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Defining a Model-Based Systems Engineering Approach for Milestone Technical Reviews

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Abstract

Program technical reviews are discrete points in time within a system's lifecycle during which the system is evaluated against a set of specific accomplishments known as "entrance criteria." These entrance criteria are used to track the system's technical progress, schedule, and program risks. The technical reviews serve as gates that, when successfully evaluated, demonstrate that the program is on track to achieve its final goals and should be allowed to proceed to the next acquisition phase.

Current technical reviews are based around lengthy evaluations of static, contractually obligated documents that are used to demonstrate successful completion of the entrance criteria. These documents represent "snap-shots" of the systems as seen through the prism of the entrance criteria, and do not represent a view of the system in its totality. As a result, the program, and system, are often viewed by the entrance criteria alone, which fail to account for the system from a holistic perspective.

Department of Defense (DoD) organizations are migrating to Model-Based Systems Engineering (MBSE) environments, with a vision of modernizing and better developing, delivering, operating and sustaining systems. This transition is important because advances in technology have led to larger and more complex systems. This migration implies a need for a clear, concise way to express the system design (clear, logically consistent semantics) and a need to represent systems differently to account for emergent behavior within the system due to the increased complexity.

Model-based reviews allow for complexity to be managed more efficiently because data, not "systems engineering products," is the commodity that will be used to evaluate the entrance criteria. The data-driven MBSE technical reviews will provide greater insights with faster comprehension for the details across a program's lifecycle. This approach will not only provide efficiencies for the technical reviews, but will improve the program's cost and schedule efficiency.

This technical report highlights the results of our FY19 Acquisition Research Project. It defines a systematic process for developing the virtual model of the system as the program progresses through the acquisition lifecycle, defines how the model of the system can be used in lieu of “artifacts” to provide decision-makers with a more complete representation of the system during technical reviews, and assesses the suitability of existing technical review criteria to MBSE-based reviews.

Key words: Technical Review, Model-Based Systems Engineering, Digital Engineering

Acknowledgments

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Mr. Carlson served 26 years in naval aviation as a pilot, the last seven years of which were at NAVAIR where he was the Military Director of Systems Engineering and led NAVAIR Systems Engineers through several years of systems engineering revitalization.

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Executive Summary

Model-based processes are one of the most widely-discussed issues within Department of Defense (DoD) today. For example, MBSE is a quarterly discussion at the Navy's Systems Engineering Stakeholders Group (SESG), has been a tenant of the National Defense Industrial Association Systems Engineering Conference for the past several years. The DoD Digital Engineering Strategy (2018) provides a vision on how DoD will modernize, develop, deliver, operate and sustain systems. This strategy is important because advances in technology have led to larger and more complex systems. This implies: a need for a clear concise way to express the system design (clear, logically consistent semantics); and, a need to represent systems differently to account for emergent behavior within the system due to the increased complexity.

The first of five goals of the DoD Digital Engineering Strategy is the most significant for this paper. However, the five goals are mutually supportive. It is therefore, impossible to have a comprehensive discussion without the goals being intertwined. Goal 1 of the Digital Engineering Strategy states (DASD(SE) 2018):

"Goal 1: Formalize the development, integration, and use of models to Inform Enterprise and Program Decision-making.

1.1 Formalize the planning for models to support engineering activities and decision making across the lifecycle

1.2 Formally develop, integrate, and curate models.

1.3 Use models to support engineering activities and decision-making across the lifecycle."

When developed properly, models can provide a precise virtual representation of the functional, physical, parametric, and program entities of the systems. Increased emphasis is on the model itself, specifically the objects and relationships it contains, rather than the diagram, to encourage better model development, usage, and decision-making.

Systems Engineering Technical Reviews (SETR) are discrete points in time, within a system's lifecycle, during which the system is evaluated against a set of

program specific accomplishments (entrance criteria). Entrance criteria are used to track the technical progress, schedule, and program risks. The SETRs serve as gates, that when evaluated successfully, demonstrate that the program is on track to achieve its final program goals, and should be allowed to proceed to the next acquisition phase.

Current SETRs are based around lengthy reviews of static, contractually obligated “artifacts” that are used to demonstrate successful completion of the entrance criteria. Participants typically ‘freeze’ these “artifacts” many days prior to the SETR in order to provide baselines from which to synchronize various products used during the review. This baselining and eventual loss of concordance between “artifacts” are the primary drawbacks when conducting reviews using “artifact-based” methods.

The first three phases of the system acquisition lifecycle, through Engineering and Manufacturing Development culminating with Acquisition Milestone C, is where the most significant systems engineering activities occur.

While various DoDAF views and other systems engineering artifacts are shown in the diagram, the instantiation of these views only represents how the system data will be displayed within the presentation framework. In a MBSE environment, the system is represented virtually, therefore the data and relationships, not the views, are the “atomic” level of detail.

A MBSE environment requires an increased emphasis on the model, specifically the objects and relationships it contains, rather than the “artifact” to encourage better model development, usage, and decision-making. The model should include structure, which defines the relationships between the system entities, establishes concordance within the model, and allows for the emergence of system behaviors and performance characterizations. Each system element should be represented only once in the model just as it is in the real-world system. The data that comprises the model is iteratively developed and maintained throughout the system lifecycle.

In a MBSE environment the model is a virtual representation of the system, and becomes the focus of a SETR. Using the model as the source for decision-making throughout the system acquisition lifecycle is a significant departure from todays practice since programs often generate unique artifacts for the sole purpose of the reviews.

This research found that MBSE can be used to satisfy the technical review criteria found throughout the Materiel Solution Analysis Phase, and during most of the Technology Maturation and Risk Reduction Phase. Existing technical reviews that are well-suited for MBSE SETRs are:

- Initial Technical Review (ITR)
- Analysis of Alternatives (AoA)
- Alternative System Review (ASR)
- System Requirements Review (SRR)
- Systems Functional Review (SFR).

Many Department of Defense (DoD) organizations are striving to evolve from a traditional systems engineering environment to a Model-Based Systems Engineering (MBSE) environment. For this transition to occur, new business processes need to be explored. The objective of this effort is to define and demonstrate a MBSE process for performing milestone reviews, in a paperless environment.

Our research found that MBSE, as it currently exists, does not adequately address the criteria for a Preliminary Design Review (PDR). Review criteria for PDRs was reviewed from the Defense Acquisition University (DAU), the Navy's Strategic Systems Program (SSP), and the Naval Air Systems Command (NAVAIR). We selected the review criteria from NAVAIR because it was the most comprehensive. During the course of this research, 846 PDR questions were evaluated for applicability to be addressed by current MBSE. Of these 846 questions, only 80 questions could be addressed directly by MBSE today. The reason for this is the diversity in review categories. Fifty-six PDR Criteria Categories were decomposed. Of these 56 categories, only eleven categories are adequately satisfied by MBSE, thirteen categories are partially satisfied by MBSE, and 32 categories are not adequately satisfied by MBSE. Formalized planning for modeling and decision-making across the lifecycle must include a new approach for SETRs. This not only includes the content of the reviews, but how the models will be assessed against the criteria (Dam, 2018). Current processes used for assessing documents are not adequate in a MBSE environment.

The DoD Digital Engineering Strategy (2018) states that there is a strong need to ensure that decision-makers understand the different model types and what information can be gleaned from them. After the results of analyzing how MBSE will satisfy a PDR, it is clear that new visualizations must be developed to adequately address the needs, and provide greater insight with faster comprehension for the details across the lifecycle. As DOD organizations migrate to a MBSE environment, efficiencies will be gained by transitioning from the traditional paper-based reviews to model-based reviews. Model-based reviews allow for complexity to be managed more efficiently because data, in lieu of “systems engineering products,” is the commodity that will be used to evaluate the entrance criteria. The MBSE milestone reviews will provide greater insight with faster comprehension for the details across a program’s lifecycle. This will not only provide efficiencies for the review, but will improve the program’s cost and schedule efficiency. MBSE requires a mindset change, a change in systems engineering processes, and a change in expectations of the artifacts required during the systems engineering process.

I. Introduction, Background, and Scope

Advancements in computing, modeling, data management, and analytical capabilities offer great opportunities for the engineering practice. Applying these tools and methods, we are shifting toward a dynamic digital engineering ecosystem. This digital engineering transformation is necessary to meet new threats, maintain overmatch, and leverage technology advancements.

- Ms. Kristin Baldwin, Acting Deputy Assistant Secretary of Defense for Systems Engineering (DASD(SE) 2018)

Today's systems are more complex, and change more rapidly than ever before. As sub-systems are added to systems, and systems are added to System of Systems (SoS), interfaces grow nonlinearly. As a result, interfaces and interactions are often difficult to comprehend and have cascading effects leading to uncertain and incomplete architectures which fail to account for emerging issues within the system. The challenge is to deal with this increased complexity in systems and SoS (Vaneman, 2017). The fundamental objective of systems engineering is to facilitate a process that consistently leads to the development of successful systems (Long and Scott, 2011). Model-Based Systems Engineering was envisioned to transform systems engineering's reliance on document-based work products to an engineering environment based on models. This transformation means more than using model-based tools and processes to create hard-copy text-based documents, drawings, and diagrams. Data in a MBSE environment is ideally maintained within a single repository and has a singular definition for any model element, and allows for the static and dynamic representations of a system from several different perspectives and levels of decomposition.

Model-based processes are one of the most widely-discussed issues within Department of Defense (DoD) today. The DoD Digital Engineering Strategy (2018) provides a vision on how DoD will modernize, develop, deliver, operate and sustain systems. This strategy is important because advances in technology have led to larger and more complex systems. This implies: a need for a clear concise way to express the system design (clear, logically consistent semantics); and, a need to represent systems differently to account for emergent behavior within the system due to the increased complexity.

The primary difference between MBSE and Digital Engineering is the scope of engineering activities addressed. MBSE addresses only system engineering related issues. On the other hand, Digital Engineering includes all engineering models. Thus MBSE is a sub-set of Digital Engineering. However, for the the purpose of this report, MBSE and Digital Engineering will be treated as synomous, since the foundation of Digital Engineering applies to both.

The Digital Engineering Strategy provides five goals[1] (DASD(SE) 2018). Goal 1 is the most significant for this paper, however, the five goals are mutually supportive. It is therefore impossible to have a comprehensive discusson without the goals being intertwined. Goal 1 of the Digital Engineering Strategy states (DASD(SE) 2018):

"Goal 1: Formalize the development, integration, and use of models to Inform Enterprise and Program Decision-making.

1.1 Formalize the planning for models to support engineering activities and decision making across the lifecycle
1.2 Formally develop, integrate, and curate models.
1.3 Use models to support engineering activities and decision-making across the lifecycle."

There is a strong need to ensure that the systems engineers and stakeholders understand the different model types and what information can be gleaned from them.

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[1] GOAL 1: Formalize the development, integration, and use of models to inform enterprise and program decision-making.

GOAL 2: Provide an enduring, authoritative source of truth.

GOAL 3: Incorporate technological innovation to improve the engineering practice.

GOAL 4: Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders.

GOAL 5: Transform the culture and workforce to adopt and support digital engineering across the lifecycle.

When developed properly, models can provide a precise virtual representation of the functional, physical, parametric, and program entities of the systems. Increased emphasis is on the model itself, specifically the objects and relationships it contains, rather than the diagram, to encourage better model development, usage, and decision-making. To enable this, new policies must be established to define model-based processes and governance.

System engineering technical reviews are discrete points in time, within a system's lifecycle, during which the system is evaluated against a set of program specific accomplishments (entrance criteria). Entrance criteria are used to track the technical progress, schedule, and program risks. The SETRs serve as gates, that when evaluated successfully, demonstrate that the program is on track to achieve its final program goals, and should be allowed to proceed to the next acquisition phase.

Current SETRs are based around lengthy reviews of static, contractually obligated "artifacts" that are used to demonstrate successful completion of the entrance criteria. Participants typically 'freeze' these "artifacts" many days prior to the SETR in order to provide baselines from which to synchronize various products used during the review. This baselining and eventual loss of concordance[2] between "artifacts" are the primary drawbacks when conducting reviews using "artifact-based" methods. This paper is the first step in defining the "artifact " development process, and approach for Systems Engineering Technical Reviews (SETR) in Model-Based Systems Engineering (MBSE).

The objective of this research is to define how DoD organizations can systematically develop the model of the system and how to conduct SETRs in a MBSE-environment. This effort requires: an examination of current SETR processes; the sequential development process of the model; and a derivation of new MBSE processes that will provide the requisite system and programmatic information needed to satisfy the review criteria.

Our research addresses the following issues:

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[2] "Concordance" is defined in Chapter II.

1. Define a systematic processes for developing the virtual model of the system, as the program progresses through the acquisition lifecycle.
2. Evaluate representative SETR entrance criteria and related questions, and determine if questions could be represented by a “virtual system” as data that is required for system and program decisions in a MBSE environment.
3. Define how the model of the system can be used in lieu of “artifacts” to provide decision-makers with a more complete representation of the system during SETRs.

The organization of this technical report is as follows:

- Chapter II – “Literature Review” provides an introduction to key MBSE concepts and terms used throughout this report;
- Chapter III – “MBSE Development Methodology During the Acquistion Lifecycle” defines a systematic process for devevleoping the model of the system in a MBSE-environment;
- Chapter IV – “Analysis of Technical Reviews in a MBSE Environment: analyzes the SETR entrance criteria, and related questions, and defines the MBSE-based SETR;
- Chapter V – “Conclusions and Recommendations” provides the summary, conclusions, and recommendations for further research.

II. Literature Review

A. MBSE Concepts and Definitions

The objective of systems engineering is to facilitate a process that consistently leads to the development of successful systems (Long and Scott 2011). Model-Based Systems Engineering (MBSE) was conceived by the International Council on Systems Engineering (INCOSE) to address the increasing complexity of systems by transforming systems engineering from a document-based to model-based discipline. One can argue that systems engineering has always used models (i.e. diagrams, documents, matrices, tables, etc.) to represent systems. In these traditional document-based models, the system's entities were represented multiple times, making it difficult, if not impossible, to view the system holistically. The transformation to MBSE means more than using model-based tools and processes to create document-based models, but shifts the focus to a virtual system model of the system, where there exists a singular definition for any system element (Vaneman and Carlson 2019).

To illustrate the concept of a virtual model of a system, consider the dimensions of a systems engineering project (Figure 1), where the cube represents a system. The system has height, width, and depth. System height provides a decomposition from the highest system level down to components and parts. System width defines the lifecycle of the system, and provides insight across the entire system lifecycle from concept definition to disposal. System depth provides the complex relationships between systems, functions, and requirements to name a few. The system:

- Satisfies capabilities;
- Performs functions and has behavior;
- Is defined by requirements;
- Is testable;
- Has risks;
- Incurs costs.

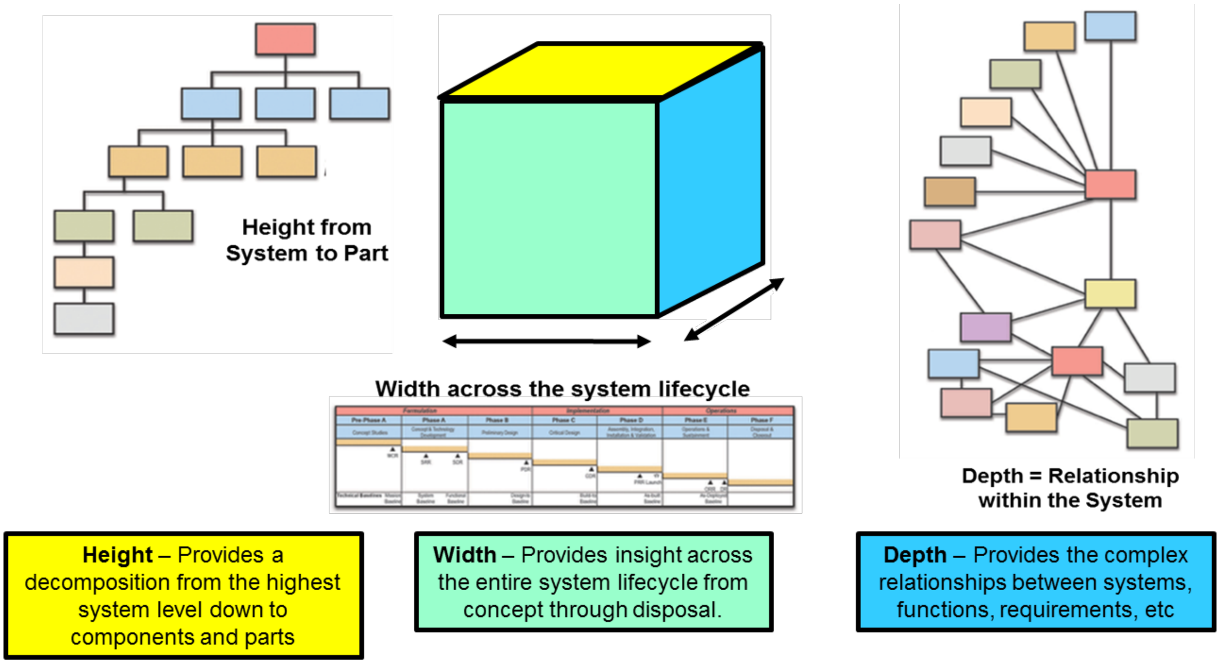


Figure 1. Dimensions of a Systems Engineering Project (Larson, *et al.* 2013; Vaneman, et al., 2019)

INCOSE (2007) defines MBSE as “the formalized application of modeling to support system requirements, design, analysis, verification, and validation activities beginning in the conceptual design phase and continuing throughout the later lifecycle phases.” This definition captures the lifecycle perspective of systems engineering, but does not suggest how MBSE is different from traditional systems engineering, nor does it address the elements required from implementation.

This report defines MBSE as the formalized application of modeling (static and dynamic) to support system design and analysis, throughout all phases of the system lifecycle, through the collection of modeling languages, structures, model-based processes, and presentation frameworks used to support the discipline of systems engineering in a model-based or model-driven context (Vaneman 2016). The four components of MBSE are described below and shown in Figure 2 (Vaneman 2016).

- **Modeling Languages** – Serves as the basis of tools, and enable the development of system models. Modeling languages are based on a logical construct (visual representation) and/or an ontology. An ontology is a collection of standardized, defined terms and concepts and the relationships among the terms and concepts.

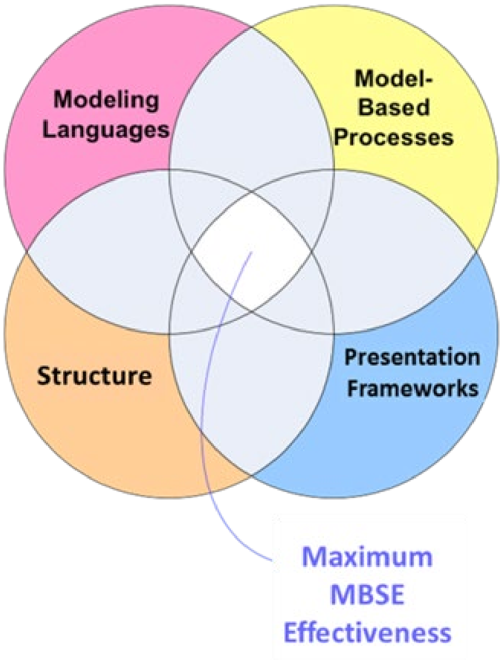


Figure 2. Four Components of MBSE (Vaneman, 2016)

- **Structure** – Defines the relationships between the system's entities. These structures allow for the emergence of system behaviors and performance characterizations within the model.
- **Model-Based Processes** – Provides the analytical framework to conduct the analysis of the system virtually defined in the model. The model-based processes may be traditional systems engineering processes such as requirements management, risk management, or analytical methods such as discrete event simulation, systems dynamics modeling, and dynamic programming.
- **Presentation Frameworks** - Provides the framework for the logical constructs of the system data in visualization models that are appropriate for the given stakeholders. These visualization models take the form of traditional systems engineering models. These individual models are often grouped into frameworks that provide the standard views and descriptions of the models, and the standard data structure of architecture models.

Maximum MBSE effectiveness occurs at the convergence of the four components. Most MBSE tools strive to be within this convergence. Model-Based Systems Engineering tools are general-purpose software products that use modeling languages, and support the specification, design, analysis, validation and verification of complex system representations. Although some tools are treated as synonymous with MBSE, this report is tool agnostic. Tools are generally popular for a period, and then are superseded by the “next best idea,” while the MBSE concepts presented here are meant to be fundamental and transcend tools.

B. The MBSE Environment

In a MBSE environment the system is represented virtually by a model consisting of entities representing system elements. Each entity is represented as data, ideally only once, with all necessary attributes and relationships of that entity being portrayed. The relationships developed between the system’s entities allows for concordance across the model.

Concordance is the ability to represent a single entity such that data in one view, or level of abstraction, matches the data in another view, or level of abstraction, when talking about the exact same thing (Vaneman 2016). In contrast, paper- or artifact-based reviews will represent the same entity multiple times. This singular representation of each entity allows the system to be explored from the various engineering and programmatic perspectives (viewpoints). A viewpoint describes data drawn from one or more perspectives and organized in a particular way useful to manage decision-making. The compilation of viewpoints (e.g. capability, operational, system, programmatic viewpoints) represents the entire system, where the system can be explored as a whole, or from a single perspective.

The MBSE environment may consist of single, or multiple, tools and data repositories. Regardless, if the environment is a single tool and data repository, or composed of multiple tools and an integrated data repository, the four components must be implemented for the MBSE environment to be fully effective. A notional MBSE environment is shown in Figure 3 (Vaneman, 2019).

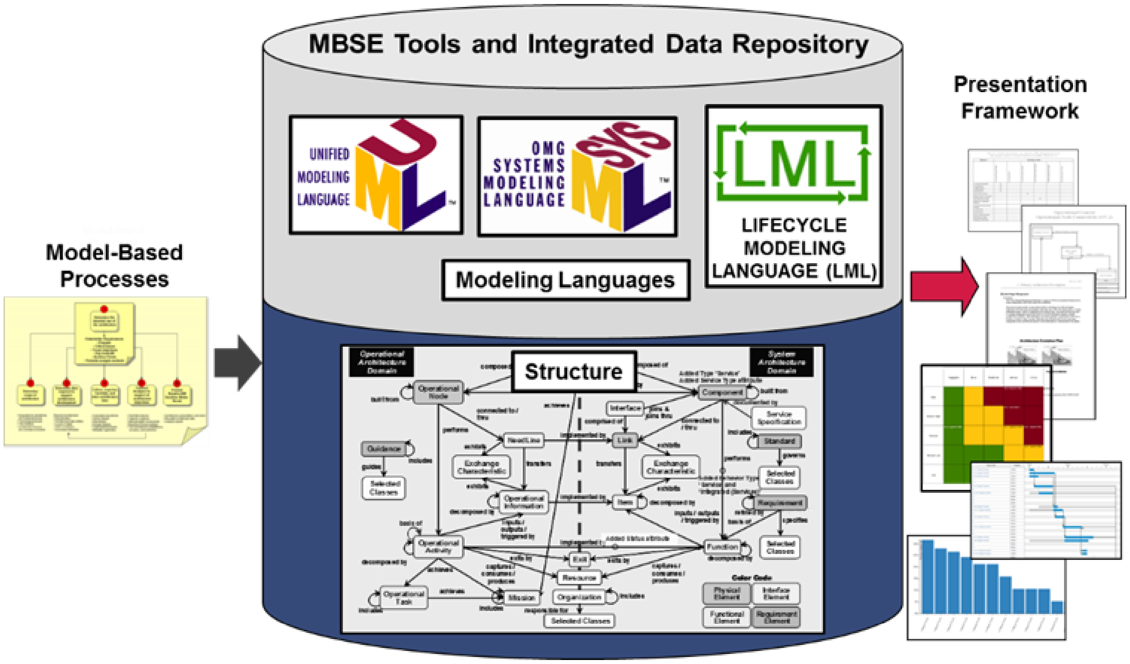


Figure 3. Notional MBSE Environment (Vaneman, 2019)

C. Modeling Languages

The foundation of the MBSE environment are the modeling languages that enable the tools. Modeling languages are based on a visual representation (logical construct), an ontology, or both. An ontology is a collection of standardized, defined terms and relationships between the terms to capture the information that describes the physical, functional, performance, and programmatic aspects of a system (LML Steering Committee 2015; Vaneman, 2016).

The two leading visualization languages are the Unified Modeling Language (UML) and the Systems Modeling Language (SysML). UML was developed to support software engineering, and consists of fourteen structural and behavior models that represent the interactions within software systems. Given the success of UML, the Systems Engineering Community created SysML based on UML. Hence SysML is a profile of UML in that it extends UML, as shown in the Venn diagram in Figure 4 (Dam, 2015). In MBSE, both UML and SysML are important because tools based on this family of languages include both the underlying structures mentioned previously.

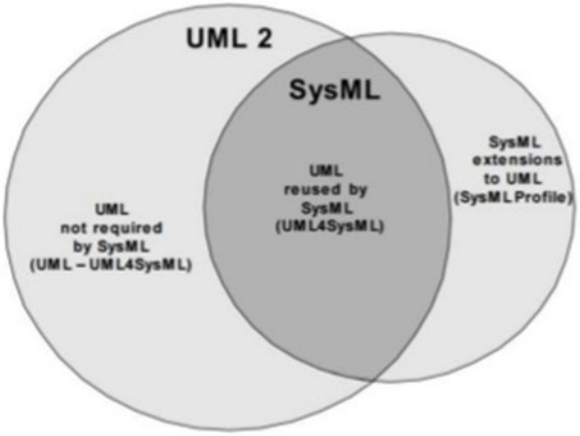


Figure 4. UML and SysML Venn Diagram (Dam, 2015)

SysML uses seven of the fourteen models from UML, plus two new models based on the needs of the systems engineering discipline. These models support requirements specification, analysis, design, validation and verification, for systems that include hardware, software, information, process, and people (Object Management Group, 2012). The SysML taxonomy is composed of nine models to represent behaviors, structures, requirements, and parametrics (Figure 5).

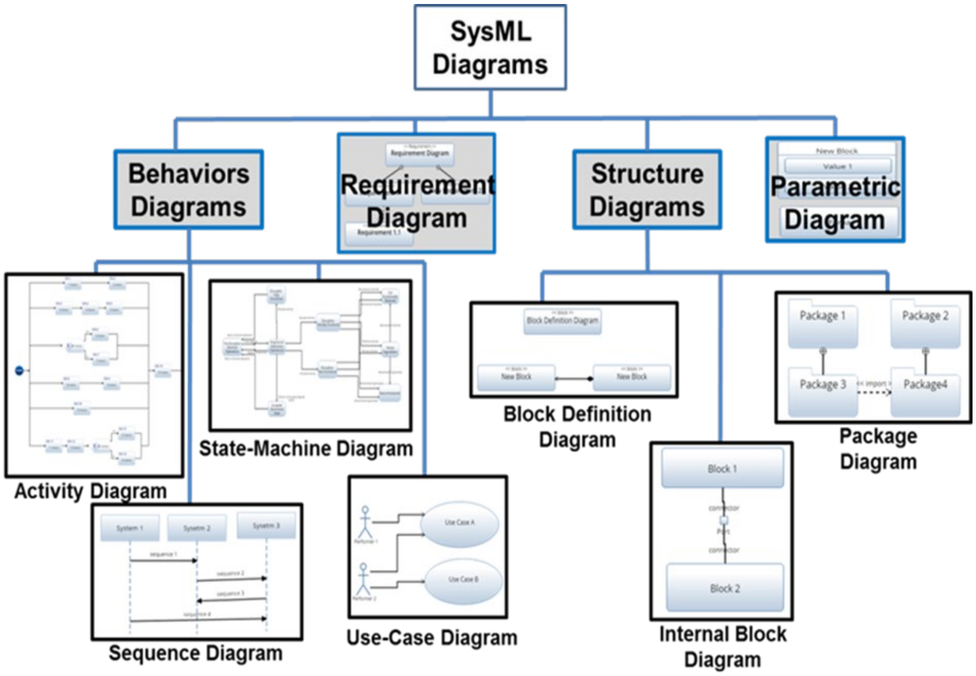


Figure 5. SysML Diagram Taxonomy (Vaneman, 2018)

The most common format for an ontology-based language is the Entity, Relationship, and Attribute (ERA) data schema. Each entity has a defined relationship allowing it to represent system complexity, and it may include multiple attributes to capture all of the dimensions of the system. An attribute is an inherent characteristic or quality that further describes an entity. The ERA approach allows for the efficient use of entities due to the attributes and relationships defined (LML Steering Committee, 2015; Vaneman, 2019).

Lifecycle Modeling Language (LML) is an example of entity, relationship, and attribute (ERA) based language. It was designed to integrate all lifecycle disciplines, including system architectures, design engineering, test, maintenance, and program management into a single framework (LML Steering Committee, 2015). LML combines the visual models with an ontology (common vocabulary and interrelationships) to capture information. It contains primary entities for a simplified language, and eight child entities defined for specific utility to capture information needed during the system's lifecycle. Table 1 shows the LML entities and their corresponding visualization models (Vaneman, 2018).

Table 1. LML Entities and their Corresponding Visualization Models (Vaneman, 2018)

LML Entity	LML Model
Action	Action Diagram
Artifact	Photo, Diagram, etc.
Asset	Asset Diagram
Resource (Asset)	Asset Diagram
Port (Asset)	Asset Diagram
Characteristic	State Machine, Entity-Relationship, and Class Diagrams
Measure (Characteristic)	Hierarchy, Spider, and Radar Charts
Connection	Asset Diagram
Conduit (Connection)	Asset Diagram
Logical (Connection)	Entity-Relationship Diagram
Cost	Pie/Bar/Line Charts
Decision	
Input / Output	State Machine Diagram
Location	Map
Physical (Location)	Geographic Maps
Orbital (Location)	Orbital Charts
Virtual (Location)	Network Maps
Risk	Risk Matrix
Statement	Hierarchy and Spider Charts
Requirement (Statement)	Hierarchy and Spider Charts
Time	Gantt Chart, Timeline Diagram
Equation	Equation

Regardless if the preferred modeling language is SysML or LML, both languages are designed for the same purpose – creating a virtual representation of the system of interest. The SysML models are based on four pillars: behavior; structure; parametric; and requirements. These four pillars correspond to the LML entity groupings; functional model; physical model; documentation entities; and parametric and program entities. Table 2 is a mapping of the SysML diagrams to the corresponding LML models and LML entities (Vaneman, 2018). Note that all LML entities are represented in Table 2 because LML models a broader range of system lifecycle activities than SysML. For example, SysML is silent with respect to risk, where LML does define a risk entity.

Table 2. Mapping of SysML Diagrams to LML Diagrams and Entities (Vaneman, 2018)

SysML Diagrams	LML Models	LML Entities
Activity	Action Diagram	Action, Input / Output
Sequence	Sequence	Action, Asset
State Machine	State Machine	Characteristic (State), Action (Event)
Use Case	Asset Diagram	Asset, Connection
Block Definition	Class Diagram, Hierarchy Chart	Input / Output (Data Class), Action (Method), Characteristic (Property)
Internal Block	Asset Diagram	Asset, Connection
Package	Asset Diagram	Asset, Connection
Parametric	Hierarchy, Spider, Radar	Characteristic
Requirement	Hierarchy, Spider	Requirement and related entities

D. Model Structure

Systems consist of "building blocks" and their relationships to each other, that allow them to come together in a designed form that satisfies the desired capabilities and functionality. Model structure defines the relationships between the system's entities, establishes concordance within the model, and allows for the emergence of system behaviors and performance characterizations within the model (Vaneman, 2016).

Each tool has its own conceptual data model that is used as the data schema. The MBSE tool CORE, developed by Vitech Corporation, has a robust deposable schema which represents elements, attributes and relationships at various levels of abstraction. Figure 6 represents a portion of the CORE schema, showing the elements and relationships needed to build an initial top-level architecture (Long and Scott, 2011). At the highest level of the diagram is “Architecture,” which is composed of Operational Nodes (left side of the diagram) and System Nodes (right side of the diagram). The “Operational Activities” are driven from “Capabilities,” as well as the “Performers” of those “Operational Activities.” The “Requirements” drive the “Functions” which are “performed” by “Components.” The connections between the left and right side of the diagram represents the corresponding Operational and System Nodes. For example, a “Capability” is “implemented by” a “Requirement,” which form the “basis of” a “Function.” The “Component” “performs” the “Function.”

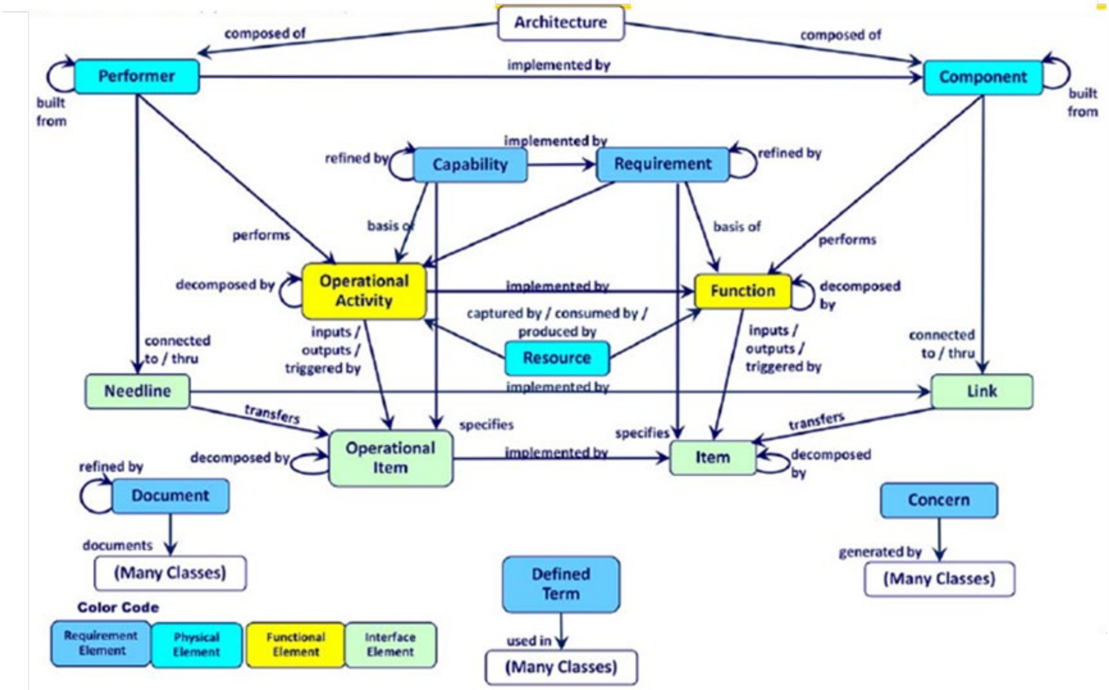
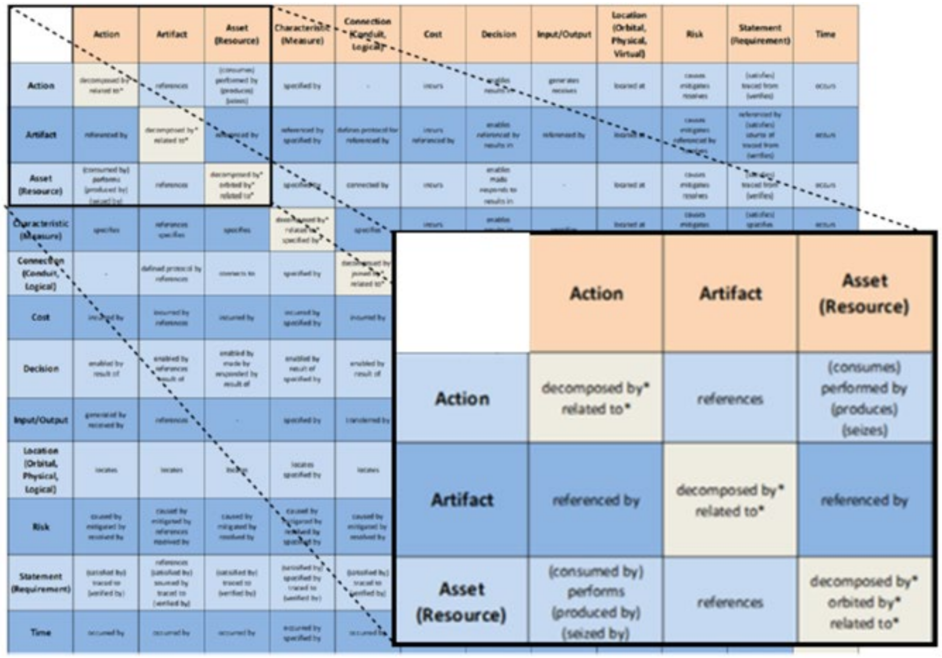


Figure 6. Data Schema (derived from Long and Scott, 2011)

Defining, and rigorously using, a conceptual data model ensures concordance across the data set. This is necessary if the model is going to be a virtual representation of the system, each individual data element is represented in the model only once, but will be able to be examined from different viewpoints.

Modelers often do not apply the model structures efficiently, thereby causing data to be represented in the model more than once. This results in data maintenance errors, leading to different representations of the same data in different views. Model structure is formed by the relationships within the data, where essentially every entity is related to every other entity (LML Steering Committee, 2015). Figure 7 shows a partial set of relationships that form the basis for the entire ontology of LML (Vaneman, 2019).



	Action	Artifact	Asset (Resource)
Action	decomposed by* related to*	references	(consumes) performed by (produces) (seizes)
Artifact	referenced by	decomposed by* related to*	referenced by
Asset (Resource)	(consumed by) performs (produced by) (seized by)	references	decomposed by* orbited by* related to*

Figure 7. Partial View of LML Ontological Relationships (Vaneman, 2018)

E. Modeling Processes

In MBSE, the modeling process provides the analytical framework to conduct the analysis of the system virtually defined in the model. Model-Based Systems Engineering is not a new discipline designed to supersede traditional systems engineering, but a new way to address systems engineering problems such as architecting, requirements management, risk management, and analytical methods such as discrete event simulation, systems dynamics modeling, and dynamic programming. Model-based processes must offer different analytical approaches used to address the various challenges throughout the system’s lifecycle (Vaneman, 2019).

Model-based processes emphasize the model itself, specifically the objects and relationships it contains, rather than the diagram to encourage better model development, usage, and decision-making. As such, model-based processes must focus on the entity as the “atomic level” to be modeled, with a holistic understanding of the system issues to be addressed. System entities have attributes such as: physical dimensions; satisfy capabilities; perform functions; exhibit behavior; have cost; are governed by a schedule; and, may have risks, just to name the most common. Essentially, each modeled entity should fully represent their corresponding system element. Traditional systems engineering artifacts typically represent the system from only one or two of these dimensions (Vaneman, 2019).

This paradigm can also serve as a bridge between system engineering, and the related disciplines that occur throughout the lifecycle. For example, the systems engineering and operations research disciplines often address similar problems, with analytical processes rooted in their own discipline. However, these communities often use different baselines of the same system when solving these problems. The MBSE environment allows each discipline to solve problems with their own methods, but provides a common baseline, that will facilitate consistencies among the understanding of the system (Vaneman, 2019).

Chapter III will discuss the modeling processes used to develop the system model throughout the system acquisition process.

F. Presentation Frameworks

Presentation frameworks provide the logical construct of the system data in visualization models that are appropriate for the given stakeholders. These visualization models take the form of traditional systems engineering models. The frameworks group thematically similar visualization models together to provide a comprehensive viewpoint that address the needs of various stakeholders. Each framework provides the definitions, references, guidance and rules for structuring, classifying, and organizing the views of systems engineering data.

One of the biggest misperceptions about presentation frameworks is that the views contained in them are unique to the framework. In fact, the visualization models contained in these frameworks are models widely used in systems engineering. Complexity in the model-based environment is significantly reduced by separating and characterizing systems issues into various data-driven viewpoints and views.

The first presentation frame work was developed by John Zachman in the mid-1980s, as a two-dimensional matrix classification schema that reflects the intersection between two classification types. The first type is known as interrogatives and asks the questions: What (data); How (function); Where (network); Who (people); When (time); and Why (motivation). The second classification type is known as transformations and considers what is needed to transform a concept into instantiations. The transformation perspectives are: Planner (scope); Owner (enterprise/business definition); Designer (system model); Builder (technology specification); and, Technician (detailed representation) (Zachman, 2008).

There are several architectural frameworks[3] common to large-scale system development efforts such as major weapon systems. Two examples of architectural frameworks are the United Kingdom’s Ministry of Defense Architecture Framework (MoDAF) and the Department of Defense Architecture Framework (DoDAF), the standard framework within DoD. The Unified Architecture Framework (UAF) is an emerging standard designed to provide a common standard for MoDAF, NATO Architecture Framework (NAF), and DoDAF. Table 3 (Vaneman, 2017) shows the correspondence between UAF, DoDAF, and MoDAF.

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[3] The difference between an *architectural framework* and a *presentation framework* is an architectural framework only addresses the models defined and developed during architectural phase of a system lifecycle. A presentation framework includes all models defined and developed across the entire system lifecycle.

Table 3. Correspondence between UAF, DoDAF, and MODAF (Vaneman, 2017)

UAF Viewpoints	DoDAF Viewpoints	MODAF Views	Purpose
Strategic Viewpoint	Capability Viewpoint	Strategic Views	Articulate capabilities, or high-level requirements that articulate stakeholder needs, goals, and enduring tasks.
Operational Viewpoint	Operational Viewpoint	Operational Views	Articulate operational scenarios, activities, processes, information flows, and requirements.
Systems Viewpoint	Systems Viewpoint	Systems Views	Articulate the legacy or planned systems, including their composition, interconnectivity, and context providing for support system functions.
Services Viewpoint	Services Viewpoint	Service Oriented Views	Articulate the performers, activities, services, and interfaces for supporting functions.
Technical Viewpoint	Standards Viewpoint	Technical Standards Views	Articulates policies, standards, guidance, constraints, and forecasts.
Acquisition Viewpoint	Project Viewpoint	Acquisition Views	Articulates program dependencies, milestones, and statuses.
All Views	All Viewpoint	All Views	Articulates the overarching information and architecture context that relate to all views of the architecture.
Custom Viewpoint	Fit-for-Purpose	Fit-for-Purpose	Articulates user-defined views of architectural data and information for presentation purposes.
N/A	Data and Information Viewpoint	N/A	Articulates the data relationships and alignment structure in the architectural context. This data is embedded throughout the UAF and MODAF views, and is not specified in a single view.

DoDAF defines eight viewpoints[4] and 52 views[5]. The framework provides the flexibility for other "fit for purpose" views to be defined as needed to address a problem, provided that the spirit of the viewpoint is maintained.

As previously stated, presentation frameworks don’t contain any unique views, but use standard systems engineering models and diagrams. Appendix A provides descriptions of the 52 views contained with the eight DoDAF viewpoints, and the corresponding systems engineering models or diagrams.

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[4] A viewpoint describes data drawn from one or more perspectives and organized in a particular way useful to management decision-making. The compilation of viewpoints (e.g. capability, operational, system, programmatic viewpoints) represents the entire system, where the system can be explored as a whole, or from a single perspective.

[5] A view is a representation of a related set of information using formats or models.

In a MBSE tool environment, DoDAF is implemented based on the modeling language. For those tools that are based on UML and SysML, the DoDAF views correspond to the appropriate UML and SysML visualization. Similarly, for tools based on LML, DoDAF will be represented by the appropriate LML visualization. Appendix B depicts the relationships between DoDAF, UML/SysML, and LML.

Again, there are only so many ways to represent systems data. Therefore, it is essential to understand the different model types and what information can be gleaned from them.

G. The DoD Acquisition Lifecycle

The System Acquisition Lifecycle Model (Figure 8) (AcqNotes, 2019) identifies five primary phases which take the system from concept development and material solution analysis through operations and support. These phases, with their associated technical reviews, are briefly described in Table 4 (derived from Manning, 2019).

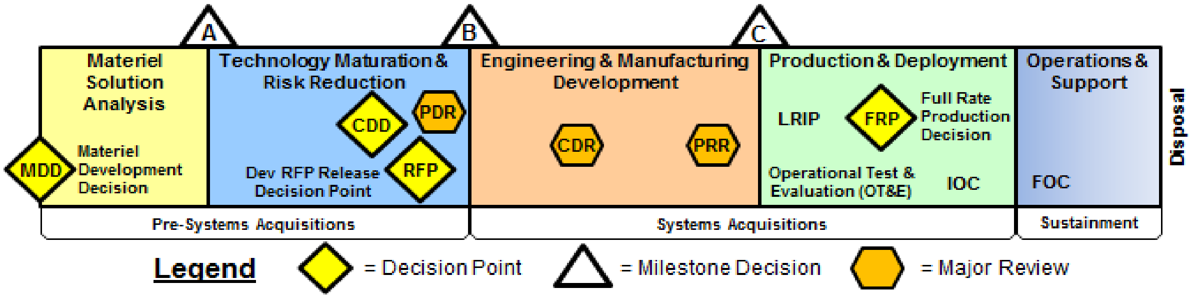

Figure 8. The Systems Acquisition Lifecycle (AcqNotes, 2019)

Milestone reviews are distinct points in time, to assess a program's "health" to determine if the program is ready to progress to the next steps. The technical reviews that are of the most interest for evaluation within a MBSE environment are (AcqNotes, 2019):

- **Initial Technical Review (ITR)** – A multi-disciplined review to support a program's initial Program Objective Memorandum (POM) within the Materiel Solutions Analysis phase (MSA).
- **Alternative System review (ASR)** - A review that assesses the preliminary materiel solutions that have been developed during MSA.
- **System Requirements Review (SRR)** - A review to ensure that system requirements have been completely and properly identified and that a mutual understanding between the government and contractor exists, during the Technology Maturation and Risk Reduction (TMRR) phase.
- **System Functional Review (SFR) –** A review to ensure that the system's functional baseline is established and can satisfying the requirements of the Initial Capabilities Document (ICD) or draft Capability Development Document (CDD) within the currently allocated budget and schedule, during TMRR.
- **Preliminary Design Review (PDR) –** A review that establishes the allocated baseline of a system to ensure a system is operationally effective. A PDR is conducted before the start of detailed design work and is the first opportunity for the Government to closely observe the Contractor's hardware and software design. This review is conducted during TMRR.

Table 4. Summary of the DoD System Acquisition Lifecycle Phases

Lifecycle Phase	Description of the Lifecycle	Technical Reviews within Lifecycle
Materiel Solution Analysis (MSA)	MSA assesses potential solutions for a needed capability in an Initial Capabilities Document (ICD) The MSA phase is critical to program success and achieving materiel readiness because it's the first opportunity to influence systems supportability and affordability by balancing technology opportunities with operational and sustainment requirements.	• Initial Technical Review (ITR) • Analysis of Alternatives (AoA) • Alternative System Review (ASR) ♦ **Milestone A**
Technology Maturation and Risk Reduction (TMRR)	The purpose of TMRR is to reduce technology risk, engineering integration, lifecycle cost risk and to determine the appropriate set of technologies to be integrated into a full system. The TMRR phase conducts competitive prototyping of system elements, refines requirements, and develops the functional and allocated baselines of the end-item system configuration.	• System Requirement Review (SRR) • System Functional Review (SFR) • Preliminary Design Review (PDR) ♦ **Milestone B**
Engineering and Manufacturing Development (EMD)	A system is developed and designed during EMD before going into production. The phase starts after a successful Milestone B - the formal start of any program. The goal of this phase is to complete the development of a system or increment of capability, complete full system integration, develop affordable and executable manufacturing processes, complete system fabrication, and test and evaluate the system before proceeding into the Production and Deployment (PD) Phase.	• Critical Design Review (CDR) • Test Readiness Review (TRR) ♦ **Milestone C**
Production and Development (PD)	A system that satisfies an operational capability is produced and deployed to an end user during PD. The phase has two major efforts; (1) Low-Rate Initial Production (LRIP) and (2) Full-Rate Production and Deployment (FRP&D). The phase begins after a successful Milestone C review.	• Full Rate Production (FRP) • Initial Operational Capability (IOC) ♦ **Full Operational Capability (FOC)**
	During OS, a system that satisfies an operational capability is produced and	• Sustainment

Operation and Support (OS)	deployed to an end user. The phase has two major efforts; (1) Low-Rate Initial Production (LRIP) and (2) Full-Rate Production and Deployment (FRP&D). The phase begins after a successful Milestone C review	♦ **Disposal**

The first three phases of the system acquisition lifecycle, through Engineering and Manufacturing Development culminating with Acquisition Milestone C, are where the most significant systems engineering activities occur. Implementing MBSE during later phases of the system acquisition lifecycle is possible, but programs should consider model adoption carefully. Beaufait (2018) demonstrated that MBSE can benefit programs post-Milestone C, however, introducing MBSE that far into the lifecycle of the program will face challenges related to cost, schedule, and a lack of understanding of MBSE. At this stage of the program, the implementation of MBSE has an additional cost that is likely not planned in the budget, and skeptical program managers are reluctant to make that investment in exchange for the promised benefits of MBSE (Beaufait, 2018).

H. Summary

The MBSE concepts in this chapter represent a fundamental change in the systems engineering discipline, practices, and processes because they allow for the precise representation of the system's entities and attributes and, through model structure, provide concordance. Complexity in the model-based environment is significantly reduced by separating and characterizing systems issues into various entity-based viewpoints and views. As such, MBSE requires a mindset change, a change in systems engineering processes, and a change in expectations of the artifacts required during the systems engineering process.

When considering conducting a technical review in a MBSE-environment, the following benefits can be expected:

- Improved communications among the development stakeholders (e.g. customer, senior management, program management, hardware, software, systems, and specialty engineers, system developers, and system testers);
- Increased ability to manage system complexity by enabling a system model to be viewed from multiple perspectives, and to analyze the impact of changes;
- Improved product quality by providing an unambiguous and precise model of the system that can be evaluated for consistency, correctness, and completeness;
- Enhanced knowledge capture and reuse of the information by capturing information in more standardized ways and leveraging built-in abstraction mechanisms inherent in model-driven approaches. This in tum can result in reduced cycle time and lower maintenance costs to modify the design.

III. MBSE Development Methodology throughout the System Acquisition Lifecycle

Successful implementation of MBSE, and the realization of the goals espoused in the Dod Digital Engineering Strategy, requires a fundamental shift in the development and use of engineering data to support system and programmatic decisions. In this environment, the model becomes central to the engineering of systems and ultimately the way that decisions are made.

The following discussion addresses model development across the system acquisition lifecycle through Engineering and Manufacturing Development. Figure 9[6] is a relationship diagram that will be used to depict and explain model development and use throughout the lifecycle. While various DoDAF views and other systems engineering artifacts are shown in the diagram, the instantiation of these views only represents how the system data will be displayed within the presentation framework. Again, in a MBSE environment, the system is represented virtually, therefore the data and relationships, not the views, are the “atomic” level of detail.

A. The System Lifecycle Model during the Materiel Solution Analysis Phase

The Materiel Solution Analysis (MSA) Phase assesses potential solutions for a needed capabilities identified by the stakeholder and formally documented in the Initial Capabilities Document (ICD). During this phase, various alternatives are analyzed to select the materiel solution and develop the strategy to fill the needed capability. This phase describes the desired performance to meet mission requirements, defines metrics, identifies the operational requirements needed to satisfy the capabilities, and provides an initial analysis of risks (Manning, 2019).

Milestone A marks the end of the MSA Phase. The purpose of Milestone A is to make recommendations, and seek permission to enter the Technology Maturation and Risk Reduction (TMRR) Phase (Manning, 2019).

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[6] Figure 9 is meant to be viewed digitally so that it can be expanded.

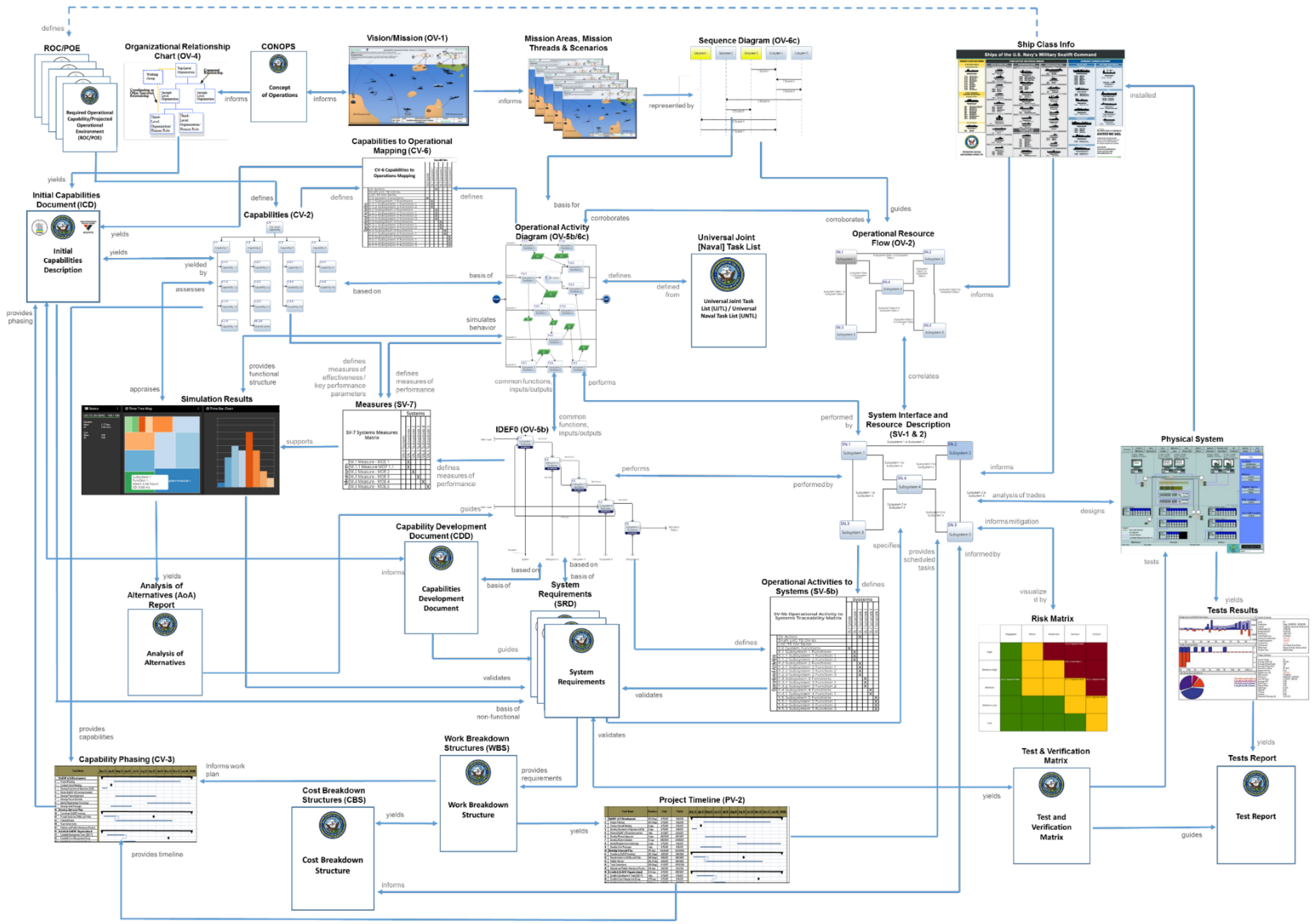

Figure 9. MBSE Development throughout the Systems Acquisition Lifecycle

The MSA model development process (Figure 10) begins with the identification of stakeholder needed capabilities, often contained in the Required Operational Capability/Projected Operational Environment (ROC/POE) documents. Often a system will be governed by multiple ROC/POE documents due the breadth of the future system deployment. The ROC/POE serves as the basis for the Capability Taxonomy (CV-2), the beginning of the modeling effort. Many ROC/POEs capture the majority of the capabilities to be satisfied but rarely contains all of them.

The Concept of Operations (CONOPS), often provided by the stakeholders, provides additional insights into the capabilities required. The CONOPS often includes an overarching High-Level Operational Concept Graphic (OV-1) which shows an overview of the operational concept, as well as the vision and mission of the system. The CONOPS usually identifies mission areas that contain mission threads and scenarios. The mission threads can be represented in scenario-focused OV-1s. These OV-1s offer sufficient detail to visualize the steps of the operations. These mission threads can be further represented by sequence diagrams (OV-6c). The OV-6c serves as the basis for the Operational Activity Model (OV-5b-6c).

The OV-5b/6c is a fit for purpose view that represents the sequence of functions as well as the inputs and outputs for each function. The functions in the OV-5b/6c are the same functions contained in the OV-6c, viewed from a different perspective. The functions can be grouped by the sub-system that they are assigned to. The OV-5b/6c can be further developed by information from the Universal Joint Task List (UJTL).

The operational entities depicted in the OV-5b/6c are based on the capability entities depicted in the CV-2. Thus, function x is based on capability y. These relationships are shown in the Capabilities to Operational Mapping (CV-6). Using the Organizational Relationship Chart (OV-4), the initial Capability Phasing (CV-3), the CV-2 and the CV-6, the ICD can be defined. In a MBSE environment, the ICD is an integral part of the model, thus has concordance with the views used to portray it.

The functions contained in the OV-5b/6c, can be viewed differently by using the IDEF0 (OV-5b). The functional entities in the OV-5b are the same functional entities in the OV-5b/6c. These entities are only represented once in the model, but can be viewed in several different ways, thus the model exhibits concordance. The OV-5b also contains the inputs and outputs included in the OV-5b/6c. The OV-5b goes further in capturing system data by identifying the policies, guidelines, rule and regulations that govern the functions. This view also initially identifies the system elements and relates them to the functions that they satisfy.

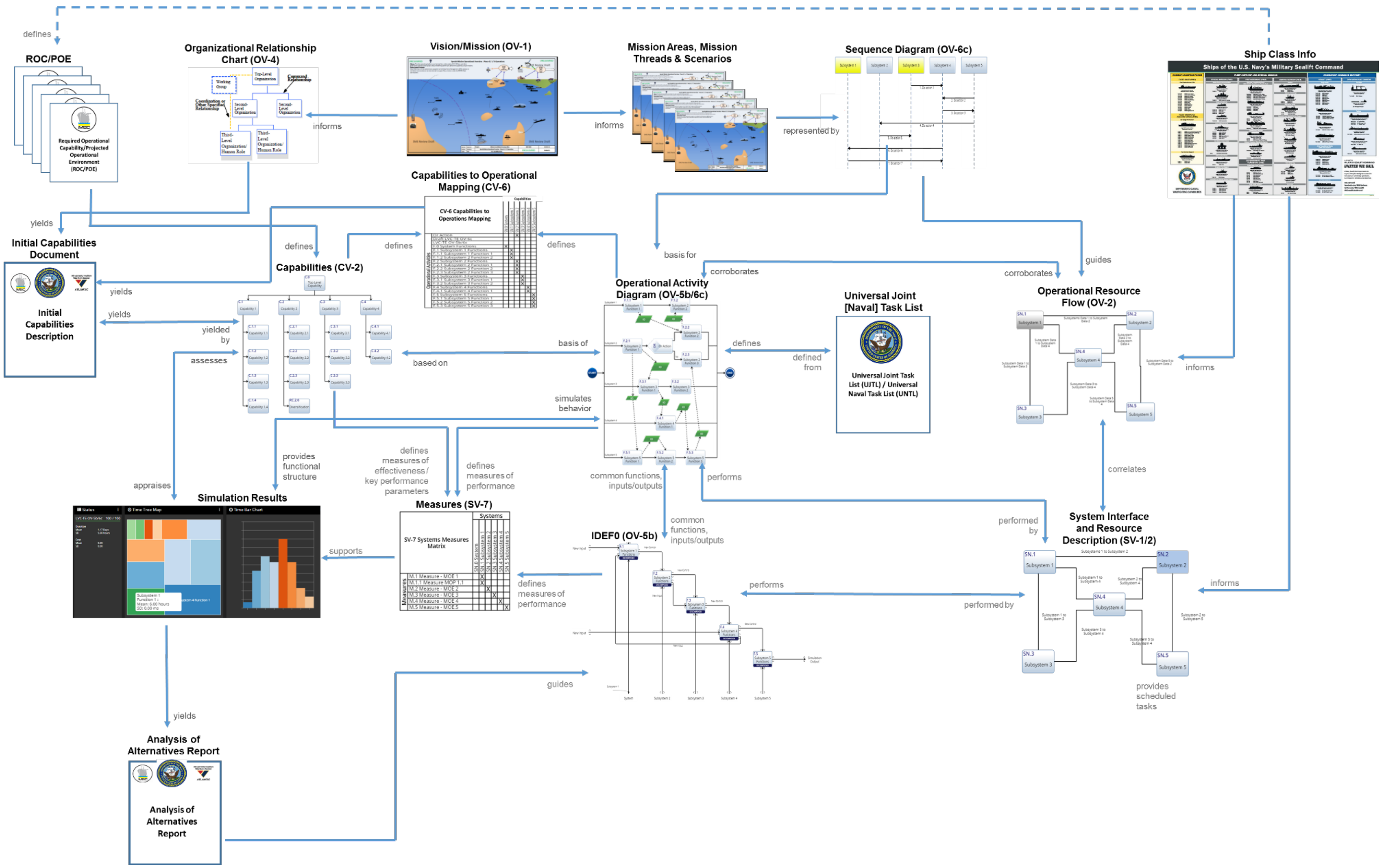

Figure 10. The MSA Development Process

With the data captured thus far, two additional complimentary views – the Operational Resource Flow (OV-2) and the System Interface Description (SV-1) - can be developed. Both of these views have a common structure that depicts the system elements that were first identified in the OV-5b. The connections in the OV-2, influenced by the functions in the OV-5b/6c, represent the data, and data characteristics (i.e. direction of flow, type, size, frequency, and duration), that flow between two system elements. The connections in the SV-1 represent the physical means (e.g. pipes, data links) by which data is transferred. The OV-2 defines the "what" that needs to be transferred, and is correlated to SV-1 which shows "how" the data is transferred.

With the data developed to this point, system measures can be defined in the Systems Measures Matrix (SV-7). The Measures of Effectiveness (MOE) and the Key Performance Parameters (KPP) are defined by the capabilities depicted in the CV-2. The Measures of Performance (MOP) are derived by the operational entities depicted in the OV-5b and OV-5b/6c.

At this point the data captured can be used to perform the analysis of alternatives (AoA). An AoA typically consist of the initial assessment of three areas – cost, risk, and performance. The system entities are related to operational entities via the OV-5b, and to risk and initial costs in the SV-1. System performance is represented mathematically within the operational entities. Many MBSE tools allow for these entities to be defined by several statistical distributions, thereby allowing for discrete event[7] and Monte Carlo simulation[8,9].

The last activity engineered in the MSA is development of the draft Capabilities Development Document (CDD). The CDD specifies the operational requirements for the system that will deliver the capabilities meeting the operational performance

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[7] Discrete event simulation models the operation of a system as a discrete sequence of events in time.

[8] Monte Carlo simulation uses a random number generator to model a series of events. This method is used when stochastic variables are present and probability of occurrence can be calculated (Downing, 1995).

[9] Discrete even and Monte Carlo simulation is often used during AoA, because it forecast the performance of the system in terms of throughput and timeliness.

requirements which are specified in the ICD and depicted by the entities developed thus far (Manning, 2019). The primary views used to develop the CDD are the CV-2 and OV-5b.

B. The System Lifecycle Model during Technology Maturation and Risk Reduction

The purpose of the Technology Maturation & Risk Reduction Phase is to reduce risks associated with technology, integration, and lifecycle cost; determine the appropriate set of technologies to be integrated into a full system; validate designs and costs; and evaluate manufacturing processes for the system build. TMRR refines requirements, conducts competitive prototyping of system elements, and develops the functional and allocated baselines of the final system configuration (Manning, 2019).

The modeling process (Figure 11) continues with the further development of the CDD. The CDD guides the development of the system requirements document (SRD). The SRD defines system level functional and performance requirements for a system (Manning, 2019). While the SRD is guided by the CDD in a document-based engineering environment, in a MBSE environment it is primarily derived from the OV-5b, SV-1, and the Operational Activities to Systems Matrix (SV-5b). As the system engineering effort progresses, these views are iteratively refined with more detailed data being developed with each iteration, thereby allowing for a natural progression of the requirements hierarchy from ICD to the CDD to the SRD, and ultimately to sub-system requirements documents.

In a MBSE environment, requirements are derived from the system-entity data, and corresponding relationships in the model. The primary view to visualize the relationships used to derive functional requirements is the OV-5b. This view contains all of the data required (system elements, functions, inputs, outputs, controls) to generate requirements. The initial system structure also influences the system requirements.

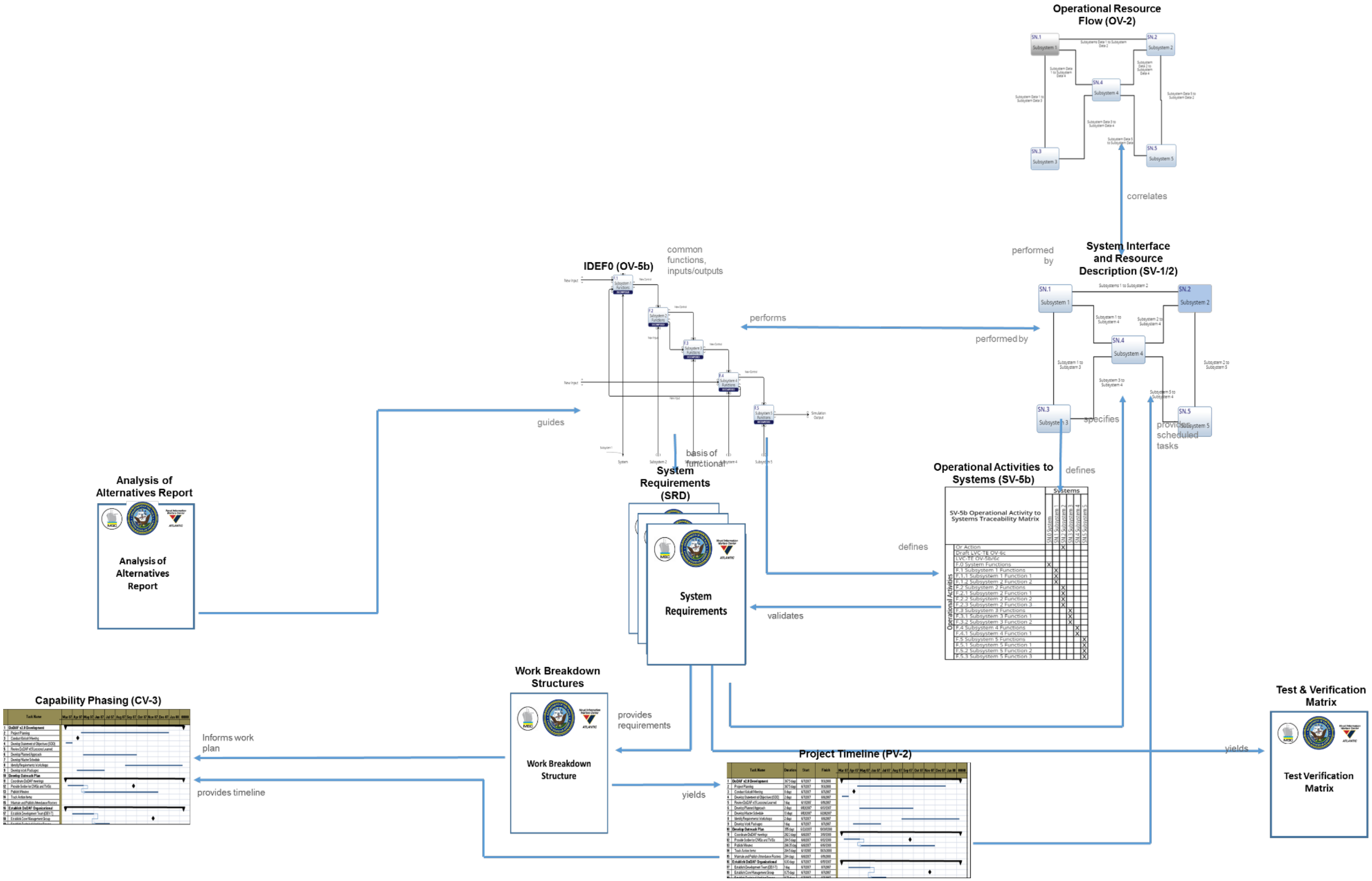


Figure 11. MBSE Development Process during Technology Maturation and Risk Reduction

The interfaces are defined via the SV-1. As previously stated, the flow interfaces between system elements in the OV-2 need to be correlated with the physical interfaces in the SV-1 to identify the proper interface requirements. The SV-5b is used to validate the system requirements by ensuring that each operation is satisfied by a system element, and each system element is assigned to an operation. The draft CV-3, which was developed in MSA, is matured here.

A corollary to the SRD is the Test and Verification Matrix, which shows how the system will be tested. Developing a Test and Verification Matrix in conjunction with the SRD is a good practice that validates that the requirements can be tested as written.

Once a detailed set of requirements is defined, the Work Breakdown Structure (WBS) can be developed. A WBS is a tool used to define a project in discrete work elements. It relates the elements of work to be accomplished to each other and to the end product. It's used for planning, development of the Cost Breakdown Structure (CBS), and the execution and control of the system development (Manning 2019). The CBS allocates costs to the various levels of the WBS.

Milestone B is considered the official start of the program (Manning 2019). The WBS informs the development of the final Capability Phasing (CV-3). A Project Timeline (PV-2) is derived from the WBS. This view depicts the detailed schedule for system development.

During TMRR, the system is iteratively developed, and a comprehensive risk assessment is conducted. The purpose of the risk assessment is to identify the root cause of cost, schedule, and performance issues within the systems. In a MBSE environment, the risks are related to system elements portrayed in the SV-1 and SV-2.

Towards the end of TMRR, system development has sufficiently matured and three-dimensional models and prototypes are developed. TMRR ends with Milestone B, where the program office seeks approval to enter the Engineering and Manufacturing Development (EMD) Phase.

C. The System Lifecycle Model during Engineering and Manufacturing Development

Systems design and development continues with the Engineering & Manufacturing Development (EMD) Phase (Figure 12), during which the system is developed and designed prior to production. The goal of EMD is to complete the development of a system or increment of capability, complete full system integration, develop affordable and executable manufacturing processes, complete system fabrication, and test and evaluate the system before proceeding into the Production and Deployment (PD) Phase (Manning, 2019).

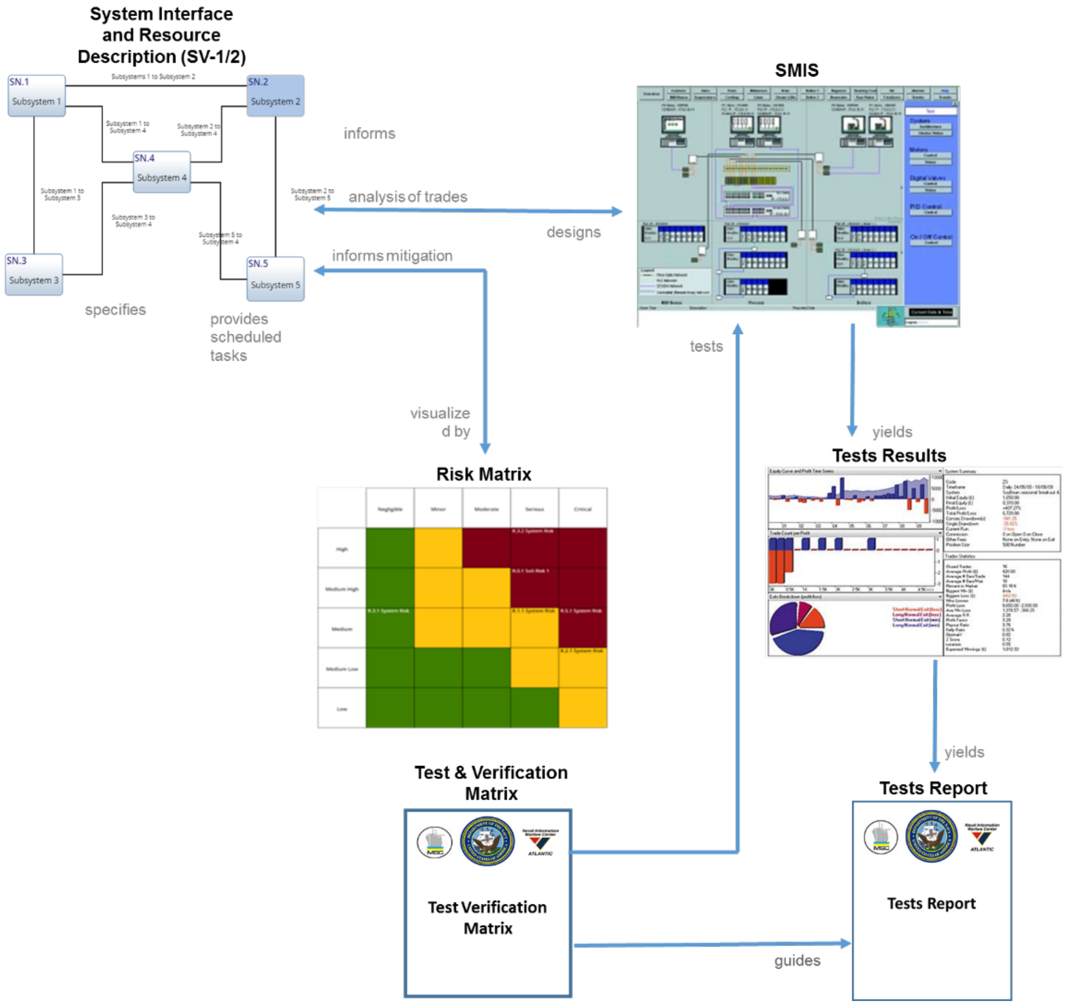


Figure 12. MBSE Development Process during Engineering and Manufacturing Development

Milestone C marks the end of the EMD Phase. The purpose of Milestone C is to make a recommendation or seek approval to enter the Production and Deployment (PD) Phase (Manning, 2019).

EMD consists of two major efforts: integrated system design and system capability; and manufacturing process demonstration. These two major efforts integrate the end item components and subsystems into a fully operational and supportable system. They also complete the detailed design to meet performance requirements with a producible and sustainable design and reduce system level risk. EMD typically includes the demonstration of a production prototype (Manning, 2019).

During EMD, MBSE is used for further system planning and development. As the system models are refined and further developed, other models within the framework must be changed to represent the new system baseline. Different system components lead to different operations. As the system and operations are changed, the capabilities must be re-evaluated to ensure that they are still being satisfied. Changes in the system baseline also impact risks – maybe new risks emerge, or current risks are mitigated. The change in the system baseline will likely have an impact on both cost and schedule. Given that the MBSE environment exhibits concordance, when a change is made in a system element it is captured in the model and then the changed element is portrayed throughout the model and all of the different viewpoints.

The MBSE environment can also be used to support the testing and verification of the system. During the development of the SRD, a Test and Verification Matrix was developed. This Test and Verification Matrix can be used to develop a test plan, which can be executed throughout the test and verification process.

D. Summary

This chapter began by referencing the DoD Digital Engineering Strategy Goal 1 to formalize the development, integration, and use of models to inform enterprise and program decision making (DASD(SE), 2018). The model development discussed in this chapter provides a systemic and repeatable process to produce the data required to make programmatic decisions throughout the acquisition lifecycle. One can argue that many of these "artifacts" have been created using document-based processes however, there are significant differences.

A MBSE environment requires an increased emphasis on the model, specifically the objects and relationships it contains, rather than the "artifact," to encourage better model development, usage, and decision-making. The model should include structure, which defines the relationships between the system entities, establishes concordance within the model, and allows for the emergence of system behaviors and performance characterizations. Each system element should be represented in the model as many times as it is represented in the real-world system – ONCE! The data that comprises the model is iteratively developed and maintained throughout the system lifecycle.

To achieve a MBSE environment that is envisioned by DoD Digital Engineering Strategy Goal 1, the strategy's Goal 5 must also be realized (DASD(SE), 2018):

> "Transform the Culture and Workforce to Adopt and Support Digital Engineering Across the Lifecycle.
>
> 5.1 Improve the digital engineering knowledge base.
> 5.2 Lead and support digital engineering transformation efforts.
> 5.3 Build and prepare the workforce."

MBSE requires a mindset change, a change in systems engineering processes, and a change in expectations of the artifacts required during the systems engineering process. The format of many systems engineering artifacts are decades old, and are treated separately from each other. For MBSE to be effective, the system data must create a virtual representation of the system, where each system entity is captured only once, and exhibits concordance.

Table 4 shows the technical reviews that are included in each phase of the acquisition lifecycle. The views developed throughout the acquisition lifecycle serve as significant contributors to the MBSE technical reviews discussed in Chapter IV. Figure 13 is a recap of the views created throughout the acquisition lifecycle, with the acquisition lifecycle phases superimposed.

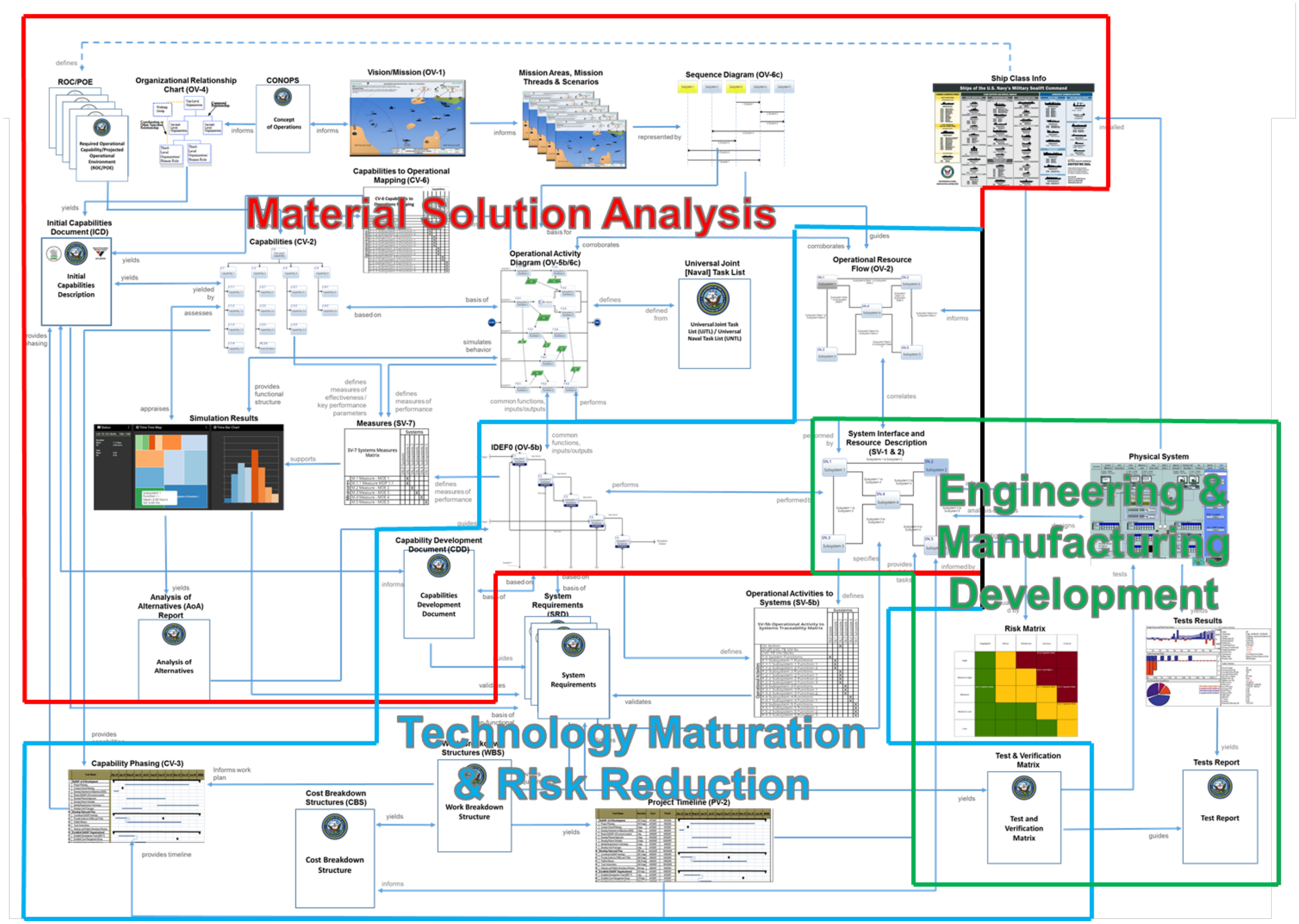


Figure 13. The MSA Development Process in Review

IV. Analysis of Technical Reviews in a MBSE Environment

A. Technical Reviews Overview

System engineering technical reviews are discrete points in time, within a system's lifecycle, where the system is evaluated against a set of program specific accomplishments (criteria). These criteria are used to track the technical progress, schedule, and program risks. SETRs serve as gates, that when successfully evaluated, demonstrate that the program is on track to achieve its final program goals, and should be allowed to proceed to the next acquisition phase. Figure 14 (an extension of Figure 8) shows the technical reviews superimposed on the Systems Acquisition Lifecycle Model (derived from Defense Acquisition University, 2018).

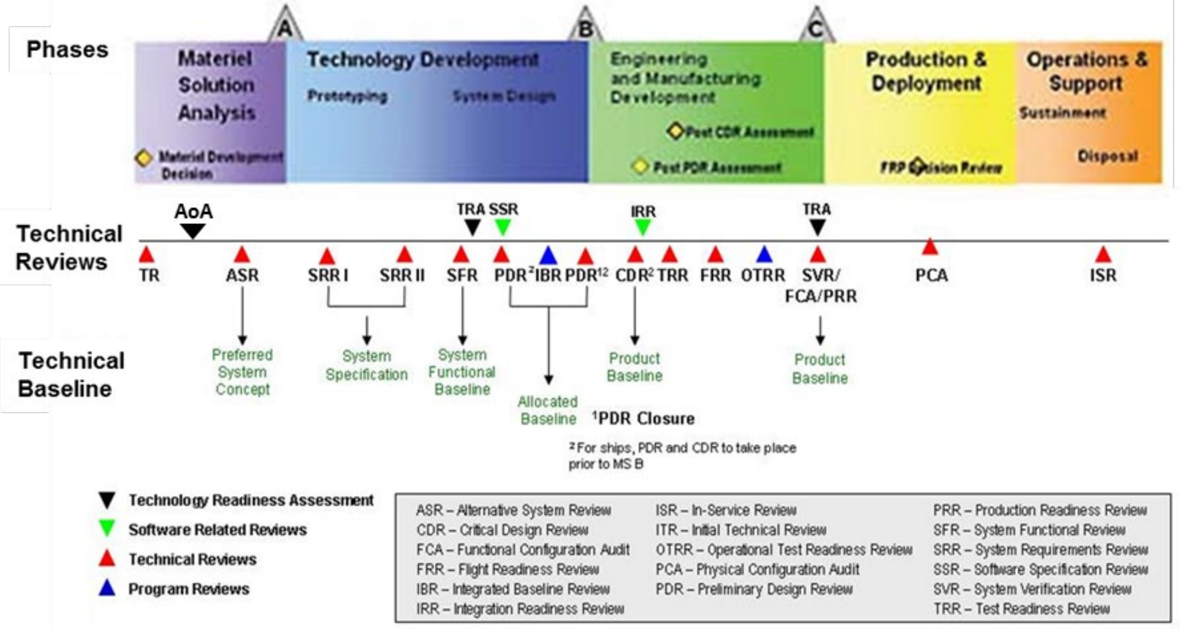


Figure 14. System Acquisition Lifecycle Model (Derived from Defense Acquisition University, 2018)

Current SETRs are based around lengthy evaluations of static, contractually obligated documents that are used to demonstrate successful completion of the exit criteria. System documents and artifacts are baselined to represent the system, and traditionally serve as evidence of programmatic progress. Typically, these documents are not synchronized, thus lacking concordance. As discussed in the MBSE approach in Chapters II and III, the "virtual" model of the system is created where each entity is ideally modeled once, but represented several times to address the information needs of various stakeholders. For SETRs, the model-based data is depicted by views within a presentation framework, similar to a document-based review.

Table 5 (Vaneman and Carlson, 2019) shows the applicability of MBSE views to the system acquisition lifecycle. The relationships in the matrix were made by correlating the generic criteria for each review, or content of the major documents, to the data in each system engineering view. The existing review criteria is designed to be addressed by document-based processes. These criteria need to be revised to account for the new insights that can be gleaned through a model-based approach.

As an example, consider the Alternative Systems Review (ASR). The ASR assesses the preliminary technology solutions that have been developed during the Materiel Solution Analysis (MSA) Phase. The SETR ensures that one or more proposed materiel solution(s) have the best potential to be cost effective, affordable, operationally effective and suitable, and can be developed to provide a timely solution at an acceptable level of risk to satisfy the capabilities listed in an Initial Capabilities Document (ICD) (Manning, 2019). Appendix C provides a description of the ASR.

The system engineering process typically has to progress to the point where the following information is available for the ASR (TTCP 2014):

- Description of how the users will conduct operations, and how they expect to use the new system in this context of major mission areas and scenarios;
- Statement of need, and capabilities, in terms oriented to the system users, the stakeholders, and independent of specific technology solutions;
- The required system characteristics and context of use of services and operational concepts are specified;

Table 5. Applicability of Systems Engineering Views with the Systems Acquisition Lifecycle (Vaneman and Carlson, 2019)

	Materiel Solution Analysis			Technology Develoment				Engineering and Manufacturing Development			Documents			
Systems Engineering Views	Analysis of Alternatives (AoA)	Alternative Systems Review (ASR)	Milestone A	System Requirements Review (SRR)	System Functional Baseline (SFB)	Preliminary Design Review (PDR)	Milestone B	Critical Design Review (CDR)	Test Readiness Review	Milestone C	Initial Capabilities Document	Capability Development Document (CDD)	System Requirements Specifications	Test Report
CV-2	x	x		x							x	x		
CV-3	x	x		x							x	x		
CV-6		x		x							x	x		
OV-1	x	x		x							x	x		
OV-2	x	x		x								x	x	
OV-4		x		x							x	x		
OV-5b	x	x		x	x	x						x	x	
OV-5b/6c	x	x		x	x	x					x	x	x	
OV-6c	x	x		x	x	x					x	x	x	
PV-2					x	x		x						
SV-1	x	x		x	x	x		x	x			x	x	x
SV-2					x	x		x	x				x	x
SV-5b				x	x	x		x	x			x	x	x
SV-7	x	x		x	x	x		x	x			x		x
Cost Esttimate	x			x				x						
Risk Matrix	x	x			x	x		x						
Similation Results	x			x		x		x	x				x	x
Test and Verification Matrix						x		x	x					x
Test Results								x	x					x
Work Breakdown Structure					x	x		x						

- Major stakeholder capabilities are identified and documented, but detailed system requirements analysis has yet to be completed;
- The constraints on a system solution are defined;
- Results of an analysis of alternatives with a recommended preferred solution;
- Initial plans for systems engineering (e.g. Overview and Summary information (AV-1), Systems Engineering Plan (SEP), Systems Engineering Management

Plan (SEMP)) providing the notion of “how” this system can be realized, including the level of process and process maturity needed to generate a system of the required complexity;

- Initial definition of the environment and the characteristics of the threat;
- Initial test & evaluation strategy including test cases derived from user operational vignettes, concept of operations and capability description;
- An understanding of where the greatest risks and challenges may reside.

An analysis of the ASR generic criteria (DAU, 2018) is shown in Table 6 (Vaneman and Carlson, 2019). First the criteria are reviewed in the context of traditional reviews. Many of the criteria were assessed to be partially satisfied. These results do not suggest that ASRs have not been performed properly in the past. Rather, given the absence of concordance in document-based reviews, the criteria requiring different types of data using different artifacts is extremely difficult to achieve efficiently and effectively. All of the criteria were assessed to be satisfied in a MBSE environment because of the concordance. The model-based systems engineering views needed to address the criteria are also shown in the table.

Table 6. ASR Criteria and Related Views (Vaneman and Carlson, 2019)

Criteria	Satisfied by Traditional Review?	Satisfied by MBSE?	Views
Is the initial CONOPS updated to reflect current user position about capability gap(s), supported missions, interfacing/enabling systems in the operational architecture?	Partial	Yes	CV-2, CV-6, OV-1, OV-6c, OV-5b/6c
Are the required related solutions and supporting references (ICD and CDDs) identified?	Partial	Yes	CV-2, CV-3, CV-6, OV-4, OV-5b, OV-5b/6c
Are the thresholds and objectives initially stated as broad measures of effectiveness and suitability (e.g., KPPs)?	Yes	Yes	CV-2, OV-5b, OV-5b/6c, SV-7
Is there a clear understanding of the system requirements consistent with the ICD?	Yes	Yes	CV-2, CV-3, CV-6, OV-4
Are high-level description of the preferred materiel solution(s) available and sufficiently detailed and understood to enable further technical analysis in preparation for Milestone A?	Partial	Yes	OV-2, OV-5b, SV-1
Are interfaces and external dependencies are adequately defined for this stage in lifecycle?	Partial	Yes	OV-2, SV-1
Are system requirements are sufficiently understood to enable functional definition?	Partial	Yes	OV-5b, OV-5b/6c
Is a comprehensive rationale available for the preferred materiel solution(s), based on the AoA?	Partial	Yes	CV-2, CV-3, CV-6, OV-2, OV-4, OV-5b, OV-5b/6c.
Can the proposed material solution(s) satisfy the user needs?	Partial	Yes	CV-2, CV-3, CV-6, OV-2, OV-5b, OV-5b/6c.
Have cost estimates been developed and were the cost comparisons across alternatives balanced and validated?	Partial	Yes	OV-2, OV-5b, SV-1
Have key assumptions and constraints associated with preferred materiel solution(s) been identified?	Partial	Yes	OV-2, OV-5b, SV-1

B. Technical Reviews in a Model-Based Environment

In a MBSE environment, as discussed in Chapter II, the model is a virtual representation of the system, and becomes the focus of a SETR. Using the model as the source for decision-making throughout the system acquisition lifecycle is a significant departure since programs often generate unique artifacts for the sole purpose of the reviews.

A significant difference between traditional document-based technical reviews and model-based technical reviews is model structure. As discussed in Chapter II, structure defines the relationships between the system entities, establishes concordance within the model, and allows for the emergence of system behaviors and performance characterizations. Structure provides decision-makers with insights that have been heretofore unavailable. This includes emerging system behavior, and the assurance that a common system baseline is used to report on various aspects of the systems.

When thinking about system structure, one can envision how the various system elements are identified, interact, and behave when combined. Structure within a MBSE environment expands the traditional thinking about system structure in that the model includes system entities that represent the system's functions, physical system, software elements, characteristics, and risks, just to name a few. Table 1 in Chapter II shows the possible entities from an LML perspective. Figure 15 (NIWC Atlantic, 2019) shows an example of a Conceptual Data Model (CDM) used to represent model structure.

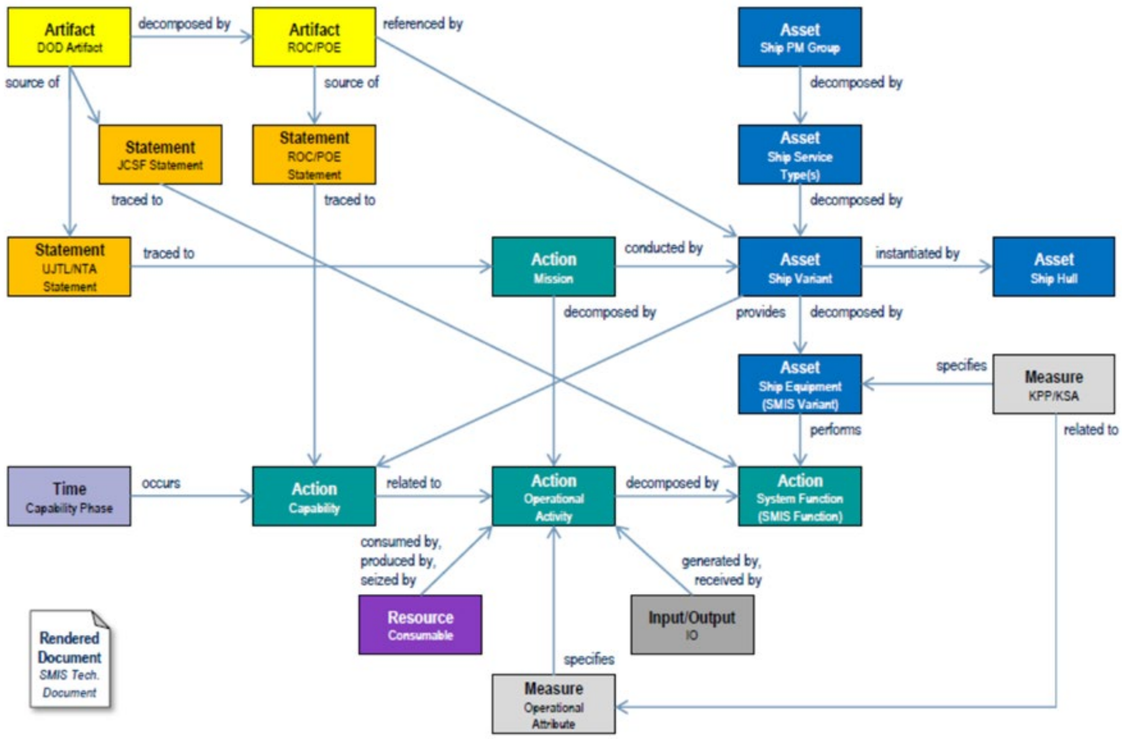


Figure 15. Example Conceptual Data Model (NIWC Atlantic, 2019)

Model structure is important to SETRs because it not only represents the possible relationships within the system, it also allows for the emergence of system behaviors, and exhibits concordance within the system. Concordance is important in MBSE SETRs because it allows one system entity to be examined from several different perspectives that a review of documents will not yield in traditional technical reviews. For example, referring to Figure 15, Asset "Ship Equipment (SMIS Variant)" is child of Asset "Ship Variant." It is related to ("performs") Action "Ship Function (SMIS Function)." Thus, a change in "Ship Variant" may impact and drive changes to the "Ship Equipment," which in turn may impact the "System Function." In a MBSE environment, where concordance is exhibited, the change to "Ship Variant" will causally trace to impacts throughout the model.

An example model, that shows how a MBSE environment can be used for a technical review, was developed for this research effort. The example shown is a partial example of a model used for an ASR, with limited inputs, but can be expanded in accordance with the ontology and relationships discussed in Chapter II.

The model was developed in SPEC Innovations Innoslate MBSE tool, which is based on the LML language. While each MBSE tool is different, the capabilities shown in this example able to be performed by other MBSE tools.

The model begins with the import of the ASR criteria (shown as a requirement document in Figure 16), and other related documents. These documents can be Concepts of Operation (CONOPS), requirements specifications, test plans, any other document use by the program office. These documents can be of various formats, but MS Word works best.

As the documents are imported, the tool parses the documents (LML Document entity) into individual statements (LML Statement entity). These statements can then be related to each other as appropriate. For example, each statement representing a review criterion can be related to the relevant supporting evidence in the systems engineering documents. This is shown in Figure 17.

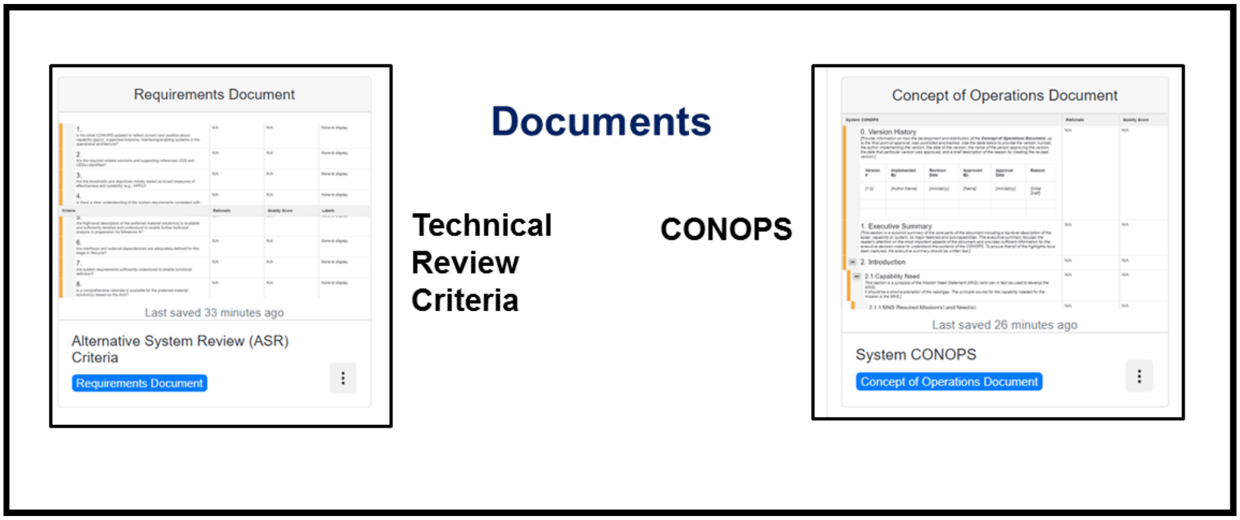
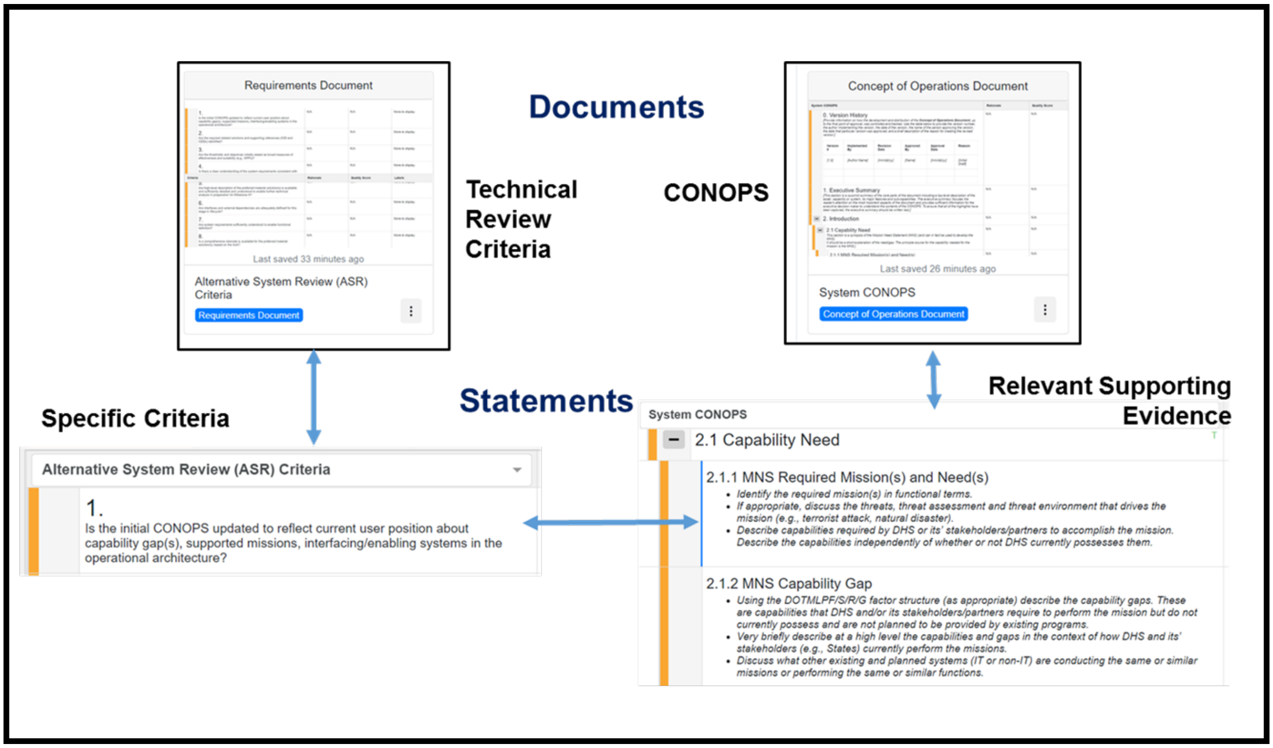


Figure 16. Documents Imported in a MBSE environment



1\.
Is the initial CONOPS updated to reflect current user position about capability gap(s), supported missions, interfacing/enabling systems in the operational architecture?

2.1 Capability Need

2.1.1 MNS Required Mission(s) and Need(s)

- *Identify the required mission(s) in functional terms.*
- *If appropriate, discuss the threats, threat assessment and threat environment that drives the mission (e.g., terrorist attack, natural disaster).*
- *Describe capabilities required by DHS or its' stakeholders/partners to accomplish the mission. Describe the capabilities independently of whether or not DHS currently possesses them.*

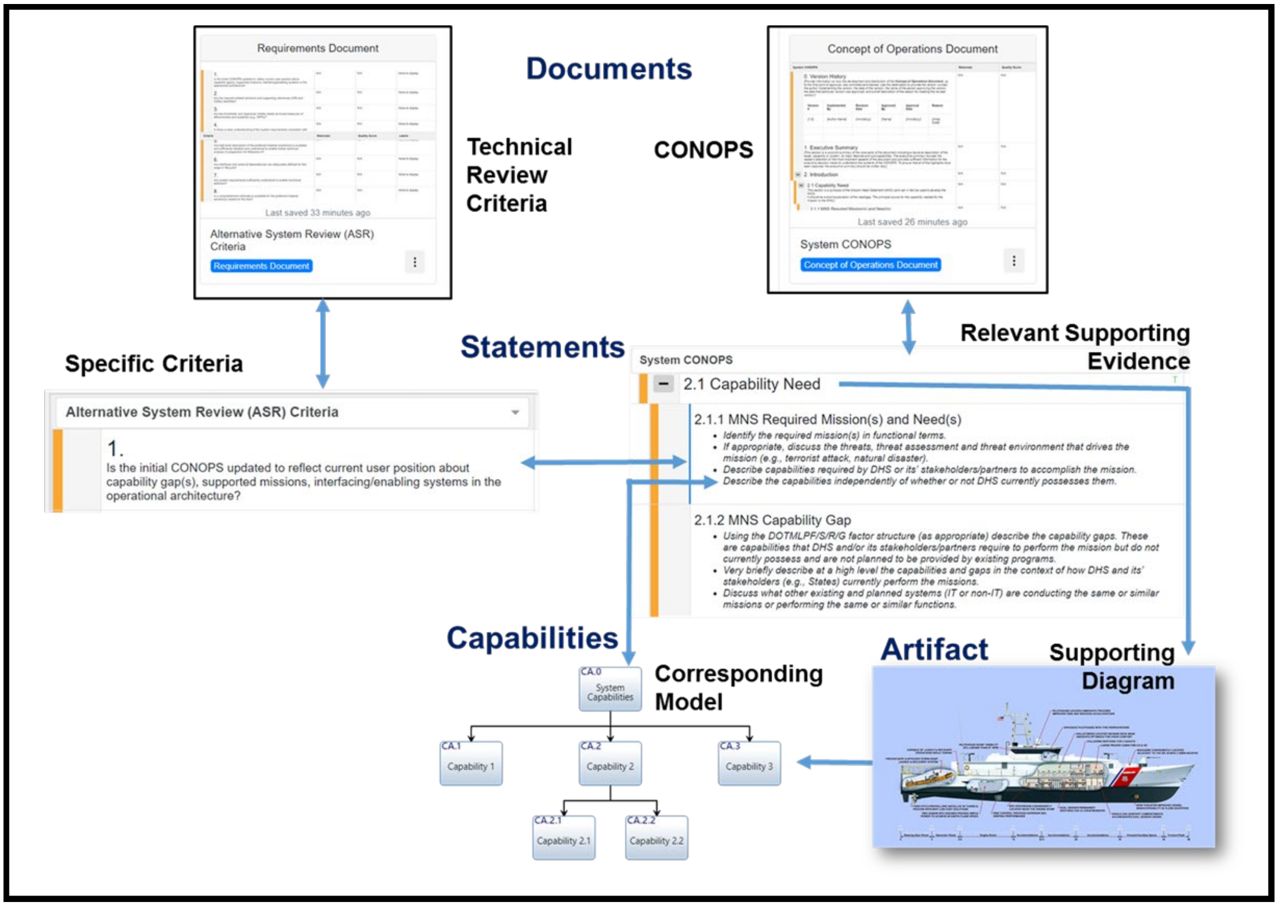
2.1.2 MNS Capability Gap

- *Using the DOTMLPF/S/R/G factor structure (as appropriate) describe the capability gaps. These are capabilities that DHS and/or its stakeholders/partners require to perform the mission but do not currently possess and are not planned to be provided by existing programs.*
- *Very briefly describe at a high level the capabilities and gaps in the context of how DHS and its' stakeholders (e.g., States) currently perform the missions.*
- *Discuss what other existing and planned systems (IT or non-IT) are conducting the same or similar missions or performing the same or similar functions.*

Figure 17. Specific Review Criteria Related to the Relevant Supporting Evidence

The SETR criteria could be related to various entities, represented in a corresponding model that support the criteria, or the statements within the documents could be related to entities, also represented in a corresponding model. In Figure 18, a statement from the CONOPS is related to a capability (LML Action entity), that is depicted as a Capabilities Hierarchy. While this capability entity is depicted in a hierarchy mode, the entity is part of the virtual model where it is represented only once.

The material for the SETR may also include artifacts (LML Artifact entity) such as diagrams, photos, and other material that is developed outside of the MBSE environment and will be used as supporting evidence for a review, and amplifying information for the systems model. In Figure 18, the supporting document is a picture that cannot be decomposed in separable parts, or modified within the MBSE environment.



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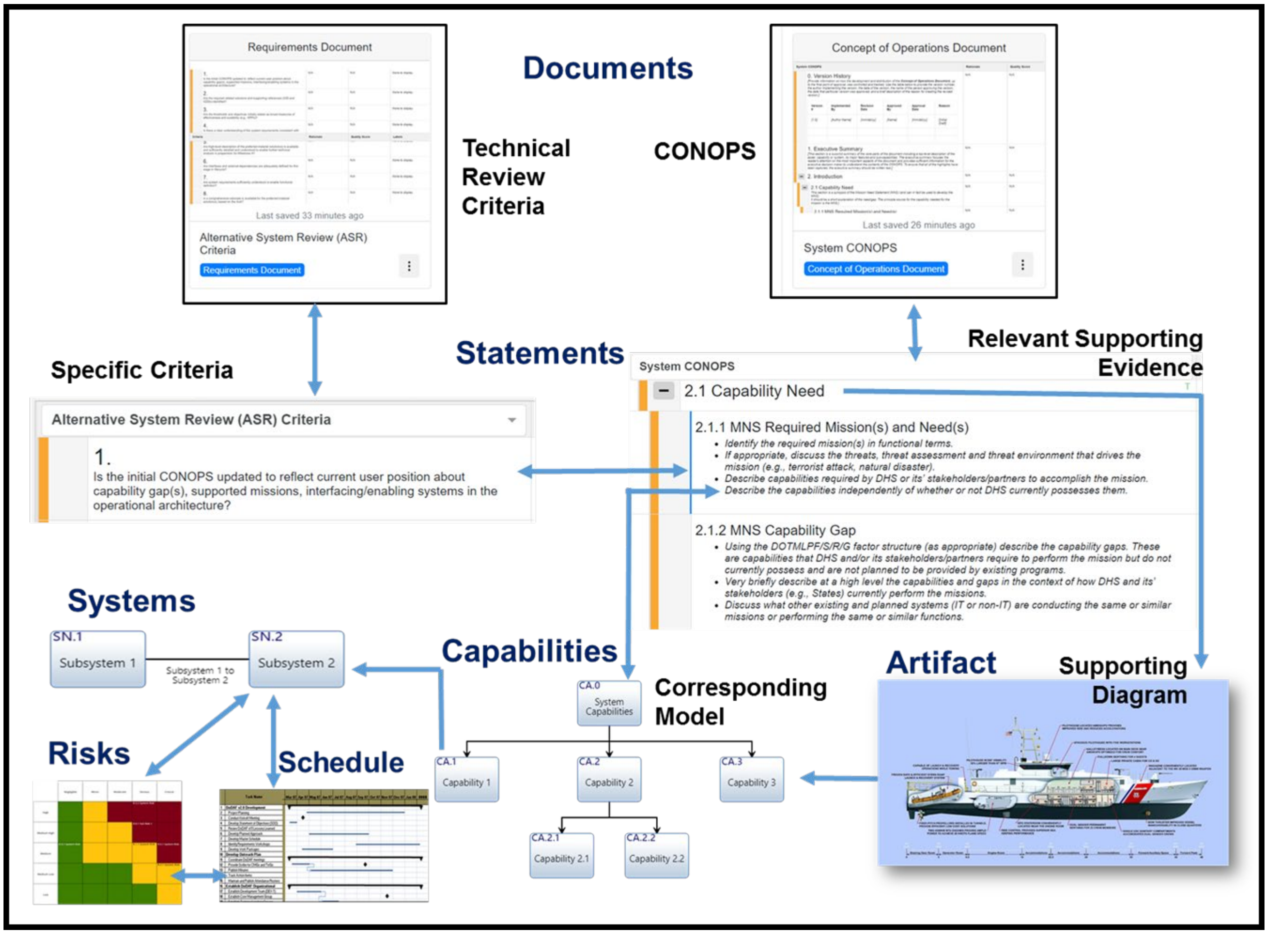
- *Discuss what other existing and planned systems (IT or non-IT) are conducting the same or similar missions or performing the same or similar functions.*

Figure 18. Supporting Statements Related to Entities and Artifacts

The model entities can be further related to other model entities. In Figure 19, capabilities (LML Action entities) are related to system (LML Asset entities). This relation means that the system entity is used to satisfy the capability entity. The system entity in Figure 19 is further related to risks and schedule entities. The relationships made are within the model and only constrained by the projects CDM. If no project CDM exists, the limit of LML ontological relationships is approximately 10^{18} relationships.

Using Figure 19, if risks are being aggressively mitigated, they can impact the project schedule as well as the system component and functionality. As the risks are mitigated, the system components may be changed, and hence the way that the related capability is satisfied may change affecting the related statement in the document that contains the supporting evidence.

Additionally, changes to the statement may change the assessment of the review criteria. This MBSE process adds a deeper level of complexity and traceability into technical reviews not available with a document-based review.



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- *Discuss what other existing and planned systems (IT or non-IT) are conducting the same or similar missions or performing the same or similar functions.*

Figure 19. Partial Traceability within the Virtual Model

C. Applicability of Current Technical Review Criteria to MBSE Technical Reviews

An initial assumption for this research was that MBSE, as it exists with the approximately 85 systems engineering models, could be used to address all SETR questions, however the questions may have to be adjusted from binary (yes or no) questions (e.g. "Does the project have a Risk Management Guide?") to questions that provide more concrete details to allow for better program and system analysis.

This research found that MBSE, as it currently exists, can be used to satisfy the criteria found throughout the MSA phase, and during most of the TMRR phase. However, current MBSE environments do not adequately address the criteria for a Preliminary Design Review (PDR). Review criteria for PDRs was reviewed from the Defense Acquisition University (DAU), the Navy's Strategic Systems Program (SSP), and the Naval Air Systems Command (NAVAIR). The criteria from NAVAIR was eventually selected to be reviewed because it was found to be the most comprehensive.

During the course of this research, 846 PDR questions were evaluated for applicability to be addressed by current MBSE. Of these 846 questions, only 80 questions could be addressed directly by MBSE today. The reason for this is the diversity in review categories. Fifty-six PDR Criteria Categories were derived. Of these 56 categories, only eleven categories were adequately satisfied by MBSE, thirteen categories were partially satisfied by MBSE, and 32 categories were not adequately satisfied by MBSE. Table 7 shows the PDR Criteria Categories and the assessed MBSE ability to satisfy those criteria.

The PDR results do not mean that MBSE should be abandoned. The DoD Digital Engineering Strategy (2018) goal 1.3 states:

> 1.3 "Use models to support engineering activities and decision making across the lifecycle."

There is a strong need to ensure that the systems engineers and stakeholders understand the different model types and what information can be gleaned from them.

Table 7. PDR Criteria Catogories and the MBSE Ability to Satisfy Them

PDR Criteria Category	MBSE Ability to Satisfy Criteria
Schedule Planning	↑
Program Critical Path	→
Cost / Schedule / Performance / Key Performance Parameters (KPP)	↑
Latest Cost Estimate	→
Production Costs Estimates	↓
Operating and Support (O&S) Costs Estimate	→
Earned Value Management (EVM)	→
Work Breakdown Structure (WBS) review	↑
Software Metrics	→
Program Management	↑
Configuration Management (CM)	↑
Systems Engineering Processes	↑
Acquisition Logistics Support Management and Staffing	↓
Automated Information Technology (AIT)	↓
Risk Management (RM) Processes	↑
Logistics Budgeting and Funding	↓
Test Processes (TEMP, T&E Strategy, etc.)	→
Production Processes (ISO 9000, etc.)	↓
Software	→
Producibility	↓
Human System Safety	↓
Aeromechanics	↓
Structures	↑
Materials	↓
Mass Properties	↓
Human Systems Integration Engineering	↓
Environmental Regulations	↓
Safety and Health	↓
System Safety	↓
Hazardous Material Management	↓
Pollution Prevention Program	↓
Maintenance Planning	→
Testability and Diagnostics	→
Manpower, Personnel and Training (MP&T)	↓
Training Outline and Curricula Design	↓
Training Material	↓

Training Devices / Simulators	↓
Supply Support	↓
Organic Support	↓
Supply Chain Management / PBL Management	↓
Warranty Management	↓
Support Equipment	↓
Technical Data	↑
Product / Technical Data Package and Publications	↓
Computer Resources	↓
Facilities	↓
Packaging, Handling, Storage and Transportation	↓
Design Interface	↑
Manufacturing Planning	↓
Parts and Materials Selection	↓
Commodity Management	↓
Root Cause Corrective Action	→
Obsolescence	↓
Platform Diagnostics Integration	→
Life Cycle Logistics	→
Performance Requirements	↑
Key	
Adequately satisfies criteria in category	↑
Partially satisfies criteria in category	→
Does not satisfy criteria in category	↓

Given this goal, it is clear that new visualization techniques must be developed to fully realize a digital engineering environment. Developing new visualizations for digital engineering also makes sense because the visualizations that are used for MBSE today are the visualizations that have evolved over time to support the system engineering community, and not many of the other technical review categories.

D. Applicability of Current Technical Review Criteria to MBSE Technical Reviews

Formalized planning for modeling and decision-making across the lifecycle must include a new approach for SETRs. This not only includes the content of the reviews, but how the models will be assessed against the criteria (Dam, 2018). We found that current processes for assessing documents are not adequate in a MBSE environment. For example, many questions are binary in nature, and do not provide any insight into the "health" of a program. For example, a question of the form, "Does the program have a risk management plan?" The answer is "yes" or "no" and does not provide any insights into the quality of the plan content or the program "health."

The DoD Digital Engineering Strategy (2018) states that there is a strong need to ensure that decision-makers understand the different model types and what information can be gleaned from them. The results of our analysis of how MBSE will satisfy a PDR were unexpected because we believed that current MBSE visualizations would address a wider range of the PDR content. While our research found only 11% of PDR questions to be adequately addressed by current MBSE methods, we do not recommend abandoning the use of MBSE for PDR assessments. Instead, it is clear from this research that new visualizations must be developed to adequately address the needs, and provide greater insight with faster comprehension for the details across the lifecycle.

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V. Conclusions and Recommendations

The systems engineering discipline is undergoing a sea change in processes; a transformation from document-based to model-based processes. DoD, the world's largest systems engineering concentration, is central to this conversion. In 2018, DoD published the Digital Engineering Strategy, which identifies five goals to achieving engineering in a digital environment. While the satisfaction of each goal is of equal importance, this research focused primarily on Goal 1 - formalize the development, integration, and use of models to inform enterprise and program decision-making. Specifically, this research explored SETRs in a MBSE environment.

The issues addressed in this research were:

1. Define a systematic process for developing the virtual model of the system, as the program progresses through the acquisition lifecycle.
2. Evaluate representative SETR entrance criteria and related questions, and determine if questions could be represented by a "virtual system" as data that is required for system and program decisions in a MBSE environment.
3. Define how the model of the system can be used in lieu of "artifacts" to provide decision-makers with a more complete representation of the system during SETRs.

The first question that was considered is, "Define a systematic process for developing the virtual model of the system, as the program progresses through the acquisition lifecycle." Chapter III discusses the iterative development of the virtual model of the system throughout the acquisition process. This development, in a MBSE environment, is significantly different than with document-based systems engineering. In a MBSE environment, the system is virtually represented in a model, where each system entity is only represented in the model as many times as it is represented in the real world – only once.

The virtual model also contains structure which defines the relationships between the system entities, establishes concordance within the model, and allows for the emergence of system behaviors and performance characterizations. These relationships between the principal entities define structure, address complexity, and ensure system traceability across the model (Vaneman, 2016). This virtual model of the system is then used by engineers and decision-makers throughout the acquisition process, and during SETRs.

The second question evaluated representative SETR entrance criteria and related questions from DAU, SSP, and NAVAIR to determine how questions could be represented by a "virtual system" as data that is required for system and program decisions in a MBSE environment. MBSE supported the early technical reviews, where traditional MBSE visualizations were very applicable. However, SETRs at PDR and later, showed less promise for being fully accomplished using current MBSE visualizations as evaluated today.

During the course of this research, 846 PDR questions were evaluated for applicability to be addressed by current MBSE. Of these 846 questions, only 80 questions could be fully addressed by MBSE today. The reason for this is the diversity in review categories. Of the 56 PDR categories which were identified through the thematic grouping of review questions, only eleven categories are adequately satisfied by MBSE, thirteen categories are partially satisfied by MBSE, and 32 categories are not adequately satisfied by MBSE. Chapter IV Table 7 shows the PDR Criteria Categories and the assessed MBSE ability to satisfy those criteria.

In addition to the PDR evaluation categories not being represented in MBSE visualizations, there is another issue. Over time, the scope of the PDR questions increased to the point where many senior leaders agree that questions were added without an appropriate audit of suitability. For PDRs to be more effective in their current form, and in a MBSE environment, a detailed evaluation of the review criteria needs to be explored, and questions need to change, to truly use MBSE to assess the program and system at PDR.

While this research found PDR results are not adequately addressed, that does not mean that MBSE should be abandoned. In the third question, this research explored how the virtual model of the system can be used in lieu of "artifacts" to provide decision-makers with a more complete representation of the system during SETRs. Current visualizations have been used in systems engineering for decades, but do not adequately represent all systems relationships and complexities. New visualizations for MBSE need to be developed to better represent the system, and its complexities.

As DOD organizations migrate to a MBSE environment, efficiencies will be gained by transitioning from the traditional paper-based reviews to model-based reviews. Model-based reviews allow for complexity to be managed more efficiently because data, in lieu of "systems engineering products," is the commodity that will be used to evaluate the entrance criteria. The MBSE milestone reviews will provide greater insight with faster comprehension for the details across a program's lifecycle. This will not only provide efficiencies for the review, but will improve the program's cost and schedule efficiency.

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Appendix A. Mapping of DoDAF Views to Systems Engineering Models

The Department of Defense Architecture Framework has eight viewpoints (Figure A1): Capabilities; Operations; Systems; Services; Standards; Program; Data and Information; and, All (Overarching Context) (DoD, 2009). These viewpoints contain 52 views (i.e. visualization models). The framework also has the flexibility to include other models, or “fit for purpose views,” that may be needed to address perspectives that are not included in the framework. A comprehensive discussion of each visualization model is beyond the scope of this paper. However, a brief introduction of the eight viewpoints is described below. Tables A1 to A8 show the DoDAF views, and corresponding system engineering model, for the eight viewpoints (DoD, 2009).

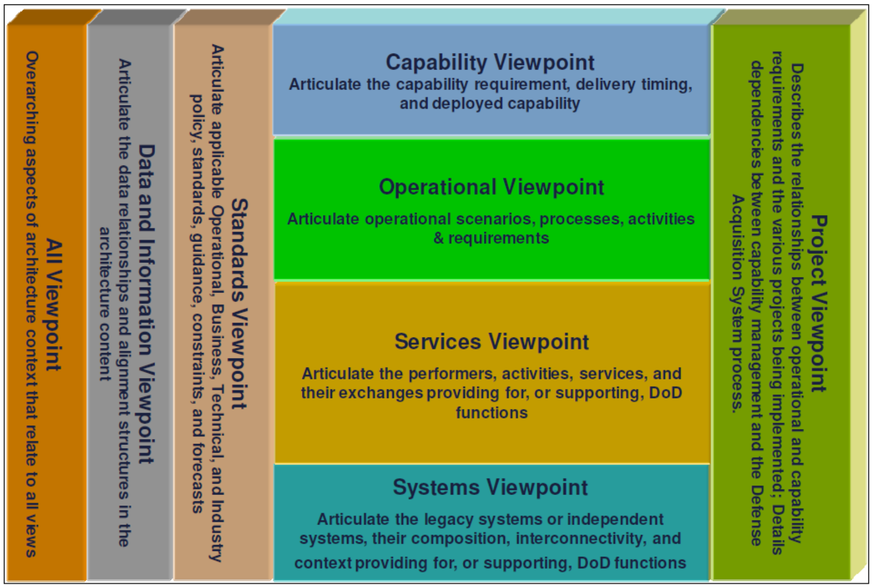

Figure A1. The DoDAF Framework (DoD, 2009)

All Viewpoints - Provides the overarching context and definitions for all of the viewpoints and views.

Table A1. Visualization Models for the All Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
All Viewpoint	AV-1: Overview and Summary Information	Textual description	Describes a Project's Visions, Goals, Objectives, Plans, Activities, Events, Conditions, Measures, Effects (Outcomes), and produced objects.
	AV-2: Integrated Dictionary	Textual description, table	An architectural data repository with definitions of all terms used throughout the architectural data and presentations.

Capability Viewpoint – Articulates the mission needs, or capability requirements, delivery and implementation timing, and deployed capability.

Table A2. Visualization Models for the Capability Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
Capability Viewpoint	CV-1: Vision	Hierarchy chart	The overall vision for transformational endeavors, which provides a strategic context for the capabilities described and a high-level scope.
	CV-2: Capability Taxonomy	Hierarchy chart	A hierarchy of capabilities which specifies all the capabilities that are referenced throughout one or more Architectural Descriptions.
	CV-3: Capability Phasing	Fishbone chart	The planned achievement of capability at different points in time or during specific periods of time. The CV-3 shows the capability phasing in terms of the activities, conditions, desired effects, rules complied with, resource consumption and production, and measures, without regard to the performer and location solutions.
	CV-4: Capability Dependencies	Table or matrix	The dependencies between planned capabilities and the definition of logical groupings of capabilities.
	CV-5: Capability to Organizational Development Mapping	Table or matrix	The fulfillment of capability requirements shows the planned capability deployment and interconnection for a particular capability phase. The CV-5 shows the planned solution for the phase in terms of performers and locations and their associated concepts.

	CV-6: Capability to Operational Activities Mapping	Table or matrix	A mapping between the capabilities required and the operational activities that those capabilities support.
	CV-7: Capability to Services Mapping	Table or matrix	A mapping between the capabilities and the services that these capabilities enable.

Operational Viewpoint - Articulates the operational scenarios (mission threads), processes, activities and requirements.

Table A3. Visualization Models for the Operational Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
Operational Viewpoint	OV-1: High Level Operational Concept Graphic	High-level graphic, Network Diagram, Asset Diagram,	The high-level graphical/textual description of the operational concept.
	OV-2: Operational Resource Flow Description	Asset Diagram, Data Flow Diagram	A description of the resource flows exchanged between operational activities.
	OV-3: Operational Resource Flow Matrix	Table or Matrix	A description of the resources exchanged and the relevant attributes of the exchanges.
	OV-4: Organizational Relationships Chart	Organizational Chart	The organizational context, role or other relationships among organizations.
	OV-5a: Operational Activity Decomposition Tree	Hierarchy Chart	The capabilities and activities (operational activities) organized in a hierarchal structure.
	OV-5b: Operational Activity Model	IDEF0 Model, Functional Flow Block Diagram, Enhanced Functional Flow Block Diagram, Action Diagram	The context of capabilities and activities (operational activities) and their relationships among activities, inputs, and outputs; Additional data can show cost, performers or other pertinent information.
	OV-6a: Operational Rules Model	"If, then, else" statements that capture sequencing constraints	One of three models used to describe activity (operational activity). It identifies business rules that constrain operations.
	OV-6b: State Transition Description	State-machine Diagram	One of three models used to describe operational activity. It identifies business process (activity) responses to events (usually, very short activities).
	OV-6c: Event-Trace Description	Sequence Diagram	One of three models used to describe operational activity. It traces actions in a scenario or sequence of events.

Systems Viewpoint – Articulates the systems, subsystems, composition, intra- and inter-connectivity, and provides the context of supporting system functions.

Table A4. Visualization Models for the Systems Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
Systems Viewpoint	SV-1 Systems Interface Description	Network Diagram, Hierarchy Diagram, Block Definition Diagram, Internal Block Diagram	The identification of systems, system items, and their interconnections.
	SV-2 Systems Resource Flow Description	Network Diagram, Package Diagram	A description of resource flows exchanged between systems.
	SV-3 Systems-Systems Matrix	Table or Matrix	The relationships among systems in a given Architectural Description. It can be designed to show relationships of interest, (e.g., system-type interfaces, planned vs. existing interfaces).
	SV-4 Systems Functionality Description	Hierarchy Diagram, IDEF0, Yourdon-Demarco Data Flow Diagram, Data Flow Diagram	The functions (activities) performed by systems and the system data flows among system functions (activities).
	SV-5a Operational Activity to Systems Function Traceability Matrix	Table or Matrix	A mapping of system functions (activities) back to operational activities.
	SV-5b Operational Activity to Systems Traceability Matrix	Table or Matrix	A mapping of systems back to capabilities or operational activities.
	SV-6 Systems Resource Flow Matrix	Table or Matrix	Provides details of system resource flow elements being exchanged between systems and the attributes of that exchange.
	SV-7 Systems Measures Matrix	Table or Matrix, Parametric Diagram	The measures (metrics) of Systems Model elements for the appropriate timeframe(s).
	SV-8 Systems Evolution Description	Timeline Chart	The planned incremental steps toward migrating a suite of systems to a more efficient suite, or toward evolving a current system to a future implementation.
	SV-9 Systems Technology & Skills Forecast	Table	The emerging technologies, software/hardware products, and skills that are expected to be available in a given set of timeframes and that will affect future system development.
	SV-10a Systems Rules Model	“If, then, else” statements that capture sequencing constraints	One of three models used to describe system functionality. It identifies constraints that are imposed on systems functionality due to some aspect of system design or implementation.
	SV-10b Systems State Transition Description	State-machine Diagram	One of three models used to describe system functionality. It identifies responses of systems to events.

	SV-10c Systems Event-Trace Description	Sequence Diagram	One of three models used to describe system functionality. It identifies system-specific refinements of critical sequences of events described in the Operational Viewpoint.

Services Viewpoint – Articulates the services, activities, performers and their exchanges providing for or supporting system functions.

Table A5. Visualization Models for the Services Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
Services Viewpoint	SvcV-1 Services Context Description	Network Diagram, Hierarchy Diagram, Block Definition Diagram, Internal Block Diagram	The identification of services, service items, and their interconnections.
	SvcV-2 Services Resource Flow Description	Network Diagram, Package Diagram	A description of resource flows exchanged between services.
	SvcV-3a Systems-Services Matrix	Table or Matrix	The relationships among or between systems and services in a given architectural description.
	SvcV-3b Services-Services Matrix	Hierarchy Diagram, IDEF0, Yourdon-Demarco Data Flow Diagram, Data Flow Diagram	The relationships among services in a given architectural description. It can be designed to show relationships of interest, (e.g., service-type interfaces, planned vs. existing interfaces).
	SvcV-4 Services Functionality Description	Table or Matrix	The functions performed by services and the service data flows among service functions (activities).
	SvcV-5 Operational Activity to Services Traceability Matrix	Table or Matrix	A mapping of services back to operational activities.
	SvcV-6 Services Resource Flow Matrix	Table or Matrix	It provides details of service resource flow elements being exchanged between services and the attributes of that exchange.
	SvcV-7 Services Measures Matrix	Table or Matrix, Parametric Diagram	The measures (metrics) of Services Model elements for the appropriate time frame(s).
	SvcV-8 Services Evolution Description	Timeline Chart	The planned incremental steps toward migrating a suite of services to a more efficient suite or toward evolving current services to a future implementation.
	SvcV-9 Services Technology & Skills Forecast	Table	The emerging technologies, software/hardware products, and skills that are expected to be available in a given set of time frames and that will affect future service development.

	SvcV-10a Services Rules Model	"If, then, else" statements that capture sequencing constraints	One of three models used to describe service functionality. It identifies constraints that are imposed on systems functionality due to some aspect of system design or implementation.
	SvcV-10b Services State Transition Description	State-machine Diagram	One of three models used to describe service functionality. It identifies responses of services to events.
	SvcV-10c Services Event-Trace Description	Sequence Diagram	One of three models used to describe service functionality. It identifies service-specific refinements of critical sequences of events described in the operational viewpoint.

Project Viewpoint - Describes the details, and dependencies, of the project and project management.

Table A6. Visualization Models for the Project Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
Project Viewpoint	PV-1: Project Portfolio Relationships	Spider diagram	Describes the dependency relationships between the organizations and projects and the organizational structures needed to manage a portfolio of projects.
	PV-2: Project Timelines	Gantt Chart	A timeline perspective on programs or projects, with the key milestones and interdependencies.
	PV-3: Project to Capability Mapping	Table or matrix	A mapping of programs and projects to capabilities to show how the specific projects and program elements help to achieve a capability.

Standards Viewpoint – Articulates applicable operational, business, technical industry and DoD standards, policies, guidance, constraints, and forecasts.

Table A7. Visualization Models for the Standards Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
Standards Viewpoint	StdV-1 Standards Profile	Textual description	The listing of standards that apply to solution elements.
	StdV-2 Standards Forecast	Table	The description of emerging standards and potential impact on current solution elements, within a set of time frames.

Data and Information Viewpoint – Articulates the data relationships and alignment structures in the architecture or model-based context.

Table A8. Visualization Models for the Data and Information Viewpoint (Vaneman, 2017)

Viewpoint	DoDAF Model Name	System Engineering Model Name	Description
Data Viewpoint	DIV-1: Conceptual Data Model	Entity-Relationship Model	The required high-level data concepts and their relationships.
	DIV-2: Logical Data Model	Logical Data Model	The documentation of the data requirements and structural business processes and rules.
	DIV-3: Physical Data Model	Database design model	The physical implementation format of the Logical Data Model entities

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Appendix B. DoDAF and Modeling Language

In a MBSE tool environment, DoDAF is implemented based on the modeling language. For those tools that are based on UML and SysML, the DoDAF views correspond to the appropriate UML and SysML visualizations. Similarly, for tools based on LML, DoDAF will be represented by the appropriate LML visualizations. Table B-1 depicts the relationships between DoDAF views, UML/SysML diagrams (NoMagic, Inc.2010), and LML models[1], [2] (SPEC Innovations, 2019).

Table A9. Mapping between DoDAF Views vs. UML / SysML Diagrams vs. LML Models

DoDAF View	UML / SysML Diagram	LML Model
All Viewpoint		
AV-1: Overview and Summary Information	N/A	*Statements*
AV-2: Integrated Dictionary	N/A	*Statements*
Capabilities Viewpoint		
CV-1: Vision	UML Use Case Diagram	Asset Diagram
CV-2: Capability Taxonomy	Activity Diagram	Hierarchy Diagram
CV-3: Capability Phasing	N/A	Timeline Chart
CV-4: Capability Dependencies	N/A	Matrix based on *Actions* and *Assets*
CV-5: Capability to Organizational Development Mapping	N/A	Matrix based on *Actions* and *Assets*
CV-6: Capability to Operational Activities Mapping	N/A	Matrix based on *Actions*
CV-7: Capability to Services Mapping	N/A	Matrix based on *Actions* and *Assets*
Operational Viewpoint		
OV-1: High Level Operational Concept Graphic	UML Use Case Diagram	Asset Diagram
OV-2: Operational Resource Flow Description	UML Class Diagram	Asset Diagram
OV-3: Operational Resource Flow Matrix	N/A	Matrix of *Input/Outputs*
OV-4: Organizational Relationships Chart	UML Class Diagram	Asset Diagram
OV-5a: Operational Activity Decomposition Tree	UML Class Diagram	Hierarchy Chart
OV-5b: Operational Activity Model	Activity Diagram	IDEFD0 Diagram
OV-5b/6c – Action Diagram (Fit-for-purpose)	N/A	Action Diagram
OV-6a: Operational Rules Model	N/A	N/A

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[1] This table uses the LML models where possible. For those DoDAF views that can be represented by LML, but not necessarily by a defined visualization model, the entity name is shown in italics. For example, the CV-5 is a matric that is based on *Actions* and *Assets*.

[2] The LML entities and their corresponding visualization models are shown in Chapter II Table 1.

OV-6b: State Transition Description	State-machine Diagram	State-machine Diagram
OV-6c: Event-Trace Description	Sequence Diagram	Sequence Diagram
Systems Viewpoint		
SV-1 Systems Interface Description	Block Definition Diagram	Asset Diagram
SV-2 Systems Resource Flow Description	Internal Block Definition Diagram	Asset Diagram
SV-3 Systems-Systems Matrix	N/A	Matrix based on *Assets*
SV-4 Systems Functionality Description	Activity Diagram	IDEF0 Diagram
SV-5a Operational Activity to Systems Function Traceability Matrix	N/A	Matrix based on *Actions*
SV-5b Operational Activity to Systems Traceability Matrix	N/A	Matrix based on *Actions* and *Assets*
SV-6 Systems Resource Flow Matrix	N/A	Matrix of *Input/Outputs*
SV-7 Systems Measures Matrix	Parametrics Diagrams	Matrix based on *Measures* and *Assets*
SV-8 Systems Evolution Description	State-machine Diagram	Timeline Diagram
SV-9 Systems Technology & Skills Forecast	N/A	Timeline Diagram
SV-10a Systems Rules Model	N/A	N/A
SV-10b Systems State Transition Description	State-machine Diagram	State-machine Diagram
SV-10c Systems Event-Trace Description	Sequence Diagram	Sequence Diagram
Services Viewpoint		
SvcV-1 Services Context Description	Block Definition Diagram	Asset Diagram
SvcV-2 Services Resource Flow Description	Internal Block Definition Diagram	Asset Diagram
SvcV-3a Systems-Services Matrix	N/A	Matrix based on *Assets*
SvcV-3b Services-Services Matrix	Activity Diagram	IDEF0 Diagram
SvcV-4 Services Functionality Description	N/A	Matrix based on *Actions*
SvcV-5 Operational Activity to Services Traceability Matrix	N/A	Matrix based on *Action* and *Asset*
SvcV-6 Services Resource Flow Matrix	N/A	Matrix based on *Input/Outputs*
SvcV-7 Services Measures Matrix	Parametrics Diagram	Matrix based on *Measures* and *Assets*
SvcV-8 Services Evolution Description	State-machine Diagram	Timeline Diagram
SvcV-9 Services Technology & Skills Forecast	N/A	Timeline Diagram
SvcV-10a Services Rules Model	N/A	N/A
SvcV-10b Services State Transition Description	State-machine Diagram	State-machine Diagram
SvcV-10c Services Event-Trace Description	Sequence Diagram	Sequence Diagram
Project Viewpoint		
PV-1: Project Portfolio Relationships	N/A	Matrix based on *Time* and *Assets*
PV-2: Project Timelines	N/A	Timeline Chart
PV-3: Project to Capability Mapping	N/A	Matrix based on *Time* and *Actions*
Standards Viewpoint		
StdV-1 Standards Profile	N/A	*Statements*
StdV-2 Standards Forecast	N/A	Timeline Chart
Data Viewpoint		

DIV-1: Conceptual Data Model	UML Class Diagram, Block Definition Diagram	*Actions*, *Assets*, and *Inputs/Outputs*
DIV-2: Logical Data Model	UML Class Diagram, Block Definition Diagram	*Actions*, *Assets*, and *Inputs/Outputs*
DIV-3: Physical Data Model	UML Class Diagram, Block Definition Diagram	*Actions*, *Assets*, and *Inputs/Outputs*

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Appendix C. Alternative System Review

"An Alternative Systems Review (ASR) is a technical review that assesses the preliminary materiel solutions that have been developed during the Materiel Solution Analysis (MSA) Phase. The review ensures that one or more proposed materiel solution(s) have the best potential to be cost effective, affordable, operationally effective and suitable, and can be developed to provide a timely solution to at an acceptable level of risk to satisfy the capabilities listed in an Initial Capabilities Document (ICD). The ASR helps the Program Manager and Systems Engineer ensure that further engineering and technical analysis needed to draft the system performance specification is consistent with customer needs" (DAG, 2019).

State of Program at this Review Point - Decision has been made to investigate a materiel acquisition to address a user needs (capability gaps), a set of alternative solutions has been analyzed and a preferred solution has been identified. This may include modifications to an existing system. The purpose of this review is to examine the results of the analysis of alternatives (AoA) and the preferred technical solution (TTCP, 2014).

Information Available at this Review Point (TTCP, 2014):

- Description of the mission areas, scenario and mission threads, how the users will conduct the operation (i.e. Concept of Operations (CONOPS)), and how they expect to use the new system in this context.
- Statement of need in terms of the system user(s), the stakeholder(s), and independent of specific technological solutions. The program should be able to describe what this system is required to accomplish, and the connection to strategic objectives of the mission.
- The required systems characteristics, context of use of services and operational concepts.
- Major stakeholder requirements should be identified and documented, but detailed requirements analysis is yet to be completed. These stakeholder requirements will eventually be validated.
- The constraints on a system solution are defined.
- Results of an AoA, a comparative analysis of candidate solutions, with a recommended preferred solution

- Preliminary system architecture – based on the work done prior to Initial Review, the architecture should be extended, in reach and in detail. This includes initial interface definitions, constraints and limitations that the system may be confronted with, ranging in scope and scale considerations.
- Initial plans for systems engineering, providing how the system can be realized, including the level of process and process maturity needed to generate a system of the required complexity and depth and the systems to properly deliver the required capability.
- Initial definition of the environment including reference material that defines the characteristics of the threat and natural environment in sufficient detail to support effective analyses.
- Initial test & evaluation strategy including test cases derived from mission threads, CONOPS, and capability description should be captured at this stage, showing that a system is testable from its onset with expectations which are aligned with the defined metrics.
- An understanding of the potential challenges as defined by the system architecture. In areas where overall technological maturity may be low, these challenges should be listed and dealt with deliberately, with contingency available in case of continued problems.

Completion of the ASR should provide the following (DAG, 2019)**:**

- An agreement on the proposed materiel solution(s) (including the corresponding product support concept) to take forward into the Milestone Decision and subsequently the Technology Development Phases.
- Hardware and software architectural constraints/drivers to address all Key Performance Parameters (KPPs).
- A comprehensive rationale for the proposed materiel solution(s), based upon the AoA that evaluated relative cost, schedule, performance, and technological risks.
- A comprehensive assessment of the relative risks associated with including Commercial off-the-Shelf (COTS) items in the program, with emphasis on host platform environmental design, diagnostic information integration, and maintenance concept compatibility.
- A comprehensive risk assessment for that will matured, and eventually be used during the Technology Development Phase.
- Joint requirements for the purposes of commonality, compatibility, interoperability, and integration.
- Defined thresholds and objectives initially stated as broad measures of effectiveness and suitability (e.g., Key Performance Parameters (KPP) / Key System Attributes (KSA)).

- A draft System Requirements Document (SRD) if one does not already exist. (The SRD is a high-level engineering document that represents the customer/user capability needs as system requirements.) The SRDs systems requirement document should include a system level description of all software elements required by the preferred system concept.

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