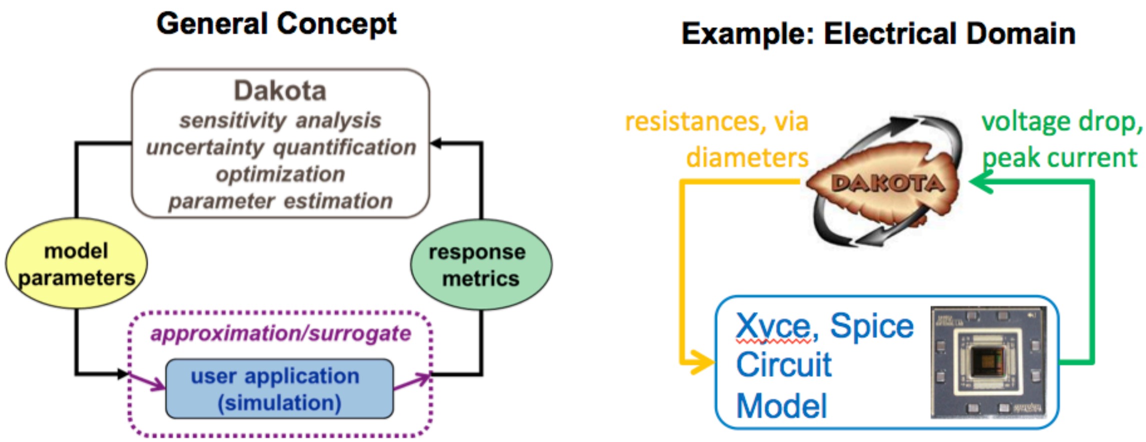


Figure 38. Dakota Framework Integration Wraps User Application

To put margins and uncertainty into context, assume that there is a device that is subject to heat, and we need assess some type of thermal uncertainty quantification. Given some results from some Design of Experiment (DoE) (also supported by Dakota) results that give a probability distribution as shown in Figure 39 [2]. The Mean of the temperature: T, to the lower bound of the threshold (e.g., 72 degrees) characterizes the Margin, and the Standard Deviation (T) characterizes the uncertainty.

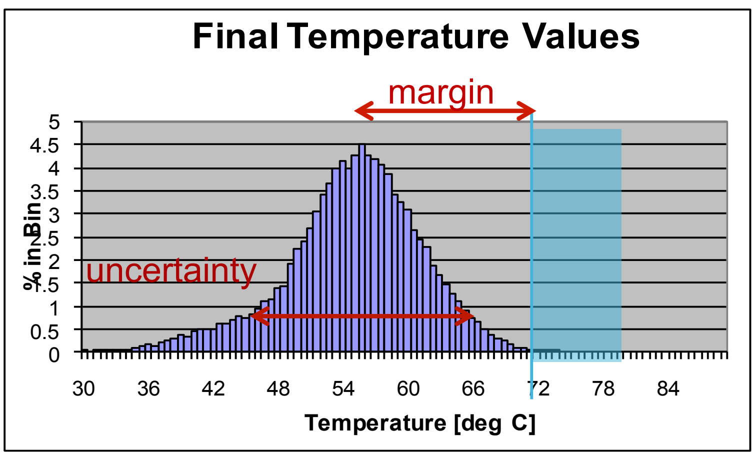


Figure 39. Example for Understanding Margins and Uncertainty

This approach and Dakota framework supports a broad set of domains, and therefore we think it can be generally applied across domain for NAVAIR, for example:

- Supports simulation areas such as: mechanics, structures, shock, fluids, electrical, radiation, bio, chemistry, climate, infrastructure
- Is best used with a goal-oriented strategy:
  - Find best performing design, scenario, or model agreement
  - Identify system designs with maximal performance
  - Determine operational settings to achieve goals
  - Minimize cost over system designs/operational settings
  - Identify best/worst case scenarios
  - Calibration: determine parameter values that maximize agreement between simulation and experiment

- Handles parallelism, which is often not feasible with commercial tools, and why HPC can play an important role
- Provides sensitivity analysis – find the most influential variables
- **Uncertainty Quantification**
  - Models inherently have uncertainty
  - Assess effect of input parameter uncertainty on model outputs
    - Determine mean or median performance of a system
    - Assess variability in model response
    - Find probability of reaching failure/success criteria (reliability)
    - Assess range/intervals of possible outcomes

5.7.2 AN OVERVIEW OF QUANTIFICATION OF MARGINS AND UNCERTAINTY

Dakota is a tool framework that can support the method of Quantification of Margins and Uncertainty (QMU). Some of the material from Sandia is categorized "Official Use Only [OUO]." We provide a summary extracted from publically available information [98].

QMU pre-dates Dakota and is not unique to Sandia as it was used at Lawrence Livermore National Laboratory and Los Alamos National Laboratory, with the original focus of the methodology to support nuclear stockpile decision-making[6]. QMU is a physics package certification methodology and although it has been around and used at Sandia dating back to 2003, and both QMU theory and implementation are still being developed/evolved [98]. We believe the methodology has more general use than just physics package certification.

QMU applies to the lifecycle of the entire weapon, with focus on:

- Specification of performance characteristics and their thresholds
  - Performance is the ability of system/component to provide the proper function (e.g., timing, output, response to different environments) when exposed to the sequence of design environments and inputs
- Identification and quantification of performance margins
  - A performance margin is the difference between the required performance of a system and the demonstrated performance of a system, with a positive margin indicating that the expected performance exceeds the required performance
- Quantification of uncertainty in the performance thresholds and the performance margins as well as in the larger framework of the decisions being contemplated

There are two types of uncertainty that are generally discussed that account for, quantify, and aggregate within QMU:

- Aleatory uncertainty (variability)
  - Variability in manufacturing processes, material composition, test conditions, and environmental factors, which lead to variability in component or system performance
- Epistemic uncertainty (lack of knowledge)
  - Models form uncertainty, both known and unknown unknowns in scenarios, and limited or poor-quality physical test data

[6] The Comprehensive Nuclear Test Ban Treaty ends full-scale nuclear weapons testing in the U.S. President Bill Clinton at the United Nations, September 24, 1996

The statistical tolerance interval methodology is an approach to quantification of margins and uncertainties for physical simulation data. There is also probability of frequency approach, commonly used in computational simulation QMU applications [98], which:

- Extends the "k-factor" QMU methodology for physical simulation data
  - k-factor, in general, is defined as margin divided by uncertainty (M/U)
    - Margin (M): difference between the best estimate and the **threshold** for a given metric
    - Uncertainty (U): the range of potential values around a best estimate of a particular metric or threshold
  - Provides essential engineering analysis to ensure the collected data sample includes measurements that may be used to infer performance in actual use
  - It is important to understand the performance requirement to understand the performance threshold and associated uncertainty
    - Threshold: a minimum or maximum allowable value of a given metric set by the responsible Laboratory
- The new method addresses the situation where performance characteristic has shown the potential for low margin or a margin is changing (likely getting smaller or there is greater uncertainty) with age [98]
  - Notionally the margin shifts from the mean of the performance characteristic (PC) and its performance requirement (PR) to the difference between a meaningful percentile of the distribution of the performance characteristic and its performance requirement
  - Need to quantify uncertainty through the computation of a statistical confidence bound on the best estimate of the chosen percentile rather than by a sample standard deviation (as reflected in Figure 39), which does not account for sampling variability
  - This is accomplished by computing a statistical tolerance interval

We created a graphic from several publically available sources, as shown Figure 40 in order to better explain a few aspects about QMU, Dakota, epistemic and aleatory uncertainty. Typically, within the Dakota framework there is an outer loop: epistemic (interval) variables and inner loop: uncertainty quantification over aleatory (probability) variables (e.g., the probability distribution). The outer loop determines interval on statistics, (e.g., mean, variance). The inner loop uses sampling to determine the responses with respect to the aleatory variables. This information can be used to understand the epistemic and aleatory uncertainties, relative to the Lower Performance Requirement (LPR).

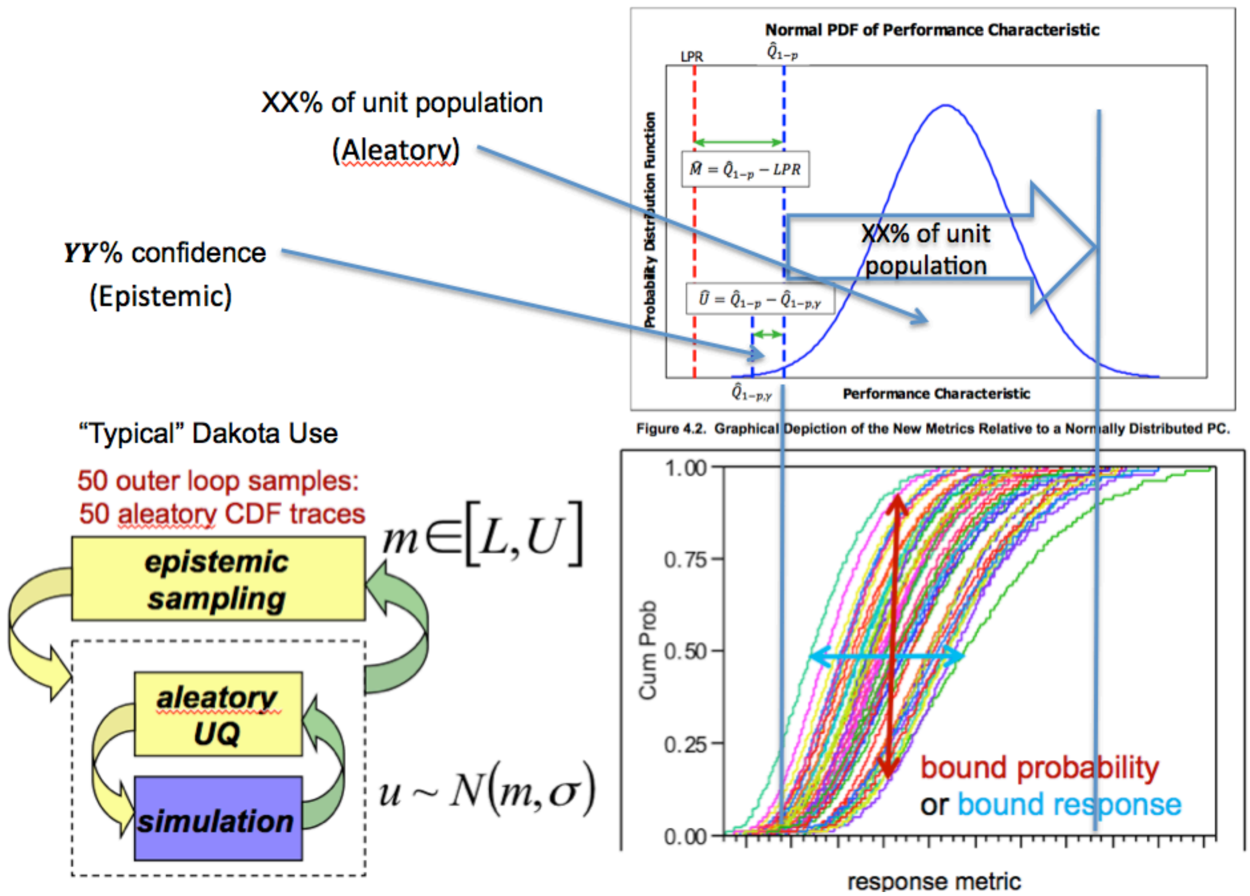


Figure 40. Pulling Together Concept Associated with QMU

The information is relevant to the risk framework as it provides evidence about methodologies and tools to deal with several of the topics. QMU and Dakota are still evolving, and there are a number of challenges:

- How do we ensure that we use the right "data" as inputs?
- How to roll up to the system level?
- Model validation and simulation qualification

5.8 Modeling Methods for Risk

The risk modeling and analysis methods addresses potential errors and uncertainties in the overuse of limited data. These types of models capture and embed knowledge associated with expert judgment, historical evidence and rules of thumbs that are used in the decision-making process. Alternative methods help deal with these type of issues. This particular example uses a Bayesian model [117].

5.8.1 Predictive Models for Risk

There are situations where we do not have good historical quantitative data and we often use expert judgment. This section discusses a predictive modeling approach when risk involves subjective information, small data sets, and "dirty" data [82].

The SERC team has developed and used models in the prediction of risk, and plans to use predictive analytic models to support risk identification and management. More generally we can use models to provide risk quantification for almost all types of decisions that are made by stakeholders (e.g., model-based reviews) [116][117]. As an example, we created a Bayesian model using factors derived from the Airworthiness standard MIL-HDBK-516B [53] as shown in Figure 41. This is conceptually similar to the approach we are using on an FAA NextGen research task for collaborative risk-informed decision-making [17] [18] [19]. The key characteristics of the approach are they ensure that all factors are considered in the decision-making process, and that all classes of stakeholders are adequately represented in the decision-making process. A systematic and comprehensive treatment of all relevant factors provides better risk identification.

We used this model and an example from a true story related to a C130 Weapon Delivery system to illustrate the concept. While this model is notional at this time, this example started a discussion with the team about how stochastic (probabilistic) models can play an important part of the Vision as they formalize many aspects of the human decision making process that will be important at many gates, reviews, and decision points of the Vision concept. Each factor covers a specific aspect of airworthiness, to ensure that all possible uncertainties and risk are considered in the quantification of risk. The risk index is a probability distribution, where for example, the mean can map to quantities in a risk matrix.

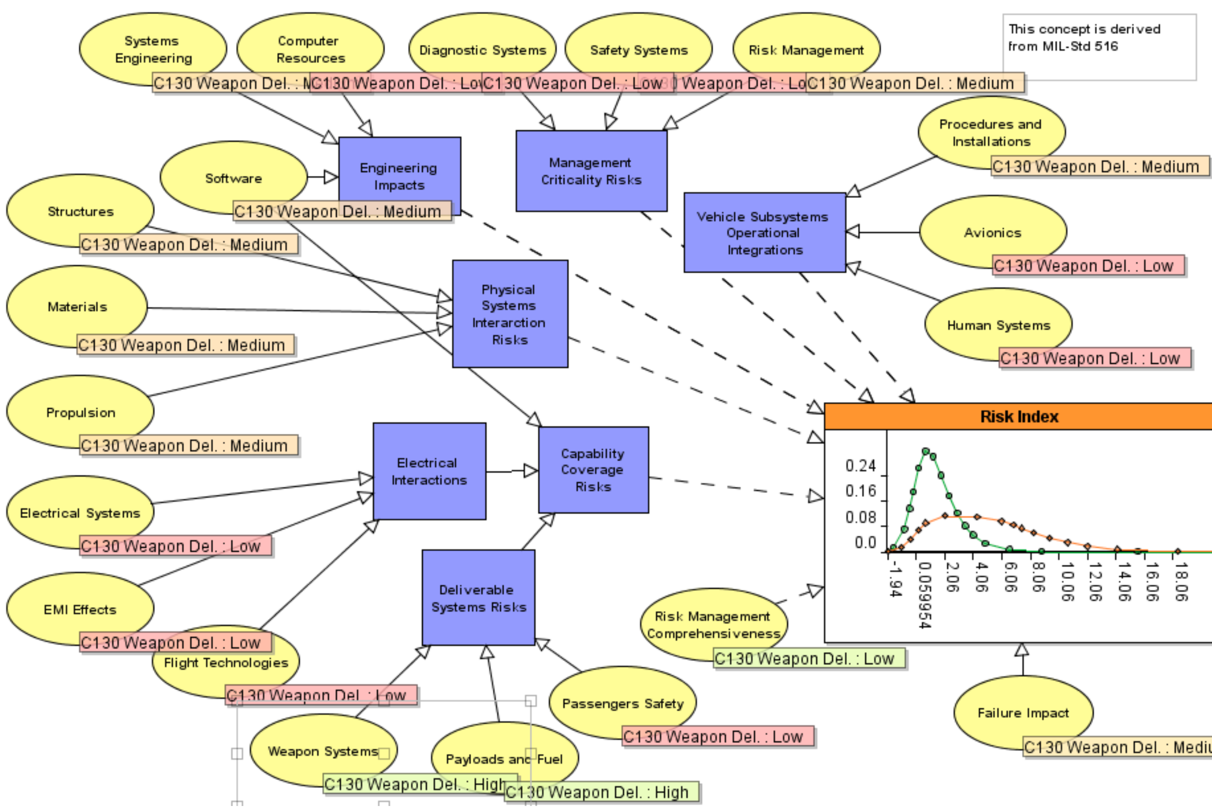


Figure 41. Bayesian Model Derived from Airworthiness Factors

5.9 CONTROLLED NATURAL LANGUAGE REQUIREMENTS INFORMATION

We acknowledge that there may not be value in modeling everything, and believe a risk-driven approach to modeling should be considered. In addition, if the concepts associated with the vision are valid, subject matter experts using a rich web view (see in Figure 10) may want to supplement models with other types of constraints. We discussed in working session research into Controlled Natural Language (CNL) Requirements and ontology-driven Natural Language Processing of requirements [5]. The fundamental premise is that we can structure textual-based requirements that we can then use automated means to formalize the requirements for analysis of consistency and completeness in the context of an ontology; there have been a number of different research efforts that have demonstrated the successful transformations of CNL requirements into an analyzable form. In addition, we also believe that while we will transition to the use of models, there will always be subject matter experts that will augment the representation from models with constraints using some form of textual-based specification. Note also, that in our industry visits there were two organizations that explicitly discussed requirement generation from models, discussed as part of the DARPA META project, and has been discussed by the Engineered Resilient System research.

- Purpose for CNL
  - Constrains the way requirement statements are constructed
  - Supports tool-based analysis
  - Improves consistency
  - Allows for template-based generation of formalized and analyzed requirements
  - Can integrate with Rich Modeling in SST
- Approach example – used by both Lockheed Martin C5 (and presented in open forum)
  - Goal: specify the behavior of the outputs in terms of the inputs
  - Use limited set of action verbs combined with structured, repeatable phrasing (syntax) for requirements, and improve understanding between the specifier and developer/reviewer
    - Eliminates confusion caused by multiple terms used for the same purpose
    - Examples: derive vs. compute vs. calculate vs. determine vs. process …
    - All of these essentially mean “execute the logical/algorithmic steps to set the output based on the input(s).”
- This provides a pattern for analysis and development of requirements
  - **Provide** requirements define the outputs
  - **Derive** requirements specify the algorithms for producing the terms which are output
  - **Acquire** & **Validate** requirements identify the input signals needed to derive the terms
    - Definition of action verbs helps ensure all issues get addressed
    - Validation of Input
    - Error Handling
    - Source/Destination Specification
- Example
  - DATA ACQUISITION:
    - Mission Processing System shall acquire <alias>.
  - DATA VALIDATION:
    - Mission Processing System shall perform data validation on <alias> per Table <table-id>.
    - Mission Processing System shall set <validity_alias> to <enumeration> when <all|any> respective data validation checks in Table <table-id> <pass|fail>.
- Has been developed using a spreadsheet to control structure, verbs, etc.

5.10 CROSS-DOMAIN INTEGRATION AND NATURAL LANGUAGE PROCESS OF REQUIREMENTS USING ONTOLOGIES

Dr. Mark Austin and Dr. Leonard Petnga from University of Maryland (UMD) joined the SERC research team. Mark discussed various applications for using “Semantic-driven Modeling and Reasoning for Systems Engineering Transformation.”

We have discussed the use of information models and ontologies, and more specifically the Web Ontology Language (OWL), which is a key standard language underlying semantic web technologies.

While it may not be completely apparent how semantic web technologies contributes to MCE, the International Council on Systems Engineering (INCOSE) Model Based System Engineering (MBSE) Roadmap identifies both ontologies as a building block for distributed repositories for crossing multiple domain. We very much believe these are critical and underlie the STT concept. Simplistically, an ontology in OWL is a type of evolvable schema, and we want to define the various domains relevant to NAVAIR and ensure we can relate information cross those domains.

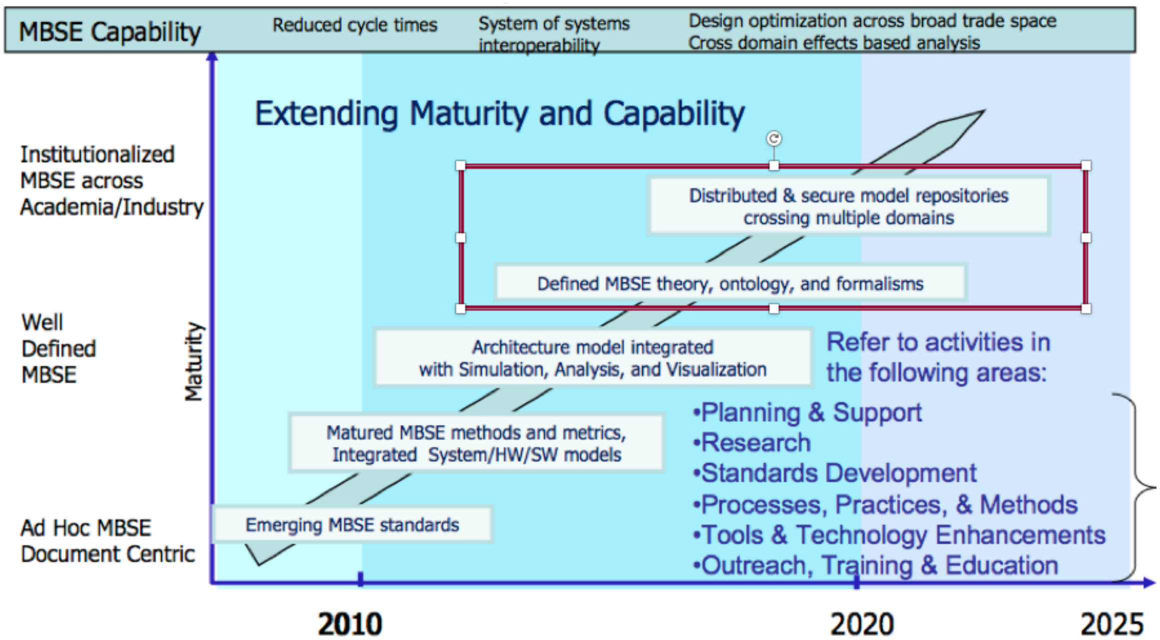


Figure 2-4: INCOSE MBSE Roadmap

Mark described a number of applications that use this underlying technology, but two resonated with the working session audience:

- An approach to Natural Language Processing (NLP) of Requirement ontologies
  - This is being advanced by a UMD masters student Ted Carney
  - Mark Austin plans to continue this research beyond that of Ted's masters project
  - The approach and working prototype:
    - Restructure requirements statement based on templates of well-formed requirements
    - Identify inconsistencies and incompleteness
- Application for distributed and cross-domain integration
  - This builds on Leonard's PhD dissertation and associated prototype [109]

Our NAVAIR sponsor discussed the potential desire to leverage the NPL and semantic web capabilities to automate the "update" planned for the Standard Work Packages. NAVAIR provided about 20 SWP and we analyzed some examples and came up with some recommendations to research improving the way that SWP are created, managed and used. The initial analysis included:

- Drivers for Model-centric Approaches to Authoring Standard Work Packages (SWP)
- Representation and issues with the sample SWPs provided to us

- Strategic approaches to (Re)generation of Defense Acquisition Process documents and SWP in the context of increasingly complex, diverse & changing regulatory, technological program environments
- Implementation strategies and technologies, and operational scenarios
- Review of research that demonstrated ability to automatically generate activity diagrams (process flows) from underlying model (this is a confirmatory story)

Finally, we believe that it would be interesting to apply the NPL processing to some of the NAVAIR requirements. We did hear at a prior meeting with David Fields that requirements (for MQ-25) are stored in a database, and in general are well structured. If those requirements were non classified, we could use them for analyzing and performing NPL on textual requirement statements in future research.

6 Task 4 – Define System Engineering Transformation Roadmap

Our plans for the roadmap at the start of RT-157 aligned with the prioritized set of goal shown in Table 1, which also highlights traceability to Technology, Methods, and Competencies. The expected development of a roadmap focused on transitioning from the traditional SETR approach, to a requirement, risk, and evidence-based approach using an evolving underlying SST. We planned to focus on MDAO to be more systematic in tradespace of the problem space. This was also focused at the POR level.

However, the acceleration of the SE transformation as altered that plan. We are now working our gaps and challenges associated with the new framework, which include, but are not limited to:

- Using an interactive approach to MDAO in a collaborative effort to develop a new type of specification, RFP & SOW
- Developing strategies to track and assess value of requirements to KSA
- Investigating a collaborative operational paradigm between government and industry
- Accelerating the awareness of modeling methods for the competencies (see Section 5)
- Considering alternative digital engineering strategies for evaluating a proposal during source selection

In support of the new operational paradigm, we were requested by our sponsor to attend a workshop to discuss strategies for how digital models could be used in the DoD acquisition process to support competitive down-selection for:

- Competitive prototyping in the Technology Maturation and Risk Reduction phase
- Engineering and Manufacturing Development

The objectives of the workshop were:

- Obtain community input on the types of digital models (design, cost, performance, mission, etc.) that could be used to support competitive down-selection
- Identify the existing gaps that must be closed to enable the use of digital models to support competitive down-selection
- Recommend changes in the DoD acquisition process and Government-Industry interactions to enable the use of digital models to support competitive down-selection
- Obtain community input on the policy and legal issues associated with the use of digital models in Requests for Proposals (RFPs), proposals, and during proposal evaluation to support competitive down-selection

Therefore, as part of the newly awarded RT-170, we will update the roadmap to include the new task as discussed in Section 2.5, and consider topics discussed in working sessions:

- Virtualization and event-driven reviews
- Implications of a Computationally Enabled System Engineering through the formalization of the Decision Framework
  - Concept to embed System Engineering through cross-domain linkages and relationships in the Information Model that underlies ISEE
  - Can we measure requirement stabilization?
- Significant discussion about the implications of Software Intensive Cyber Physical System (CPS)
  - Insights gained from working with JSF
  - Revisit RT-142 on Risk Leading Indicator on SW-intensive CPS
- Models enable new possibilities for verification at proposal evaluation
- Collaborative approach to decisions-in-the-loop
  - Measure of design maturing
- Integrated System Engineering Environment (ISEE)
  - Variant management, which relates capturing tradespace analysis
  - Template-based approach to requirement generation (and possibly contract generation)
- Formalizing contracting
  - Examples include contracts specification language (GCSL) developed by the Designing for Adaptability and evolutioN in System of systems Engineering (DANSE) project
  - Make Contract Data Requirements List (CDRLs) about Verification and Validation (V&V) and Model Integrity
- Early planning for sustainment
  - Digital Twin – "An integrated, multiphysics, multiscale, probabilistic simulation of an as-built system, enabled by Digital Thread, that uses the best available models, sensor information, and input data to mirror and predict activities/performance over the life of its corresponding physical twin."
- Risks
  - Airworthiness and Safety (most critical in Technical Feasibility assessment)
  - Program execution (cost, schedule and performance)
  - Competencies may not be ready for the first pilot (see Figure 1)
- Use of a surrogate pilot project to evaluate this approach to MCE-based contracting and collaboration

7 SERC Research Synergies

This section discusses 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.

7.1 RT-141 Integrated Framework for Risk Identification and Management

Many of the topics from the RT-141 final report [21] describing model integrity and modeling methodologies and tools for a risk-based framework are still relevant, but have not been included in this report. We believe that many of these topics are still potential challenges in the new operational paradigm characterized by the SET framework.

Model-centric development introduces a different risk – the risk of uncritical review of the modeling and analysis methods and results. In document-centric development there is usually health skepticism, and reliance on experienced subject matter experts to review the development documents. In model-centric development, DoD will need to develop a cadre of experts with expertise both in the domain and in modeling and analysis methods.

7.2 RT-168 Decision Framework

Our NAVAIR sponsor was also informed about the relationships between Systems Engineering (SE) activities and the decision framework (related to Dr. Matt Cilli's dissertation [39]) under the RT-168 research task for U.S. Army Armament Research, Development and Engineering Center (ARDEC). This framework relates to the digital thread concept that can show how to leverage analysis in each of the areas to develop a digital thread to support repeatable analysis, where a "fully" integrated operational analysis is missing currently.

We are researching to assess if the Decision Framework can demonstrate how data from the underlying information model (SST) can be used to populate the Decision Framework as implemented in the Armament Analytics Multiple Objectives Decision Analysis Tool (AAMODAT) tool with potential refinements and extensions. We believe this capability serves many purposes:

- Provide senior management and program managers with visual representations of key tradeoff defined in terms of Performance, Cost, Time and Risk as shown in Figure 42
- Scatterplot shows in a single chart how all system level alternatives respond in multiple dimensions of stakeholder value
- Assessment Flow Diagrams (AFDs) trace the relationships between physical means, intermediate measures, and fundamental objectives
- Provides methodological guidance for identifying Key Performance Parameters (KPPs)
- Can be used with uncertainty analysis as a measure for understanding maturing design
- Enables bi-directional analysis throughout lifecycle

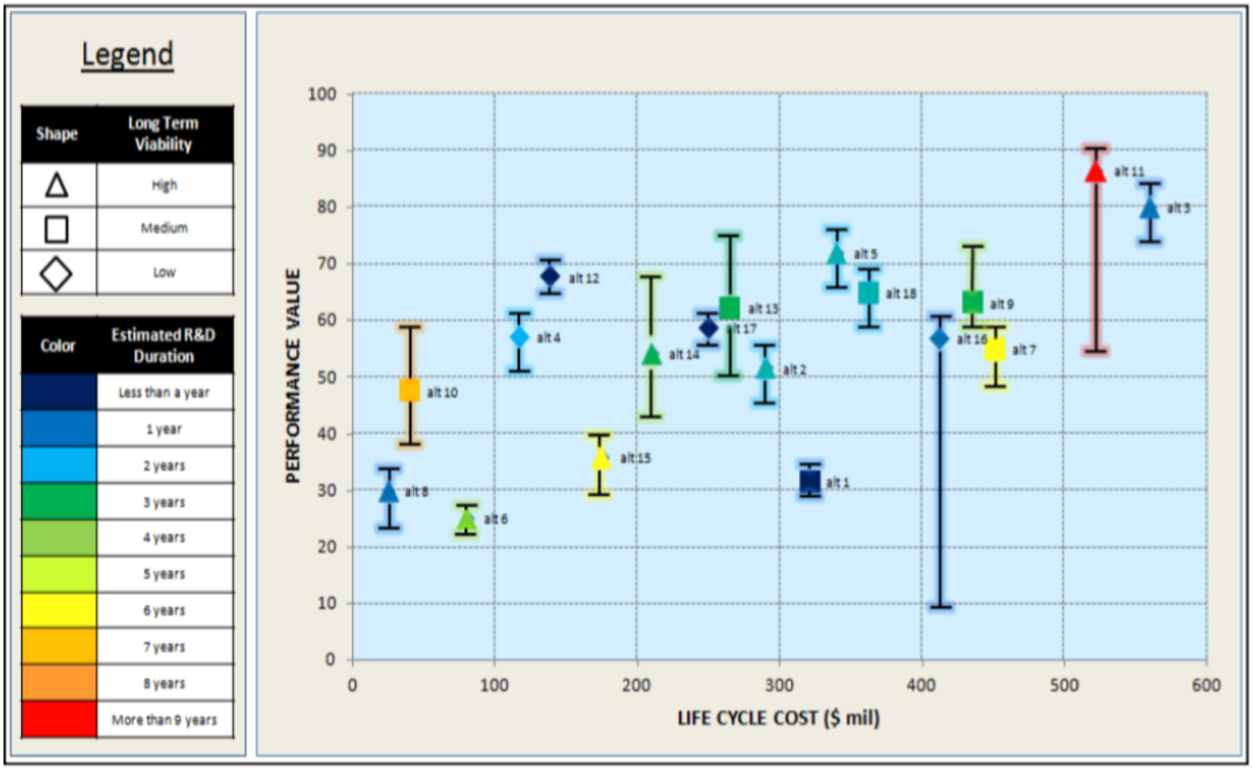


Figure 42. Decision Support Model Construct

7.3 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 be aligned with the ongoing research from RT-157 and RT-170. RT-176 aims to leverage and extend existing research in the area of methods, processes and tools (MPT) for performing early Verification & Validation (V&V) of requirements and architecture models managed within its organization, and to educate its workforce in the use of automated tools for conducting early and continuous V&V across the entire lifecycle. We have shared our UAV system model discussed in Section 5 with Kristin. We hope that this model will be developed as a surrogate to actual systems under development at NAVAIR for use as a case study to test new or improved MPTs that are developed based on those summarized in the background and as a result of this task, which are expected to apply to other systems in many domains throughout DoD.

7.4 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.

The effort for this year involves many of the industry contractors to NAVAIR and DoD. The results should produce a white paper describing a CONOPS for how industry and government can collaborate through MCE.

8 PART II SUMMARY

Our research suggests that model-centric engineering is in use and adoption seems to be accelerating. As described herein, our sponsor recognized the need to make a radical transformation and are developing a strategic plan based on a new operational paradigm for acquisition and design to accelerate SET. We are adapting our research strategy and focus to align with their evolving plan. This message has been shared more broadly with SERC sponsors, government sponsors of SERC research, and industry both through SERC and NDIA events.

In a recent Government-Industry Model Centric Engineering forum conducted by the Systems Engineering Research Center (SERC) and the Office of the Undersecretary of Defense, the following four perceived areas of benefits were found to be the key themes to implementing [40]:

1. Improved Acquisition – accepting digital deliverables could improve the governments understanding of a projects status and risk along with allowing them to "validate" the contractor's deliverables.
2. Improved Efficiency and Effectiveness – reduce time and effort in the performance of existing tasks using a digital "twin" of the system.
3. Improved Communication; Better Trade-Space Exploration; Reduced Risk – using ontology-based information models to translate and extract useful information between a variety of models and model types could allow for improved communication among specialists.
4. Improved Designs and resulting Systems and Solutions – being able to understand the impact of requirement and/or design decisions early could help improve the overall system design and identify adverse consequences of the design before committing to a design choice.

The future research of MCE will need to take into account these four perceived areas of benefit and help make progress toward these dimensions. The path forward to transitioning to MCE has both challenges and many opportunities, both technical and sociotechnical. The modeling infrastructure for a digital engineering environment is a critical step to enable a SST, which we believe can better link information across domains for better and earlier decision making. While there are thousands of tools they are often federated and there is currently not one single solution that can be purchased to span the MCE lifecycle. Every organization providing inputs to this research has had to architect and engineer their own model-centric engineering environment. Most have selected commercial tools and then developed the integrating fabric between the different tools, model, and data. This often uniquely positions them with some advantages among others in theirs industry. Some organizations have encoded historical knowledge in reference models, model patterns to embed methodological guidance to support continuous orchestration of analysis through new modeling metrics, automated workflow, and more. Our immediate challenge is provide research to the SET "roll out" strategy as reflected in Figure 1.

9 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.

AADL	Architecture Analysis & Design Language
ACAT	Acquisition Category
AFT	Architecture Framework Tool of NASA/JPL
AGI	Analytical Graphics, Inc.
AGM	Acquisition Guidance Model
ANSI	American National Standards Institute
AP233	Application Protocol 233
ATL	ATLAS Transformation Language
ASR	Alternative System Review
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
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CDR	Critical Design Review
CEO	Chief Executive Officer
CESUN	International Engineering Systems Symposium
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integration
CORBA	Common Object Requesting Broker Architecture
CREATE	Computational Research and Engineering for Acquisition Tools and Environments
CWM	Common Warehouse Metamodel
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)
DL	Descriptive Logic
DoD	Department of Defense
DoDAF	Department of Defense Architectural Framework
DoE	Design of Experiments
DSL	Domain Specific Languages
DSM	Domain Specific Modeling
DSML	Domain Specific Modeling Language
E/DRAP	Engineering Data Requirements Agreement Plan
ERS	Engineered Resilient Systems
FAA	Federal Aviation Administration
FMEA	Failure Modes and Effects Analysis
FMI	Functional Mockup Interface
FMU	Functional Mockup Unit

GAO	Government Accounting Office
HPC	High Performance Computing
HPCM	High Performance Computing Modernization
HW	Hardware
I&I	Integration and Interoperability
IBM	International Business Machines
IBD	SysML Internal Block Diagram
ICD	Interface Control Document
ICTB	Integrated Capability Technical Baseline
IDEF0	Icam DEFinition for Function Modeling
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
IPR	Integration Problem Report
IRL	Integration Readiness Level
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 of NASA
KPP	Key Performance Parameter
KSA	Key System Attributes
Linux	An operating system created by Linus Torvalds
LOC	Lines of Code
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
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®
MDD™	Model Driven Development
MDE	Model Driven Engineering
MDSD	Model Driven Software Development
MDSE	Model Driven Software Engineering
MIC	Model Integrated Computing
MMM	Modeling Maturity Model
MoDAF	United Kingdom Ministry of Defence Architectural Framework
MOE	Measure of Effectiveness
MOF	Meta Object Facility
MOP	Measure of Performance
MVS	Multiple Virtual Storage
NASA	National Aeronautics and Space Administration
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
OCL	Object Constraint Language
OMG	Object Management Group
OO	Object oriented
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
PDM	Product Data Management
PDR	Preliminary Design Review
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
RT	Research Task
RFP	Request for Proposal
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
SFR	System Functional Review
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
SRR	System Requirements Review
SRS	Software Requirement Specification
STOVL	Short takeoff and vertical landing
SVR	System Verification Review
SW	Software
SysML	System Modeling Language
TARDEC	US Army Tank Automotive Research
TBD	To Be Determined
TRL	Technology Readiness Level

TRR	Test Readiness Review
UML	Unified Modeling Language
XMI	XML Metadata Interchange
XML	eXtensible Markup Language
US	United States
XSLT	eXtensible Stylesheet Language family (XSL) Transformation
xUML	Executable UML
Unix	An operating system with trademark held by the Open Group
UQ	Uncertainty Quantification
VHDL	Verilog Hardware Description Language
V&V	Verification and Validation
VxWorks	Operating system designed for embedded systems and owned by WindRiver

10 TRADEMARKS

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