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MONTEREY, CALIFORNIA

**DEVELOPING AN MBSE LAND DOMAIN CONSTRUCT FOR
MARINE CORPS SYSTEMS COMMAND**

by

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ABSTRACT

The purpose of this research is to consider four major areas for designing and analyzing an ontology, and conceptual data model (CDM) that can be applied across the Land Domain. Focus area 1 considers the importance of designing a generic (simple) ontology that comprehensively represents the system across the lifecycle. As such, an ontology that will serve as the foundation of the Land Domain is defined. Focus area 2 analyzes the relationships between entities defined within the ontology. System structure identifies the elements of the system that connect and interact with each other to achieve the system's purpose, and depicts how behavior will emerge within the system. Focus area 3 considers the ontology as a foundation for an authoritative source of truth. This research demonstrates the utility of having authoritative data within a defined structure, and validate the generic ontology and CDM using an example mission thread. Finally, focus area 4 provides some preliminary thoughts on recommended path to transition from document-based systems engineering to a true MBSE-based Land Domain.

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ACKNOWLEDGEMENTS

The Naval Postgraduate School (NPS) was established in 1909, as an institution to provide advanced education to Naval Officers, and research opportunities to support the fleet. This was the era when the Navy was experiencing a multi-decade technological revolution where wooden hulled, sail powered ships were being replaced by steel hulled, steam powered ships. The United States was becoming a strategic naval power, as demonstrated via the circumnavigation of the Great White Fleet. This voyage was not only the largest armada the world had ever seen; it was the largest integration and demonstration of technology. NPS was established in the wake of the lessons learned from the voyage of the Great White Fleet, where it was learned that engineering education and research was need for the effective integration and operation of new technology.

During the past century, NPS has been providing relevant education and advance research to address the most pressing issues of the Naval Services, and the Department of Defense (DoD). Today, concepts such as “cyber warfare,” “internet of things,” and “system of systems” are prevalent across the Department of Navy (DoN) and DoD. Similar to the Voyage of the Great White Fleet, the net-centric technology that is being integrated into operations today requires a new engineering acumen, achieved through education and research, to be truly effective. Model-Based Systems Engineering (MBSE) and Digital Engineering are being implemented within DoD and DoN to better engineer and manage these complex systems.

The Naval Research Program (NRP) enables NPS faculty to continue the institution rich tradition of research. We would thank the NRP for funding this research and providing support during the preparation and execution of it. We realize that not all proposed research efforts are funded, and we are humbled and honored to have been selected for Fiscal Year 2022.

Research often has challenges with getting topic sponsor support. This was not the case with this effort. Thanks to Mr. James Howell, III, the level of involvement and support from Marine Corps Systems Command greatly exceeded the participation that we envisioned.

The majority of the Marine Corps support was from the MPSE Integrated Product Team (IPT). The participation, feedback, and data provided was invaluable. We most sincerely thank you for being active participants in this research.

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EXECUTIVE SUMMARY

Project Summary

The purpose of this research was to develop and evaluate a generic ontology and conceptual data model (CDM) that was created to support the naval domain, for applicability to Marine Corps Systems Command (MCSC) and the land domain using Force Design 2030 (Congressional Research Service Insight, 2022) for overarching guidance. The generic ontology and CDM were developed as part of an exploratory study, which considered system data entities, attributes, and relationships. This research effort identified a generic ontology and defined a CDM that represents the system of interest from multiple perspectives and allows for the exploration of the system holistically. This is fundamental to the implementation of a model-based systems engineering (MBSE) environment. A parsimonious ontology allows system entities to be reduced to their atomic level, and then by establishing a CDM (i.e., data schemas) allows for a virtual representation of the system to be defined. The ontology and CDM identify areas where interfaces must be developed to exchange data and identify data boundaries between organizations, modeling languages, presentation frameworks, and tools. The study approach considers the importance of designing a generic ontology that comprehensively represents the system across the lifecycle, analyzes the relationships between entities defined within the ontology, considers the ontology as a foundation for an authoritative source of truth and finally, designs a modeling plan that depicts the recommended path to transition from document-based systems engineering to a true MBSE-based land domain. In Summary, an ontology and CDM were developed to define the entities and relationships for an entire system throughout its lifecycle. These products were verified utilizing a mission thread from Force Design 2030 representing the USMC land domain. Utilizing this ontology and CDM, and the derived modeling plan, the MCSC can begin transitioning from document-based systems engineering to a true MBSE-based land domain.

Keywords: *Digital Engineering, Model-Based Systems Engineering, Marine Corps Force Design 2030, Land Domain, Ontology, Conceptual Data Model,*

Background

MCSC strives to evolve from a traditional document-based systems engineering environment to an MBSE environment. The importance of MCSC transitioning to MBSE has recently been elevated when the Department of the Navy (DoN) assigned MCSC to define an MBSE environment for the land domain.

This represents a significant change for the Marine Corps since it marks the transition to mission-focused system design and development. This focus requires several Marine Corps Commands to coordinate their modeling efforts to insure a system-of-systems perspective with an end-to-end mission focus. The land domain is part of a larger DoN effort to model the full-spectrum of activities and systems within naval warfare. This effort is being prescribed to gain better insights, and make better programmatic decisions, to support system development and influence integration across the naval warfare domains. The purpose of this study is to develop an ontology, CDM, and a transition approach that can be utilized by the MCSC to transition to an MBSE-based environment for the land domain.

This research adopts a portion of the lifecycle modeling language (LML) ontology as the basis because it represents an ontology that uses an economy of entities that have defined relationships and attributes to create a parsimonious list of entities. This research is not promoting the use of the

LML nor endorsing any MBSE tool based on LML. The LML entities are only used because they are well-defined, establish relationships, and are parsimonious. This type of ontology is known as an entity, relationship, attribute, or ERA. This research expanded the ERA ontology approach to include labels (ERA(L)). The labels allow for data to be further identified within an entity class to entity subclasses. Finally, to further facilitate mapping a data type was added.

Once a comprehensive ontology was created, the relationships between the entities defined within it were examined. This formal structure resulted in a CDM that serves as the basis of a common terminology and structure. This generic ontology and CDM were validated using real world systems. Three interim test cases were utilized, the Amphibious Combat Vehicle, Joint Air Domain Command and Control (JADC2) concept as well as the Marine Corps Enterprise Network (MCEN) architecture. Lastly, a mission thread derived from the United States Marine Corps (USMC) reorganization taking place under the Force Design 2030 initiative was utilized. Since the goal is to examine the entire lifecycle of a system, the conceptual data model is all inclusive but for presentation has been segmented into sections. A fundamental premise of this research is that an ontology should use an economy of entities approach to create a parsimonious list that allows entities from a data dictionary to be reduced to their atomic level, thereby identifying like entities. A parsimonious ontology is important to focus the engineers on a limited (but comprehensive from a systems perspective) set of entities. Having too many entities may lead engineers to use different entities for the same system element. Conversely, having too few entities will not fully identify the system elements.

Findings and Conclusions

The ontology was developed to reduce seemingly disparate entities from various program data dictionaries to the “atomic level” using a parsimonious set of entities. The relationships between them were then established in the CDM. In an ideal system model, each data type will be represented only one time as it is in the real-world, but can be viewed from several perspectives.

For MBSE to be successful, the full scope of the system should be modeled, most likely via different MBSE tools that represent a portion of the system. The purpose of the CDM is to model the various aspects of the system, using the ontology entities and relationships to create a virtual representation of the system. Using a combination of the ontology and CDM facilitates a “Rosetta Stone” to exchange data between different modeling languages, MBSE tools, and presentation frameworks, thus allowing system data to be developed with the best approach for the problem.

The Land Domain, as articulated in Force Design 2030, was applied to both the ontology and the CDM. Utilizing the developed ontology and the CDM, the system entities related up to the highest-level missions defined by strategic guidance as well as were decomposable and defined by the lowest levels of components. In the USMC, the series of model creation and ownership resides at various levels starting with Combat Development and Integration (CDNI), USMC Systems Command (SYSCOM), program offices, contractors as well as the multitude of subcontractors and other government components. Utilizing a defined ontology and CDM ensures that as different organizations create the various levels of the model, utilizing various languages and MBSE tools, the final product will have a consistent schema and fully represent the system.

In summary, an ontology and CDM were developed to define the entities for an entire system throughout its lifecycle. These products were verified utilizing a mission thread from Force Design 2030 representing the USMC land domain. The USMC Systems Command can now utilize the developed ontology and CDM, along with the derived modeling plan, to begin its path towards transitioning from document-based systems engineering to a true MBSE-based land domain.

Continued research will also be accomplished to verify this ontology and CDM against a wider set of systems and domains both within the Naval Domain as well as other services.

Recommendations for Further Research

This research has made great advances in defining a universal ontology and conceptual data model (CDM). The following opportunities for further research were identified.

First, while this research applied the generic ontology and CDM to the United States Marine Corps land domain, additional effort is needed to demonstrate its applicability to other domains. Validating the ontology and CDM with the Naval Operational Architecture, as well as other service component models such as the Army, is recommended. The success of this proposed research will enable the standardization of an ontology and CDM.

Second, for the ontology and CDM to be most effective, it needs to be implemented as a formal data exchange standard. An exploration of approaches that represent the complex knowledge about entities, the relationships between entities, and additional information needed to exchange data will provide a more holistic and comprehensive view to share data across various modeling languages, model-based systems engineering tools, and presentation frameworks.

Third, additional “model curation” research is needed. Currently, few efforts are exploring how system models will be governed in the future. Implementation of a universal ontology and CDM will require a more defined process for “model curation.”

References

Congressional Research Service Insight. (2022). *New U.S. Marine Corps Force Design Initiative: Force Design 2030*. <https://crsreports.congress.gov/product/pdf/IN/IN11281>

Acronyms

CDM	Conceptual Data Model
DoN	Department of the Navy
ERA	Entity, Relationship, Attribute
LML	Lifecycle Modeling Language
MBSE	Model Based Systems Engineering
MCEN	Marine Corps Enterprise Network
MCSC	Marine Corps Systems Command
NPS	Naval Postgraduate School
NRP	Naval Research Program
SYSCOM	Systems Command
USMC	United States Marine Corps

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I. INTRODUCTION

A. BACKGROUND

The enduring challenge for the Systems Engineering Community is how to deal with increased systems complexity, while ensuring a comprehensive and high-quality design. Model-Based Systems Engineering (MBSE) was conceived to address the increasing complexity of systems by replacing a traditional document-based approach with a model-based approach where the models can be easily tailored to changing conditions and needs, re-used. One can also observe the system architecture from a static perspective, or explore system behavior from a dynamic perspective. MBSE transcends across multiple domains, for example, engineering program managers orchestrate communication across multiple stakeholders with various perspectives and areas of interests. MBSE has built on foundational systems engineering methods to provide a quick, flexible, traceable, rigorous approach to make changes and provide the same information in multiple views that resonates with each stakeholder.

The term “Model-Based Systems Engineering” was defined and popularized by the International Council on Systems Engineering (INCOSE) MBSE Initiative in 2007 to transform systems engineering to a model-based discipline (INCOSE, 2007). Long and Scott (2011) state MBSE “is fundamentally a thought process. It provides the framework to allow the systems engineering team to be effective and consistent right from the start of any project. At the same time, it is flexible enough to allow the ‘thought’ process to adapt to special constraints of circumstances present in the problem.”

In spite of the emphasis being placed on MBSE, systems engineering methods have failed to keep pace with the ever-increasing complexities of systems. As a result, many system engineering activities have been relegated to the beginning of the system’s lifecycle, thereby neglecting the holistic approach that is the cornerstone of the systems engineering discipline. (Vaneman 2016).

Marine Corps Systems Command (MCSC) strives to evolve from a traditional document-based systems engineering environment to a MBSE environment. The importance of MCSC transitioning to MBSE has recently been elevated, when the Department of the Navy (DoN) assigned MCSC to define a MBSE environment for the Land Domain. The emergence of the Land Domain represents a significant change for the Marine Corps since this marks the transition to a mission-focused system design and development. The mission focus requires several Marine Commands to better coordinate their modeling efforts to insure a system of systems perspective with an end-to-end mission focus. The Land Domain is part of a larger DoN effort to model the full-spectrum of activities and systems within Naval Warfare. This effort is being prescribed to gain better insights, and thereby make better programmatic decisions, to support Marine Corps system development, and influence integration across the Naval Warfare domains.

B. THE ESSENCE OF MODEL-BASED SYSTEMS ENGINEERING

1. The System Model

The purpose of a model is to glean insights and inform decisions about the subject being modeled. Therefore, to understand MBSE, the system that is being modeled must be understood. A system is an integrated set of elements, designed to function together to achieve some defined objective. The key words of this definition are:

- Integrated – A series of system elements that when combined work as one.
- Design – The deliberate planning and arranging of system elements.
- Function – The way in which the integrated system elements work together through rules and procedures that were established during the design.
- Objective – The purpose, or goal, the system was designed to satisfy.

It is clear from the definition that the system is more than the physical components, but includes all aspects of the system.

In MBSE, the model must serve as a virtual representation of the system, thus the “dimensions” of a system project must be considered. To illustrate, assume that the cube in Figure 1 (Larson et al., 2013; Vaneman et al., 2019) is a system. The system has “width” that provides insight across the entire system lifecycle from the definition of need to system disposal. The system has “height” which provides for the decomposition from the holistic view of the system at the highest level to the components, and eventually the parts, at the lowest levels. The system also has “depth,” which includes the complex relationships between systems, functions, requirements, analysis, risk, costs, schedule, etc. (Larson et al., 2013; Vaneman et al., 2019).

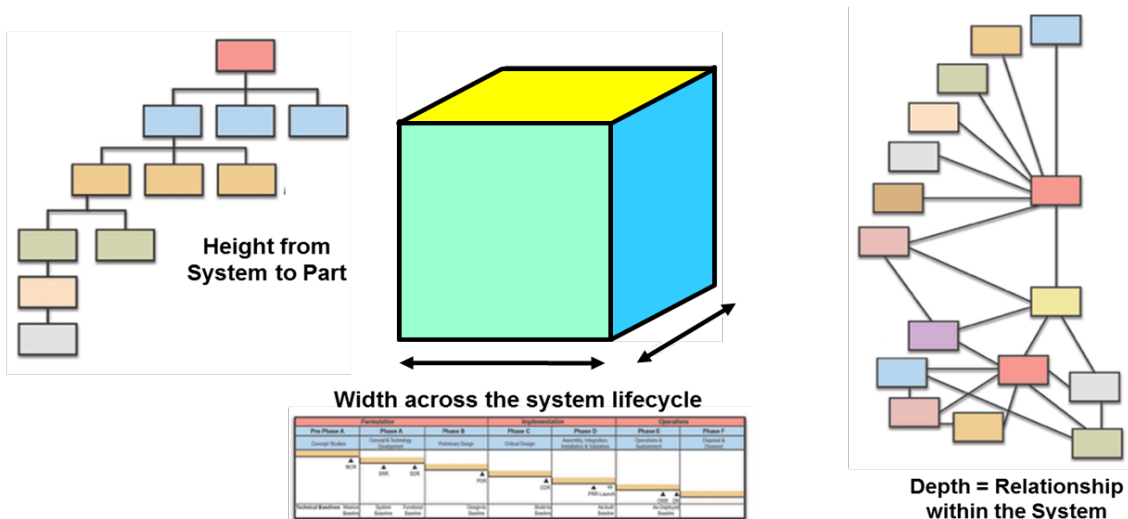


Figure 1. Dimensions of a System (Larson et al., 2013; Vaneman, 2019).

2. MBSE Defined

Model-Based Systems Engineering, as defined by INCOSE, seeks to transform systems engineering from a document-based to a model-based discipline, but doesn't include any insights on what that transition means. The Long and Scott (2011) definition suggests that MBSE establishes a framework to support a system thought process. This definition also falls short of establishing the purpose of the "thought framework" and what it is composed of.

To provide additional insight, Vaneman (2016) defined Model-Based Systems Engineering 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, structure, model-based processes, and presentation frameworks, all based on a modeling tool, used to support the discipline of systems engineering in a model-based or model-driven context (Vaneman, 2016b). The five components of this definition are shown in Figure 2 and further elaborated as follows:

- Modeling Languages – Serve 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 (meta-model).
- Structure – Defines the relationships between the system entities, establishes concordance within the model, and allows 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 Framework - Provides the framework for the logical constructs of the system data in visualization models that are appropriate for the given stakeholders. These visualization models typically 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.
- Modeling Tool - The software application the engineering team uses to generate, modify, and manage the system model (Giachetti and Vaneman, 2021).

These four components are considered to be essential and enduring to the implementation and application of MBSE. As such, they are projected to withstand the test of time. To implement these components, MBSE requires tools for application to systems engineering problems. MBSE tools are general purpose software applications that use modeling languages, and support the specifications, to generate, modify, and manage the system model and complex system representations therein. Each MBSE tool has different strengths and weaknesses with respect to the four components. The center of the Venn diagram represents the model-based tool trade-space. Given that MBSE applies to both static and dynamic models, a wide range of models are required in the MBSE environment to meet the needs of the systems engineering effort.

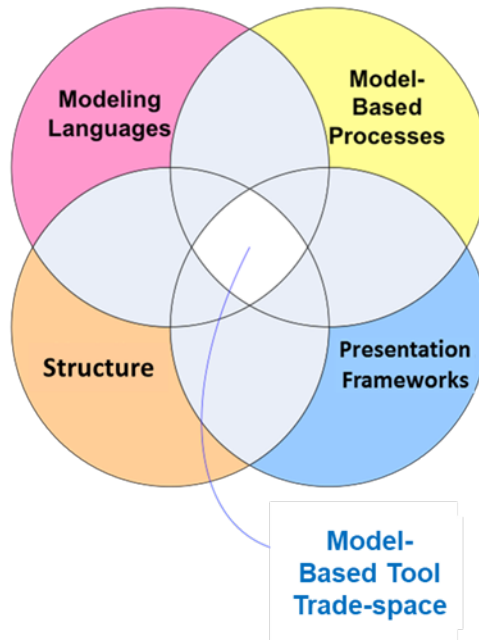


Figure 2. The Components of MBSE (Vaneman, 2016b).

Figure 3 (Vaneman, 2016b) is a notional description of how the four components work together in a MBSE environment. Organizations use model-based tools to execute appropriate processes to address various systems engineering problems. The tools are based on modeling languages, and use varying degrees of structure, to develop a virtual representation of the system (i.e. the model of the system of interest). Data from the system model can be shown in visualizations that are governed by the presentation framework. In a model in a single MBSE tool, each model entity will be represented as many times as it is contained in a real-world system - ONCE. This approach solves one of the problems inherent within document-based systems engineering, where each entity may be represented multiple times. With each entity represented only one time, and related to other entities via structure, the model exhibits concordance. 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.

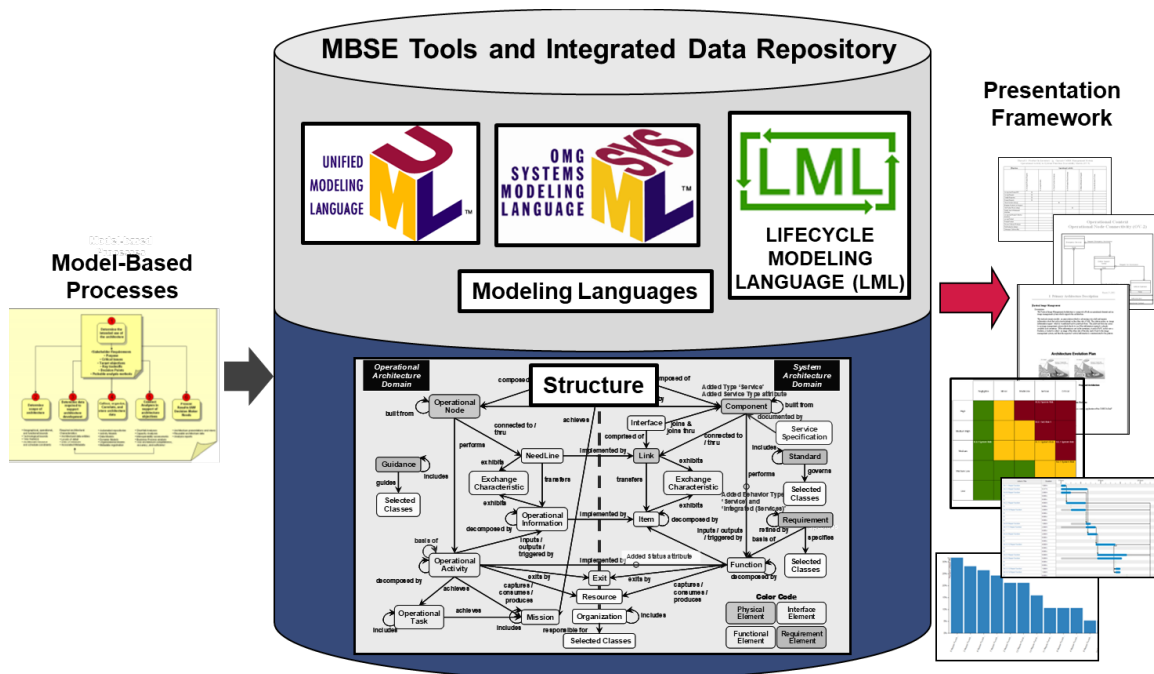


Figure 3. Notional MBSE Environment (Vaneman, 2016b).

C. THE VISION FOR MBSE

While the purpose of MBSE is to transition systems engineering to a model-based discipline, an envisioned state wasn't defined. As a result, various modeling-languages and MBSE tools emerged without clear-cut corresponding systems engineering processes. In 2018, the Department of Defense (DoD) defined the term digital engineering "as an integrated digital approach that uses authoritative sources of system data and models as a continuum across disciplines to support lifecycle activities from concept through disposal." While this definition is clear that digital engineering has a wider scope than MBSE, it is helpful because it establishes a vision [that](#) encompasses MBSE. While there are subtle differences between the definitions, for the purpose of this research MBSE and digital engineering are considered synonymous.

Goal 4 of the DoD Digital Engineering Strategy (2018) promotes the establishment of robust modeling and information technology infrastructure that incorporates advanced methods, processes, and tools, to perform engineering and analysis activities, collaborate and communicate across all stakeholders. The Department of the Navy (DoN) Digital Systems Engineering Transformation Strategy (2020) reinforces this notion by calling for the incorporation of technological innovation to improve engineering processes (Goal 3), and establish a supporting digital engineering infrastructure (Goal 4).

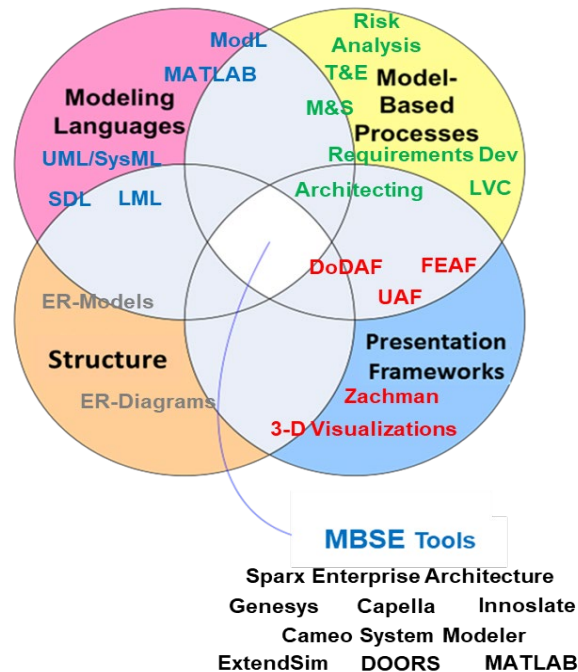


Figure 4. The Components of MBSE with Representative Examples.

The four components of the MBSE definition support the DoD and DoN Digital Engineering goals since these components are implementation agnostic, and can be further defined to include current, and near-term, modeling technology and practices. Figure 2 is further defined in Figure 4 to illustrate the additional detail.

Modeling languages accounts for all languages, static and dynamic, that support systems engineering and analysis. Structure allows for relationships to be made in whatever form is natural to the native modeling language. Entity relationships are representations of different entities within a system and how they relate to each other. Entity relationships can be made within the diagram, within the model data, or both.

The Model-Based Processes component accounts for all systems engineering and analysis activities that are appropriate for modeling. Heretofore, prevailing MBSE practices focus on the early systems engineering activities from a static perspective. The Model-Based Processes component accounts for all systems engineering activities across the system's lifecycle. This includes activities that are not currently mainstream in systems engineering, such as live virtual and constructive (LVC), and allows for new processes to be developed.

The Presentation Framework component is currently comprised of various architecture frameworks, thus limiting the scope to the early systems engineering activities. However, since MBSE spans the full system lifecycle, presentation frameworks include the portrayal of all systems engineering and analysis data, to include 3-dimensional, and eventually n-dimensional data.

To address this robust MBSE environment, multiple modeling tools are already available. These tools support the DoD and DoN goals by contributing to the robust infrastructure and improve systems engineering by representing portions of the system of interest. Figure 5 illustrates the concept of a robust modeling and information technology systems engineering environment (Source unknown).

D. CHALLENGES IMPLEMENTING THE MBSE VISION

Notionally, each of the tools represented in Figure 5 models a portion of a system's lifecycle. While there is often a lot of focus on the modeling language, the MBSE tool, or the presentation framework used for visualizations, the actual "atomic level" of the model is with the data where the entities and relationships are captured.

Figure 6 depicts two tools within a MBSE environment that are meant to exchange data. There are three issues with this interaction between tools. First, a strict naming convention needs to be established to be able to definitively ensure the entity in one is the same as the entity in another tool. For example, if an entity common between two tools is named "SYSTEM123" in one tool, and "SYSTEM_123" in another tool, the MBSE environment will treat the entity as two separate entities.

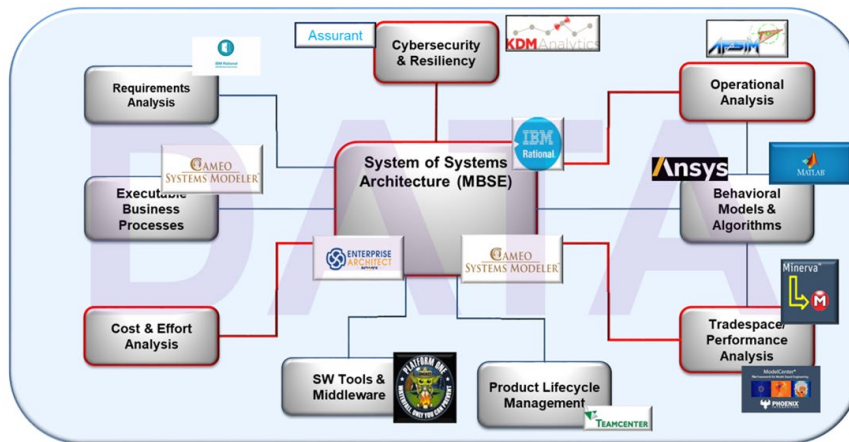
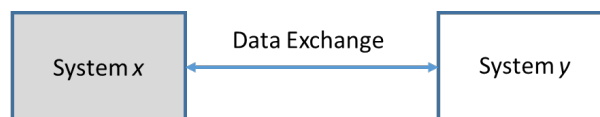


Figure 5. The Data Environment Vision (Source Unknown).



Three Challenges with Exchanging Data

1. Strict naming convention of entities needs to be established.
2. Each entity has a unique identifying number.
3. Exchanging or combining data from different model-based tools requires more than data exchange standard (i.e. xmi).

Figure 6. Data Exchange Challenges.

Establishing, maintaining, and enforcing a naming convention is one of the envisioned responsibilities of the model curator. The model curator will be a new responsibility in the system's engineering discipline, and represents one of the necessary organizational changes as robust MBSE environments are implemented. Model curation is currently being researched by the Massachusetts Institute of Technology (MIT) (Rhodes, 2021).

The second challenge is with the unique number assigned to entity by the various tools. This problem is very similar to the naming convention, but the number is tool generated and cannot be manipulate or changed. This problem is better suited for research by the computer science discipline than by systems engineering.

The third challenge is using /combining data from different model-based tools in a MBSE environment requires more than just a data exchange standard (e.g .xml) to exchange data between tools. Physically exchanging data between two tools is possible now, but once the data is physically exchanged, the utility of that data is often lost due to the tools application of data being incompatible. In addition to the exchange standard, a mapping of how data from different system models are related is required.

This research addresses the third challenge by identifying a common ontology and defining a corresponding Conceptual Data Model (CDM). The ontology and CDM are not just an academic exercise, but fundamental to the implementation of a MBSE environment. The ontology and CDM are anticipated to identify area where interfaces must be developed to exchange data, and identify data boundaries between organizations, modeling-languages, presentation frameworks, and tools. Currently organizations have little, or no, insights into these data exchange issues.

Having this common naming convention (as highlighted in the first challenge), a means to combine entities with different entity numbers (as highlighted in the second challenge) and having a well-defined ontology and CDM allows each tool used to contribute to defining individual system entities by the strengths of the tool. For example, when considering Figure 5, one tool may model a system entity from a static perspective while another tool may model the behavior of that entity from a dynamic perspective. The real-world element exists only once, therefore the entity within the virtual representation of the system should be represented virtually only once. The various tools contribute to the entity definition, therefore must provide a means to combine the data to appear as a single entity, therefore facilitating concordance. This problem is one of the main drivers of a comprehensive ontology and CDM that models the system of interest.

Another challenge that cannot explicitly be seen in Figure 5, but warrants an honorable mention in this research, and is a major goal elsewhere, is the authoritative source of truth for the data. Goal 2 in the DoD Digital Engineering Strategy (2018) and Goal 2 in the DoN Digital Systems Engineering Transformation Strategy (2020) call for the establishment of an enduring, authoritative source of truth. The purpose of the authoritative source of truth is to allow for communication between models so that they are discoverable, available,

trustable, and ready to use when needed by authorized personnel (DoD, 2018; DoN, 2020). Authoritative data must be available from any model within the MBSE environment to perform their designated roles, maintain data integrity, and show how changes will “ripple” through the model of the system of interest.

E. RESEARCH QUESTIONS AND APPROACH

The purpose of this research is to identify a generic ontology and define a CDM that represents the system of interest from multiple perspectives, and allows for the exploration of the system holistically. This research considers four major areas for designing and analyzing an ontology that can be applied across the Land Domain.

Focus area 1 considers the importance of identifying a generic ontology that comprehensively represents the system across the lifecycle. As such, an ontology that will serve as the foundation of the Land Domain will be described.

A conservation of entities principle will be employed when identifying the entities within the ontology. Describing the system with fewer entities will allow for a “common denominator of entities” to be used to describe the system. The entities within the data dictionary of individual programs and systems will be able to be mapped to the ontology, thereby facilitating data exchanges to define the virtual model of the system. Chapter 2 discusses the research approach of using a parsimonious list of entities. Chapter 3 expands on this basic approach.

Focus area 2 analyzes the relationships between entities defined within the ontology. System structure identifies the elements of the system that connect and interact with each other to achieve the system’s purpose, and depicts how behavior will emerge within the system. A generic CDM will be defined to serve as the basis of a common terminology and structure, and will be able to be applied to the Land Domain.

Figure 7 depicts an example CDM (SMIS, 2019). In addition to depicting the relationships between the model entities, the CDM identifies where the single source of truth resides, data boundaries, and interactions to allow for data exchange between models, and highlights issues that need to be addressed by model governance policies.

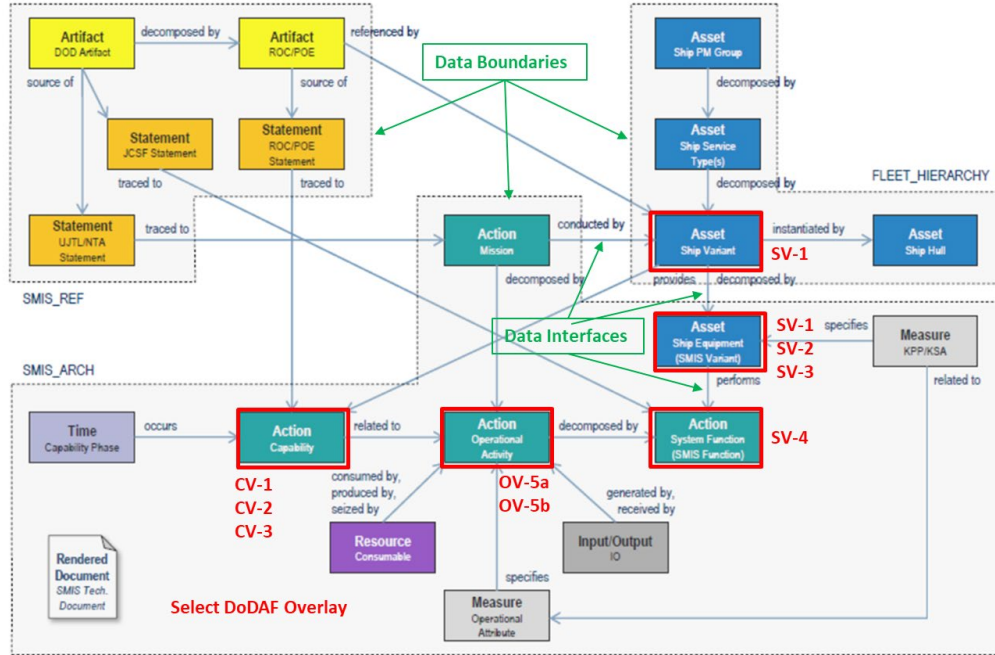


Figure 7. Example Conceptual Data (SMIS, 2019).

Focus area 3 considers the ontology as a foundation for an authoritative source of truth. This research will demonstrate the utility of having authoritative data within a defined structure, and validate the generic ontology and CDM using an example mission thread. The authoritative source of truth is widely discussed because it is emphasized in DoD's and DoN's digital strategy and transition documents, but the discussions are usually at a high-level. This research will also explore the concept of developing a numbering scheme which can be used to assist with managing the authoritative source of truth by identifying the data type, the system hierarchy, and which organization has purview over that data type.

Focus area 4 will design a framework for a roadmap that will help MCSC transition from document-based systems engineering to a true MBSE-based Land Domain. When this research was formulated, focus area 4 made sense. However, as the research progressed it became apparent that this focus area was orthogonal to the core parts of the research. However, some effort was applied in developing a six-step process for transitioning to a MBSE environment, and is provided in Appendix B.

F. LAYOUT OF THIS DOCUMENT

This chapter laid the framework by highlighting the MBSE background, introduced key concepts, and identified the research challenges and assumptions. Chapter II is a literature review which discusses the concepts that serve as a point of departure for this research. The generic ontology and CDM are defined in Chapter III. Chapter IV exercises the ontology and CDM by applying a Land Domain scenario. Conclusions and recommendations for further research are presented in Chapter V. Concepts and issues that are important to this research but do not fit neatly into one of the chapters are in the Appendices.

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II. LITERATURE REVIEW

A. DIGITAL ENGINEERING VISION AND STRATEGY

The impetus for Digital Engineering is derived from two primary sources – The Department of Defense Digital Engineering Strategy (2018) and the Naval Digital Engineering Transformation Strategy (2021). Both documents espouse a similar vision, which is positive as it focuses the digital engineering transformation efforts in a common direction.

The DoD and Naval strategy documents list five similar goals as follows.

- Goal 1
 - DoD: Formalize the development, integration and use of models to inform enterprise and program decision making.
 - DoN: Formalize the development, integration and use of models.
- Goal 2
 - DoD: Provide an enduring, authoritative source of truth.
 - DoN: Provide an enduring authoritative knowledge source.
- Goal 3
 - DoD: Incorporate technological innovation to improve the engineering practice.
 - DoN: Incorporate technological innovation to improve the engineering practice.
- Goal 4
 - DoD: Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across.
 - DoN: Establish the supporting infrastructure and environments for the Digital Engineering practice.
- Goal 5
 - DoD: Transform the culture and workforce to adopt and support digital engineering.
 - DoN: Transform the culture and workforce to adopt and support Digital Engineering across the lifecycle.

The foundation of this research is based on Goal 4, where a digital modeling environment is established that capitalizes on using the best tool to represent the perspective of the system being modeled. To achieve this goal, system data must be able to be exchanged. Heretofore, exchanging data has been problematic even when working with common modeling languages and MBSE tools. This research uses Goal 4 as the impetus for defining the ontology and CDM to facilitate exchanging data between modeling languages, MBSE tools, and presentation frameworks.

Goal 2 calls for the establishment of an authoritative source of truth, but offer few details on what that means. Massachusetts Institute of Technology (MIT) is exploring the concept of “model curation” to govern and manage models (Rhodes, 2021). Others have attempted

to provide authority to models by defining disciplined data dictionaries, or reusable model entities.

Goal 2 motivates this research in three ways. First, a parsimonious ontology is defined which allows entities defined within various data dictionaries to be reduced to an “atomic level” which allows like entity classes to be defined and treated the same way regardless of modeling language, MBSE tools, or presentation frameworks. Second, from the ontology, the relationships between entity classes can be defined. These relationships allow for commonality – a key ingredient when exchanging data. Third, a numbering schema facilitates the data type, where (which level) the data resides within the system model and identifies the organization that is the authoritative source of the data.

B. THE BASIS OF THE ONTOLOGY AND CONCEPTUAL DATA MODEL

Initial exploration of this research led to defining an ontology and a data schema (Conceptual Data Model). Budin (2005) defines an ontology as:

“An ontology encompasses a representation, formal naming, and definition of the categories, properties, and relations between the concepts, data, and entities that substantiate one, many, or all domains of discourse. More simply, an ontology is a way of showing the properties of a subject area and how they are related, by defining a set of concepts and categories that represent the subject.”

During the initial exploration, it became apparent that the ontology needs to be parsimonious to make it usable to the widest range of engineers. Heretofore, a common perspective was to use the data dictionary as the ontology. The problem with this is data dictionaries are typically program dependent therefore making it impossible to reduce data to an “atomic level” where like data can be treated similarly. Also, data dictionaries typically contain dozens or more terms. The goal for an ontology is to have few terms to represent the system (Vaneman, 2017).

For example, the English dictionary contains more than 400,000 words. However, the typical graduate with a Master of Arts degree in English has a vocabulary of 22,000-30,000 words (Quora, 2022). As a result, one person may use words of their choosing to describe a thing while another person may use different words to describe that same thing. The same phenomena are true when there are a large number of terms in a data dictionary; one engineer uses one set of terms, while another engineer will use another set of terms when describing the same thing. To reduce this ambiguity, a parsimonious list of data entities is desired.

The Lifecycle Modeling Language (LML) Specification (v 1.4, 2015) has an ontology that describes a system with 22 entities. These entities serve as the basis for the ontology defined in Chapter III. It should be noted, that the (LML) ontology is being used only as the basis of the ontology defined in Chapter III because it is an existing and well-defined ontology, thereby allowing the research team to modify the ontology and not completely develop one.

In addition to LML, the System Design Language (SDL) (Vitech, 2015) was evaluated. Like LML, a minimal set of entities (although a greater number than with LML) were defined, with each entity having defined relationships between entities. The strength of the Vitech approach is the data schema as it depicts the common relationships between entities. The Vitech Core and GENESYS MBSE tools seek to model the system, therefore their schema is a form of a system model. Figure 8 is a partial Vitech Core Schema (Vitech, 2008; Long and Scott, 2011). This schema served as motivation for developing the Conceptual Data Model.

Both LML and SDL are known as an entity, relationship, attribute, or ERA languages. A relationship (often considered the verbs of an ontology) connects entities (the nouns of the ontology) to each other through a standardization terms (LML, 2022). An attribute, in ERA is an inherent characteristic or quality of an entity. It further describes the entity, enhancing its uniqueness.

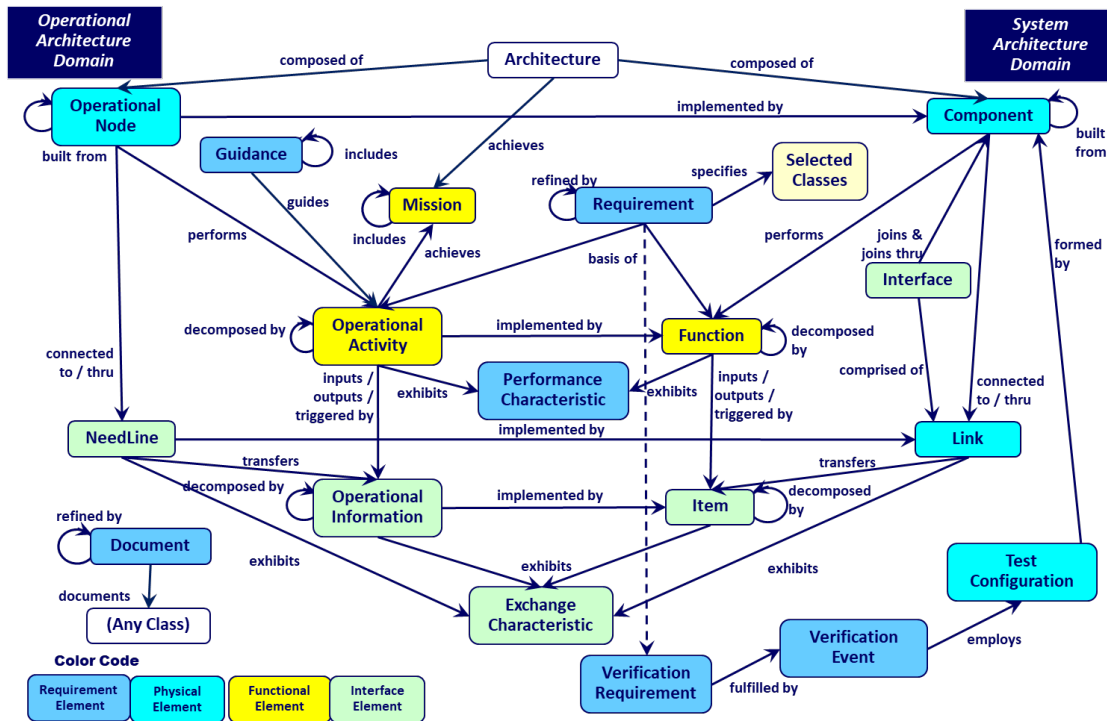


Figure 8. Vitech CORE Schema (2008).

This research combines the approaches used by both LML and the Vitech CORE Schema. The ontology defined in Chapter III is derived from LML. The CDM is based on the lessons learned from analyzing the CORE Schema. The LML Specification (v 1.4, 2022) defines the relationships between entities. These relationships are shown in the Summary of LML Relationships in Figure 9.

Unlike the succinctly defined Vitech CORE schema, the LML shows all possible relationships, where most entities are related. While LML contains 22 entities, given these complex relationships there are approximately $22!$ or 10^{21} possible combinations. These

combinations exist because the relationships are not one-to-one. Like the Vitech CORE Schema, not all relationships are used in the CDM, however, with very few exceptions, the relationships between entities shown in the CDM are derived from the summary of LML relationships shown in Figure 9.

	Action	Artifact	Asset (Resource)	Characteristic (Measure)	Connection (Conduit, Logical)	Cost	Decision	Input/Output	Location (Orbital, Physical, Virtual)	Risk	Statement (Requirement)	Time
Action	decomposed by* related to*	references	(consumes) performs by (produces) (seizes)	specified by	-	incurs	enables results in	generates receives	located at	causes mitigates resolves	(satisfies) traced from (verifies)	occurs
Artifact	referenced by	decomposed by* related to*	referenced by	referenced by specified by	defines protocol for referenced by	incurs referenced by	enables referenced by results in	referenced by	located at	causes mitigates referenced by resolves	referenced by (satisfies) source of traced from (verifies)	occurs
Asset (Resource)	(consumed by) performs (produced by) (seized by)	references	decomposed by* obtained by* related to*	specified by	connected by	incurs	enables made responds to results in	-	located at	causes mitigates resolves	(satisfies) traced from (verifies)	occurs
Characteristic (Measure)	specifies	references specifies	specifies	decomposed by* related to* specified by*	specifies	incurs specifies	enables results in specifies	specifies	located at specifies	causes mitigates resolves specifies	(satisfies) specifies traced from (verifies)	occurs specifies
Connection (Conduit, Logical)	-	defined protocol by references	connects to	specified by	decomposed by* joined by* related to*	incurs	enables results in	transfers	located at	causes mitigates resolves	(satisfies) traced from (verifies)	occurs
Cost	incurred by	incurred by references	incurred by	incurred by specified by	incurred by	decomposed by* related to*	enables incurred by results in	incurred by	located at	causes incurred by mitigates resolves	incurred by (satisfies) traced from (verifies)	occurs
Decision	enabled by result of	enabled by references result of	enabled by made by responded by result of	enabled by result of specified by	enabled by result of	enabled by incurs result of	decomposed by* related to*	enabled by result of	located at	causes enabled by mitigated by result of resolves	alternative enabled by traced from result of	date resolved by decision due occurs
Input/Output	generated by received by	references	-	specified by	transferred by	incurs	enables results in	decomposed by* related to*	located at	causes mitigates resolves	(satisfies) traced from (verifies)	occurs
Location (Orbital, Physical, Logical)	locates	locates	locates	locates specified by	locates	locates	locates	locates	decomposed by* related to*	locates mitigates	locates (satisfies) traced from (verifies)	occurs
Risk	caused by mitigated by resolved by	caused by mitigated by references resolved by	caused by mitigated by resolved by	caused by mitigated by resolved by specified by	caused by mitigated by resolved by	caused by incurs mitigated by resolved by	caused by enables mitigated by results in resolved by	caused by mitigated by resolved by	located at mitigated by	caused by* decomposed by* related to* resolved by*	caused by mitigated by resolved by	occurs mitigated by
Statement (Requirement)	(satisfied by) traced to (verified by)	references (satisfied by) sourced by traced to (verified by)	(satisfied by) traced to (verified by)	(satisfied by) specified by traced to (verified by)	(satisfied by) traced to (verified by)	incurs (satisfied by) traced to (verified by)	alternative of enables traced to results in	(satisfied by) traced to (verified by)	located at (satisfied by) traced to (verified by)	causes mitigates resolves	decomposed by* traced to* related to*	occurs (satisfied by) (verified by)
Time	occurred by	occurred by	occurred by	occurred by specified by	occurred by	occurred by	date resolves decided by occurred by	occurred by	occurred by	occurred by mitigates	occurred by (satisfies) (verifies)	decomposed by* related to*

Figure 9. Summary of LML Relationships (LML, 2022).

C. TRANSLATIONS BETWEEN DIAGRAM-BASED MODELS

While LML and SDL are ontology-based languages with corresponding visualizations (i.e. diagrams), other languages, such as the Unified Modeling Language (UML) and the System Modeling Language (SysML), are diagram-based languages (OMG, 2012). These languages represent systems in great detail through diagrams but have a limited ontology. Regardless if the modeling language is diagram-based, or ontology-based, once the “atomic level” of the entities is modeled the system exchanging data is possible.

In addition to that way modeling languages present the data; another aspect of the way data is portrayed is through architecture frameworks. The primary architecture frameworks used by DoD are the DoD Architecture Framework (DoDAF) (DoD, 2009) and the Unified Architecture Framework (UAF) (OMG, 2020).

DoDAF consists of 52 views (i.e. diagrams) within eight viewpoints (i.e. thematic areas) to represent the various perspectives of the system (Dam, 2015). UAF takes a different approach to defining data perspectives (i.e. Metadata, Strategic, Operational, Services, Personnel, Resources, Security, Projects, Standards, and Actual Resources) and are combined with data parameters (i.e. Taxonomy, Structure, Connectivity, Processes, Status, Interaction Structures, Information, Parameters, Constraints, Roadmap, and Traceability), and includes 77 views (OMG, 2020). Figure 10 shows the UAF structure (OMG, 2019).

UAF will eventually replace DoDAF as the architecture framework used by DoD. UAF does include all of the views with DoDAF, and adds a few additional. The mapping between DoDAF and UAF is shown in Figure 11 (OMG, 2020).

There are only so many ways to represent system data. While the names may be different between modeling languages and architecture frameworks, there is commonality among the diagrams, therefore a translation between the modeling languages and architecture frameworks is possible. This translation will facilitate the exchange of data between modeling languages, MBSE tools, and architecture frameworks. This is important, because it serves as the foundation of the “Rosetta Stone,” defined in Chapter III, that allows data to be modeled in the modeling language, MBSE tool, and presentation framework that is best for the defined problem. Table 1 shows DoDAF and UAF views mapped to UML/SysML, (NoMagic,2010) and LML (SPEC, 2019).

The term “architecture framework” is commonly used in MBSE. In the definition proposed by Vaneman (2016), the term “presentation framework” is used. The difference in the two terms is the scope of the model. An “architecture framework” models the views that are part of the architecture, during the early portions of the system lifecycle. Therefore, “architecture frameworks” do not include views (e.g. requirements, risk diagram, etc.) used during other phases of system lifecycle. The term “presentation framework” is inclusive of all views required across the system lifecycle. This change in terminology is required because MBSE and Digital Engineering cover the entire system lifecycle.

	Taxonomy Tx	Structure Sr	Connectivity Cn	Processes Pr	States St	Interaction Scenarios Is	Information If	Parameters Pm	Constraints Ct	Roadmap Rm	Traceability Tr
Metadata Md	Metadata Taxonomy Md-Tx	Metadata Structure Md-Sr	Metadata Connectivity Md-Cn	Metadata Processes Md-Pr	Metadata States Md-St	-	Conceptual Data Model,	Environment Pm-En	Metadata Constraints Md-Ct	Metadata Roadmap Md-Rm	Metadata Traceability Md-Tr
Strategic St	Strategic Taxonomy St-Tx	Strategic Structure St-Sr	Strategic Connectivity St-Cn	-	Strategic States St-St	-			Strategic Constraints St-Ct	Strategic Deployment, St-Rm Strategic Phasing St-Rm	Strategic Traceability St-Tr
Operational Op	Operational Taxonomy Op-Tx	Operational Structure Op-Sr	Operational Connectivity Op-Cn	Operational Processes Op-Pr	Operational States Op-St	Operational Interaction Scenarios Op-Is			Operational Constraints Op-Ct	-	Operational Traceability Op-Tr
Services Sv	Service Taxonomy Sv-Tx	Service Structure Sv-Sr	Service Connectivity Sv-Cn	Service Processes Sv-Pr	Service States Sv-St	Service Interaction Scenarios Sv-Is			Service Constraints Sv-Ct	Service Roadmap Sv-Rm	Service Traceability Sv-Tr
Personnel Pr	Personnel Taxonomy Pr-Tx	Personnel Structure Pr-Sr	Personnel Connectivity Pr-Cn	Personnel Processes Pr-Pr	Personnel States Pr-St	Personnel Interaction Scenarios Pr-Is	Logical Data Model,	Measurements Pm-Me	Competence, Drivers, Performance Pr-Ct	Personnel Availability, Personnel Evolution, Personnel Forecast Pr-Rm	Personnel Traceability Pr-Tr
Resources Rs	Resource Taxonomy Rs-Tx	Resource Structure Rs-Sr	Resource Connectivity Rs-Cn	Resource Processes Rs-Pr	Resource States Rs-St	Resource Interaction Scenarios Rs-Is	Physical schema, real world results		Resource Constraints Rs-Ct	Resource evolution, Resource forecast Rs-Rm	Resource Traceability Rs-Tr
Security Sc	Security Taxonomy Sc-Tx	Security Structure Sc-Sr	Security Connectivity Sc-Cn	Security Processes Sc-Pr	-	-	Security Constraints Sc-Ct		-	Security Traceability Sc-Tr	
Projects Pj	Project Taxonomy Pj-Tx	Project Structure Pj-Sr	Project Connectivity Pj-Cn	Project Processes Pj-Pr	-	-	-		Project Roadmap Pj-Rm	Project Traceability Pj-Tr	
Standards Sd	Standard Taxonomy Sd-Tx	Standards Structure Sd-Sr	-	-	-	-			-	Standards Roadmap Sd-Rm	Standards Traceability Sd-Tr
Actual Resources Ar		Actual Resources Structure Ar-Sr	Actual Resources Connectivity Ar-Cn	Simulation						Parametric Execution/ Evaluation	-
Dictionary Dc											
Summary & Overview Sm-Ov											
Requirements Req											

Figure 10. UAF Framework (OMG, 2019)

	Taxonomy Tx	Structure Sr	Connectivity Cn	Processes Pr	States St	Interaction Scenarios Is	Information If	Parameters Pm	Constraints Ct	Roadmap Rm	Traceability Tr		
Metadata Md	-	-	-	-	-	-	DIV-1	ScV-7	-	-	-		
Strategic St	CV-2	CV-1	CV-4	-	-	-			-	CV-3 CV-5	CV-6		
Operational Op	OV-2 OV-1	OV-2	OV-2 OV-3	OV-5a OV-5b	OV-6b	OV-6c			OV-6a	-	-		
Services Sv	SvcV-1	SvcV-1 SvcV-2	SvcV-3a SvcV-3b SvcV-6	SvcV-4	SvcV-10b	SvcV-10c			SvcV-10a	SvcV 8 SvcV-9	SvcV-5 CV-7		
Personnel Pr	OV-4	OV-4	OV-4 SV-6	SV-4	SV-10b	SV-10c			DIV-3	OV-4 SV-10a SV-7	PV-2 SV-8 SV-9	SV-5a SV-5b	
Resources Rs	SV-1 SV-2	SV-1 SV-2	SV-3 SV-6	SV-4	SV-10b	SV-10c				SV-7	SV-10a	SV-8 SV-9	SV-5a SV-5b
Security Sc	-	-	-	-	-	-				-	-	-	-
Projects Pj	PV-1	PV-1	PV-2	-	-	-				-	PV-2	PV-3	
Standards Sd	StdV-1	StdV-1	-	-	-	-				-	StdV-2	StdV-1	
Actual Resources Ar		OV-4	OV-4 SV-1 & SV-2	Simulation						Parametric Execution/Evaluation	-	-	
Dictionary Dc (AV-2)													
Summary & Overview SmOv (AV-1, OV-1)													
Requirements -													

Figure 11. DoDAF to UAF Mapping (OMG, 2019).

Table 1. DoDAF and UAF Vies Mapped to UML/SysML, and LML.

DoDAF View	UAF View	UML/SysML Diagram	LML Model
AV-1: Overview and Summary Information	Sm-Ov: Summary and Overview	N/A	<i>Statements</i>
AV-2: Integrated Dictionary	Dc: Dictionary	N/A	<i>Statements</i>
CV-1: Vision	St-Sr: Strategic Structure	UML Use Case Diagram	Asset Diagram
CV-2: Capability Taxonomy	St-Tx: Strategic Structure	Activity Diagram	Hierarchy Diagram
CV-3: Capability Phasing	St-Sm: Strategic Deployment	N/A	Timeline Chart
CV-4: Capability Dependencies	St-Cn: Strategic Connectivity	N/A	Matrix based on <i>Actions</i> and <i>Assets</i>
CV-5: Capability to Organizational Development Mapping	St-Rm: Strategic Phasing	N/A	Matrix based on <i>Actions</i> and <i>Assets</i>
CV-6: Capability to Operational Activities Mapping	St-Tr: Strategic Traceability	N/A	Matrix based on <i>Actions</i>
CV-7: Capability to Services Mapping	Sw-Tr: Service Traceability	N/A	Matrix based on <i>Actions</i> and <i>Assets</i>
OV-1: High Level Operational Concept Graphic	Op-Tx: Operational Taxonomy Sm-Ov: Summary & Overview	UML Use Case Diagram	Asset Diagram
OV-2: Operational Resource Flow Description	Op-Sr: Operational Structure Op-Tx: Operational Taxonomy Op-Cn: Operational Connectivity	UML Class Diagram	Asset Diagram
OV-3: Operational Resource Flow Matrix	Op-Cn: Operational Connectivity	N/A	Matrix of <i>Input/Outputs</i>
OV-4: Organizational Relationships Chart	Ar-Sr: Actual Resources Structure Ar-Cn: Actual Resources Connectivity Pr-Tx: Personnel Taxonomy Pr-Sr: Personnel Structure Pr-Cn: Personnel Connectivity Pr-Ct: Competence	UML Class Diagram	Asset Diagram
OV-5a: Operational Activity Decomposition Tree	OP-Pr: Operational Processes	UML Class Diagram	Hierarchy Chart

OV-5b: Operational Activity Model	OP-Pr: Operational Processes	Activity Diagram	IDEFD0 Diagram
OV-5b/6c – Action Diagram (Fit-for-purpose)	Op-Is: Operational Interaction Scenarios Op-Is: Operational Interaction Scenarios	N/A	Action Diagram
OV-6a: Operational Rules Model	Op-Ct: Operational Constraints	N/A	N/A
OV-6b: State Transition Description	Op-St: Operational States	State-machine Diagram	State-machine Diagram
OV-6c: Event-Trace Description	Op-Is: Operational Interaction Scenarios	Sequence Diagram	Sequence Diagram
SV-1 Systems Interface Description	Rs-Tx: Resource Taxonomy Rs-Sr: Resource Structure Ar-Cn: Actual Resource Connectivity	Block Definition Diagram	Asset Diagram
SV-2 Systems Resource Flow Description	Rs-Sr: Resource Structure Rs-Tx: Resource Taxonomy Ar-Cn: Actual Resource Connectivity	Internal Block Definition Diagram	Asset Diagram
SV-3 Systems-Systems Matrix	Rs-Cn: Resource Connectivity	N/A	Matrix based on <i>Assets</i>
SV-4 Systems Functionality Description	Rs-Pr: Resource Processes Pr-Pr: Personnel Processes	Activity Diagram	IDEF0 Diagram
SV-5a Operational Activity to Systems Function Traceability Matrix	Rs-Tr: Resource Traceability Pr-Tr: Personnel Traceability	N/A	Matrix based on <i>Actions</i>
SV-5b Operational Activity to Systems Traceability Matrix	Rs-Tr: Resource Traceability Pr-Tr: Personnel Traceability	N/A	Matrix based on <i>Actions</i> and <i>Assets</i>
SV-6 Systems Resource Flow Matrix	Rs-Cn: Resource Connectivity Pr-Cn: Personnel Connectivity	N/A	Matrix of <i>Input/Outputs</i>
SV-7 Systems Measures Matrix	Pm-Me: Measurements	Parametrics Diagrams	Matrix based on <i>Measures</i> and <i>Assets</i>
SV-8 Systems Evolution Description	Rs-Rm: Resource Evolution Pr-Rm: Personnel Availability	State-machine Diagram	Timeline Diagram
SV-9 Systems Technology & Skills Forecast	Rs-Rm: Resource Forecast Pr-Rm: Personnel Evolution	N/A	Timeline Diagram
SV-10a Systems Rules Model	Rs-Ct: Resource Constraints Pr-Ct: Drivers	N/A	N/A

SV-10b Systems State Transition Description	Rs-St: Resource States Pr-St: Personnel States	State-machine Diagram	State-machine Diagram
SV-10c Systems Event-Trace Description	Rs-Is: Resource Interaction Scenarios Pr-Is: Personnel Interaction Scenarios	Sequence Diagram	Sequence Diagram
SvcV-1 Services Context Description	Sv-Tx: Service Taxonomy Sv-Sr: Service Structure	Block Definition Diagram	Asset Diagram
SvcV-2 Services Resource Flow Description	Sv-Sr: Service Structure	Internal Block Definition Diagram	Asset Diagram
SvcV-3a Systems-Services Matrix	Sv-Cn: Service Connectivity	N/A	Matrix based on <i>Assets</i>
SvcV-3b Services-Services Matrix	Sv-Cn: Service Connectivity	Activity Diagram	IDEF0 Diagram
SvcV-4 Services Functionality Description	Sv-Pr: Service Processes	N/A	Matrix based on <i>Actions</i>
SvcV-5 Operational Activity to Services Traceability Matrix	Sv-Tr: Service Traceability	N/A	Matrix based on <i>Action</i> and <i>Asset</i>
SvcV-6 Services Resource Flow Matrix	Sv-Cn: Service Connectivity	N/A	Matrix based on <i>Input/Outputs</i>
SvcV-7 Services Measures Matrix	Pm-En: Environment	Parametrics Diagram	Matrix based on <i>Measures</i> and <i>Assets</i>
SvcV-8 Services Evolution Description	Sv-Rm: Service Roadmap	State-machine Diagram	Timeline Diagram
SvcV-9 Services Technology & Skills Forecast	Sv-Rm: Service Roadmap	N/A	Timeline Diagram
SvcV-10a Services Rules Model	Sv-Ct: Service Constraints	N/A	N/A
SvcV-10b Services State Transition Description	Sv-St: Service States	State-machine Diagram	State-machine Diagram
SvcV-10c Services Event-Trace Description	Sv-Is: Service Interaction Scenarios	Sequence Diagram	Sequence Diagram
PV-1: Project Portfolio Relationships	Pj-Tx: Project Taxonomy Pr-Sr: Project Structure	N/A	Matrix based on <i>Time</i> and <i>Assets</i>
PV-2: Project Timelines	Pj-Cn- Project Connectivity Pj-Rm: Standards Roadmap	N/A	Timeline Chart
PV-3: Project to Capability Mapping	Pj-Tr: Project Traceability	N/A	Matrix based on <i>Time</i> and <i>Actions</i>

StdV-1 Standards Profile	Sd-Tx: Standard Taxonomy Sd-Sr: Standards Structure Sd-Tr: Standards Traceability	N/A	<i>Statements</i>
StdV-2 Standards Forecast	Sd-Rm: Standards Roadmap	N/A	Timeline Chart
DIV-1: Conceptual Data Model	Conceptual Data Model	UML Class Diagram, Block Definition Diagram	<i>Actions, Assets, and Inputs/Outputs</i>
DIV-2: Logical Data Model	Logical Data Model	UML Class Diagram, Block Definition Diagram	<i>Actions, Assets, and Inputs/Outputs</i>
DIV-3: Physical Data Model	Physical Schema, Real World Results	UML Class Diagram, Block Definition Diagram	<i>Actions, Assets, and Inputs/Outputs</i>

D. INTERNATIONAL STANDARDS FOR THE EXCHANGE OF PRODUCT MODEL DATA

The International Standard for the Exchange of Product Model Data (ISO 10303), commonly known as “STEP,” is a series of standards for the computer-interpretable representation and exchange of product manufacturing information. The objective of these is to provide a mechanism that is capable of describing product data throughout the life cycle of a product, independent from any particular system. The nature of these standardized descriptions makes it suitable not only for neutral file exchange, but also as a basis for implementing and sharing product databases and archiving (ISO 10303-1, 1994). The STEP family of international standards is especially relevant to Digital Engineering because they can be used to exchange data between Computer Aided Design (CAD), computer-aided manufacturing, computer-aided engineering, product data management/enterprise data modeling and modeling and simulation data. STEP is decomposed into series of subordinate documents known as “Application Protocols (AP)” as listed below (ISO 10303-1, 1994, ISO 10303-243, 2021):

- Mechanical
 - AP 207, Sheet metal die planning and design
 - AP 209, Composite and metallic structural analysis and related design
 - AP 235, Materials information for the design and verification of products
 - AP 236, Furniture product data and project data
 - AP 242, Managed model based 3d engineering
- Connectivity oriented electric, electronic and piping/ventilation
 - AP 210, Electronic assembly, interconnect and packaging design. The most complex and sophisticated STEP AP.
 - AP 212, Electrotechnical design and installation.
 - AP 227, Plant spatial configuration
- Ship
 - AP 215, Ship arrangement
 - AP 216, Ship molded forms

- AP 218, Ship structures
- Manufacturing APs
 - AP 219, Dimensional inspection information exchange
 - AP 223, Exchange of design and manufacturing product information for cast parts
 - AP 224, Mechanical product definition for process plans using machining features
 - AP 238 - Application interpreted model for computer numeric controllers
 - AP 240, Process plans for machined products
- Life cycle support APs
 - AP 239, Product life cycle support
 - AP 221, Functional data and schematic representation of process plants
 - AP 241, Generic Model for Life Cycle Support of AEC Facilities
 - AP 243, Modeling and Simulation Information in a Collaborative Systems Engineering Context

The most significant of the ISO 10303 standards for this research is the International Standard for Modeling and Simulation Information in a Collaborative Systems Engineering Context (MoSSEC) (ISO 10303-243). MoSSEC considers data exchanges across the lifecycle of a system, recognizing that different phases of the system's lifecycle have different information needs. For example, MoSSEC lists the following examples of the type of information being exchanged across the system's lifecycle (ISO 10303-243, 2021):

- Business/Mission Analysis: Problems and opportunities; solution space; potential solutions; decisions, rationale and assumptions.
- Stakeholder Needs and Requirement Definition: Stakeholder expectations, goals, needs; value drivers; quantified objectives. All providing traceability for the stakeholder requirement definitions.
- System Requirement Definition: Operations / operational needs; system requirements.
- Architecture Design: study management; requirement cascade and emergence; interfaces; architectures; assumptions and decisions.
- Design definition: interfaces; requirements; physical, functional, and logical models.
- System Analysis: methods and tools; simulation models; performance, behavior, feasibility, sensitivity results.
- Integration: physical, functional, logical models linked to architecture and requirements.
- Verification: architecture, system requirements satisfaction, verification and evidence; procedures; reviews; test results and reports.
- Validation: architecture, stakeholder requirements satisfaction, verification and evidence; procedures; reviews; test results and reports.

MoSSEC is also based on traceability across domain, platform and systems. To achieve this traceability, all domains, platforms and organizations need to be able to exchange the representative and relevant technical data (ISO 10303-243). The premise of MoSSEC falls

short on the goal of this research of defining a means to share system data derived from modeling languages, MBSE tools, and presentation frameworks in an agnostic manner. STEP is critical to Digital Engineering because of the various standards defined by the APs. While each standard provides an important piece of the Digital Engineering puzzle, the MoSSEC standard can be used to bring the various standards together. Figure 12 shows the interactions of MoSSEC with other APs within the STEP standards (ISO 10303-243, 2021).

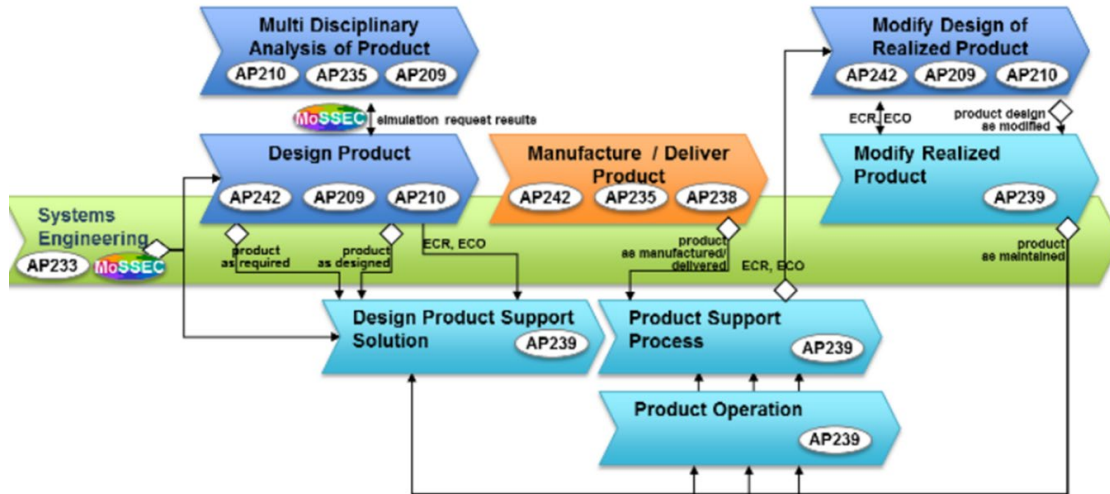


Figure 12. Interaction of MoSSEC and TEP Standards (ISO 10303-243, 2021).

MoSSEC recognizes the need to exchange data to address systems engineering questions in a modeling environment, and traceability of the data. These themes are also two of the goals of this research, and is achieved through a virtual representation of the system defined by the CDM.

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III. THE ONTOLOGY AND CONCEPTUAL DATA MODEL

A. OVERVIEW AND APPROACH

Three challenges to exchanging digital data were identified in Chapter 1, and were illustrated in Figure 6. Those challenges are:

1. A strict naming convention of entities needs to be established.
2. Each entity has a unique identifying number, thus making it difficult to save digital data between MBSE tools, even if it is commonly named.
3. Exchanging or combining data from different model-based tools requires more than a common data exchange format (e.g. xmi).

Establishing, maintaining, and enforcing a naming convention is one of the envisioned responsibilities of the model curator. The model curator will be a new responsibility in the system's engineering discipline, and represents one of the necessary organizational changes as robust MBSE environments are implemented. Model curation is currently being researched by the Massachusetts Institute of Technology (MIT) (Rhodes, 2021).

The second challenge is with the unique number assigned to entity by the various tools. This problem is very similar to the naming convention, but the number is tool generated and cannot be manipulate or changed. This problem is better suited for research by the computer science discipline than by systems engineering.

The third challenge is using/combining data from different model-based tools in a MBSE environment requires more than just a data exchange standard (e.g .xml) to data between tool. Physically exchanging data between two tools is currently possible, but once the data is physically exchanged, the utility of that data is often lost due to the tools application of data being incompatible. In addition to the exchange standard, a mapping of how data from different system models are related is required. This research addresses the third challenge. Heretofore, most MBSE efforts within the Naval Domain have focused on a single modeling language and a single MBSE tool. Data schemas and data dictionaries have been developed in an attempt to standardize modeling with a focus on reuse. Several gains have been made, however, exchanging data between models, but within a single modeling language and MBSE tool, has mixed results at best, and sharing data between modeling languages and MBSE tools is a challenge yet to be conquered. However, the spirit of Goal 4, "Establish a supporting infrastructure and environments to perform activities, collaborate, and communicate across stakeholders," (DoD 2018, DoN 2020), the best modeling language and best MBSE tool are used to produce the requisite system data. This concept was illustrated in Chapter 1 Figure 5.

This research addresses the challenge of exchanging data between different modeling languages, presentation frameworks, and MBSE tools by defining a parsimonious ontology that allows system entities to be reduced to their atomic (or most basic) level, and by establishing a conceptual data model (CDM) (i.e. data schemas) that allows for a virtual representation of the system to be defined.

The concept defining a virtual representation of the system is fundamental to this research as it places the focus on what is being modeled – the system! This system model allows modeling languages, MBSE tools, and presentation frameworks to be treated agnostically. This means that the entities that represent various portions of the system can be modeled with the best MBSE tool, using the best modeling language, and represented by the best view within a presentation framework.

The CDM allows for the identification of entity interfaces, thereby showing where data exchange standards need to be established. The inherent relationships within the ontology will allow for the development of a system model. By coupling the ontology and CDM, a “Rosetta Stone” can be established to identify the translation between entities, modeling languages, presentation frameworks, and MBSE tools. This will allow system data to be created using the best approach for the aspect of the system model being developed.

The coupling of the ontology and CDM allows for:

- System entities within individual data dictionaries to be mapped to the ontology, and reduced to an atomic level where like entities are identified;
- System entities within individual data dictionaries to be mapped to a system model within the CDM;
- The opportunity for system data to be developed using the best modeling language, presentation framework, or MBSE tool for the problem;
- The identification where further data exchange standards need to be developed to translate the data between entities (i.e the “Rosetta Stone”) that are created in disparate modeling languages, presentation frameworks, or MBSE tools.

B. THE ONTOLOGY

Ontologies¹ have been discussed in MBSE for several years, with different approaches, and limited results. In August 2020, the Navy Chief Engineer released a white paper attempting to restate the problem. The Naval Research Program effort is the direct result of that white paper.

A fundamental premise of this research is that an ontology should use an economy or entities approach to create a parsimonious list of entities that allow entities from a data dictionary to be reduced to their atomic level, thereby identifying like entities. A parsimonious ontology is important to focus the engineers on a limited (but comprehensive from a systems perspective) set of entities. Having too many entities may lead engineers to use different entities for the same system element. Conversely, having too few entities will not fully identify the system elements.

Describing the system with fewer entities will allow for a “common denominator of entities” to be used to describe the system. The hundreds of defined entities within the data dictionary of individual programs and systems will be able to be mapped to the parsimonious ontology, thereby facilitating data exchanges to define the virtual model of

¹ An ontology is a collection of standardized entities (terms), the relationships among the entities, and the attributes of the entities.

the system. Figure 13 illustrates the concept of mapping entities from a data dictionary to an ontology.

The purpose of this parsimonious list of entities is to reduce systems to their atomic level to illustrate like data, which allows them to have defined relationships and attributes. For example, an Amphibious Combat Vehicle (ACV), the Joint Strike Fighter (F35), and Guided Missile Destroyers (DDG), are all systems, therefore are categorized as Assets within the ontology, and have common relationships and attributes. Furthermore, these Assets not only include the hardware and software elements, they perform Action, have Requirements, Costs, and Risk to name a few.

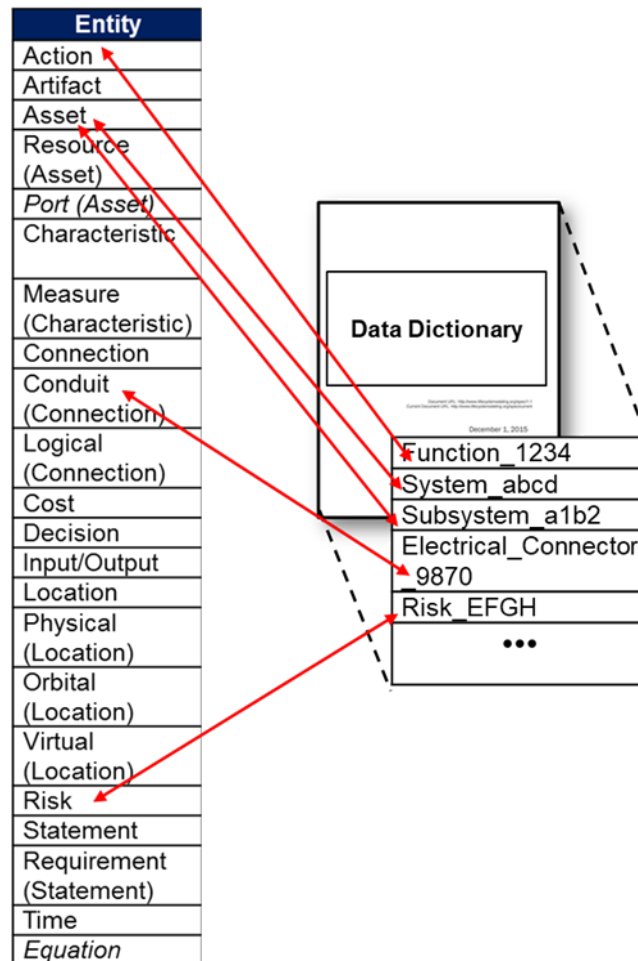


Figure 13. Example of Data Dictionary mapped to an Ontology

Data dictionaries highlight the uniqueness of each system, thereby helping the program offices managing the system lifecycle. However, while systems may be unique to individual programs, they are still characterized as systems, and therefore are similar to other systems at the atomic level.

This research adopts a portion of the LML ontology as the ontological basis, because it represents an ontology that uses an economy of entities approach to create a parsimonious list of entities, that have defined relationships and attributes. By adopting the LML

ontology, the research team was able to focus on other aspects of the research without having to develop a unique ontology. There are a few caveats that should be stated. First, this research is not promoting the use of the LML and a language, nor endorsing any MBSE tool based on LML. Second, the LML entities are only used because they are well-defined, and established relationships, and are parsimonious. Even with the parsimonious nature of the LML ontology, not all entities were used. Table 2 shows the entities and their definitions, that comprise the atomic level of a system model (DoD (2009); LML 1.4 (2022)).

This type of ontology used in this research is known as an entity, relationship, attribute², or ERA. A relationship (often considered the verbs of an ontology) connects entities to each other through a standardization terms (LML, 2022). These relationships are defined in Chapter 2 and are shown in Figure 8, and are applied in Section C.

This research expanded the ERA ontology approach to include labels (ERA(L)). The labels allow for data to be further identified within an Entity Class to Entity Subclasses. The Entity Subclasses have inheritance, therefore have the same relationships and attributes, as their parent entity class. Inheritance maintains the economy of entities spirit of this research. For example, the Action entity could identify capabilities, operations activities, functions, and program. It is important to further delineate these Entity Subclasses, while maintaining inheritance. The Entity Subclasses and definition are shown in Table 3.

² Attributes were not used in this research. For the ERA discussion to be complete, attributes describe the inherent characteristics or quality of an entity. It further describes the entity, enhancing its uniqueness. The definitions of these attributes are shown below (LML 1.4, 2022).

- Text - Text data type represents: a single character, single word, or multiple words.
- Number - Number data type represents any individual real number.
- Boolean data type represents the two possible logical values “true” and “false”.
- Percent - Percent data type represents a special case of Number where the value is restricted to values between zero and one hundred.
- DateTime - DateTime data type represents a specific method of storing a given date and time value. Commonly stored as “YYYY-MM-dd hh:mm:ss”. Where “YYYY” is the four-digit year, “MM” is the two-digit month, “dd” is the two-digit day, “hh” is the two-digit hour (in twenty-four hours), “mm” is the two-digit minute, and “ss” is the two digits second.
- URI - Uniform Resource Identifier (URI) data type represents a special case of Text where the value must be a URI. Examples of URI: “C:/Program Files”, “http://www.google.com”, and “test@test.com”.
- Enumeration - Enumeration data type represents a set of defined choices, where the selection of only one choice is permitted. An enumeration must contain at minimum two choices. All choices within the set must be of the same data type (having a set containing both Text data type and Number data type is not permitted). Also, within a set, a repeated choice is not permitted.

Table 2. Entity Classes and Definitions.

Entity Class	Definition
<i>Artifact</i>	An Artifact entity specifies a document or other source of information that is referenced by or generated in the knowledgebase.
<i>Action</i>	An Action entity specifies the mechanism by which inputs are transformed into outputs.
<i>Asset</i>	An Asset entity specifies an object, person, or organization that performs Actions, such as a system, subsystem, component, or element.
<i>Resource</i>	A Resource entity specifies a consumable or producible Asset. (e.g. Fuel, billets, missiles, people).
<i>Characteristic</i>	A Characteristic entity specifies properties of an entity. (e.g power, size, weight, role).
<i>Measure</i>	A Measure entity specifies properties of measurements and measuring methodologies, including metrics. (e.g. Key Performance Parameter (KPP), Measure of Effectiveness (MOE), Measure of Performance (MOP), Metric).
<i>Cost</i>	A Cost entity specifies the outlay or expenditure (as of effort or sacrifice) made to achieve an objective associated with another entity. (e.g. Earned Value, Work Breakdown Structure, Actual Cost, Planned Cost).
<i>Location</i>	A Location entity specifies where an entity resides.
<i>Statement</i>	A Statement entity specifies text referenced by the knowledgebase and usually contained in an Artifact. (e.g. Need, Goal, Objective, Assumption).
<i>Requirement</i>	A Requirement entity identifies a capability, characteristic, or quality factor of a system that must exist for the system to have value and utility to the user.
<i>Risk</i>	A Risk entity specifies the combined probability and consequence in achieving objectives. (e.g. cost risk, technical risk, schedule risk)
<i>Time</i>	A Time entity specifies a point or period when something occurs or during which an action, asset, process, or condition exists or continues. (e.g. Milestone, phase, date-time group).

Table 3. Entity Subclasses and Definitions.

Entity Class	Entity Subclass	Entity Subclass Definition	Definition Source
<i>Artifact</i>	Guidance	An authoritative documented intended to lead or steer the execution of actions.	DoD (2009)
	Governance	The set of rules, policies, and decision-making criteria that will guide the SoS to achieving its goals and objectives.	
	Agreement	A consent among parties regarding the terms and conditions of activities that said parties participate in.	DoD (2009)
	Standard	A formal agreement documenting generally accepted specifications or criteria for products, processes, procedures, policies, systems, and/or personnel.	DoD (2009)
<i>Action</i>	Activity	Work, not specific to a single organization, weapon system or individual that transforms inputs (Resources) into outputs (Resources) or changes their state.	DoD (2009)
	Capabilities	The ability to achieve a Desired Effect under specified (performance) standards and conditions through combinations of ways and means (activities and resources) to perform a set of activities.	DoD (2009)
	Function	Constitutes a specific or discrete action required to achieve a desired objective.	Blanchard & Fabrycky (2010)
	Program	The process for controlling the cost, schedule, and performance of a project or group of projects to achieve a stated goal.	AcqNotes (2022)
<i>Asset</i>	Platform	A system that is able to host other systems. The platform retains all of the relationships, attributes, and characteristics of a system.	
	System	A functionally, physically, and/or behaviorally related group of regularly interacting or interdependent elements.	DoD (2009)
	Service	A mechanism to enable access to a set of one or more capabilities, where the access is provided using a prescribed interface and is exercised consistent with constraints and policies as specified by the service description. The mechanism is a Performer. The capabilities accessed are Resources -- Information, Data, Materiel, Performers, and Geo-political Extents.	DoD (2009)

Resource	Organization	A specific real-world assemblage of people and other resources organized for an on-going purpose.	DoD (2009)
	Performer	Any entity - human, automated, or any aggregation of human and/or automated - that performs an activity and provides a capability.	DoD (2009)
	Installation	A military of industrial establishment.	
	Logistics	The detailed coordination of a complex operation involving many people, facilities, or supplies:	
	Information	The state of a something of interest that is materialized -- in any medium or form -- and communicated or received.	DoD (2009)
Characteristic	Condition	The state of an environment or situation in which a Performer performs.	DoD (2009)
	Skill	The ability, coming from one's knowledge, practice, aptitude, etc., to do something well.	DoD (2009)
Measure	Measures of Effectiveness (MOE)	The “operational” measures of success that are closely related to the achievement of the mission or operation being evaluated, in the intended operational environment, under a specified set of conditions.	Roedler & Jones (2005)
	Key Performance Parameters (KPP)	Key Performance Parameters are a special case of Measures of Effectiveness, that are so critical that failure to achieve the KPP may result in program cancellation or significant program restructuring.	Roedler & Jones (2005)
	Measures of Performance (MOP)	The measures that characterize physical or functional attributes relating to the system operation, measured or estimated, under specific testing and/or operational environment conditions.	Roedler & Jones (2005)
	Technical Performance Measures (TPM)	Metrics which measure the attributes of a system element to determine how well a system, or system element, is satisfying, or expected to satisfy, a technical requirement or goal.	Roedler & Jones (2005)
Cost	Cost	An amount that has to be paid or spent to buy or obtain something:	
Location	Orbital	An Orbital entity specifies a location along an orbit around a celestial body. (e.g. Orbit).	LML v1.4 (2022)
	Physical	A Physical entity specifies a location on, above, or below the surface. (e.g. geographic coordinates).	LML v1.4 (2022)

	Virtual	A Virtual entity specifies a location within a digital network. (e.g. URL).	LML v1.2 (2022)
Statement	Guidance	An authoritative statement intended to lead or steer the execution of actions.	DoD (2009)
	Standard	The set of rules governing the arrangement, interaction, and interdependence of parts or elements of the system or model, of the system.	
Requirement	Originating	Requirements that are the cornerstone upon which the systems engineering process is based. These requirements do not just appear, but involve a great deal of work using several important systems engineering tools: the operational concept, the external systems diagram, and the objectives hierarchy.	Buede (1997)
	Derived	Requirements that result from the analysis and allocation of Technical Requirements to logical functional architectures that are developed as part of the requirements analysis process. Derived technical requirements become the basis for the solution-specified requirements for the system model and are a ‘design-to’ requirement for the system.	AcqNotes (2022)
Risk	Risks	The potential that something will go wrong as a result of one or a series of events. It is measured as the combined effect of the probability of occurrence and the assessed consequence given the occurrence.	

To further facilitate mapping from a program’s data dictionary to the ontology, a Data Type was added. The majority of the Data Types were derived from the Department of Defense Meta-Model 2.0 (DM2). While programs may find it difficult to map entities from the data dictionary to the Entity Subclasses, and certainly to the Entity Classes, they will find it easier to map the data dictionary entities to the Data Type. Once mapped to the Data Type, further mapping to the Entity Subclasses and Entity Classes are already defined, thereby reducing the entities from the data dictionary to the atomic level (found in the Entity Classes).

Table 4 shows the full ontology to include: Entity Classes, Entity Subclasses, and Data Types.

Table 4. Ontology.

Entity Class	Entity Subclass	Data Type	Numbering Schema
Artifact	Guidance	Strategic Objectives & Policies	STRT.x
		Directives	Dir.x
		Defense Planning Guidance	DPG.x
		Plans	PLAN.x
		Tactics, Techniques, and Procedures (TTP)	TTP.x
		Doctrine	Doc.x
		Program of Record	POR.x
	Governance	Regulations	REG.x
		Policy	POL.x
	Agreement	Memorandum of Understanding (MOU)	MOU.x
		Memorandum of Agreement (MOA)	MOA.x
	Standard	Joint Capabilities Areas Document (JCA)	JCA.x
		Mission Essential Tsk List (METL)	METL.x
Required Operational Capabilities/Projected Operational Environment		ROC/POE.x	
	Technical Standard	TS.x	
Action			
	Activity	Operational Activity	OA.x
		Training	TRA.x
		Maintenance	MNT.X
	Capabilities	Capabilities	CA.x
	Function	Function	F.x
		System Function	SF.x
		Service Function	SVC.x
SOA Function		SOA.x	
Test Process		TP.x	
	Test and Diagnostic	TD.x	

	Program	Program Activity	PM.x
Asset			
	System	Enterprise	ES.x
		System of Systems (SoS)	SOS.x
		Family of Systems (FoS)	FOS.x
		Platform	S.x
		System	SN.x
		Sub-System	SN.x.x
		Assembly	SN.x.x.x
		Sub-Assembly	SN.x.x.x.x
		Component	SN.x.x.x.x.x
		Hardware	SN.x.x.x.x.x.x
		Software	SW.x
	Service	Service	SER.x
Resource			
	Organization	Organization	ORG.x
	Performer	User/Person	PER.x
	Installation	Facility	FAC.x
		Property	IN.x
		Site	IN.x.x
	Logistics	Consumables	LO.x
		Support Equipment	
		Test & Diagnostic Equipment	TDE.x
		Training Devices & Simulators	TDS.x
	Information	Data	IN.x
Characteristic		Environmental State	CE.x
	Condition	Operational Condition	
		Quality of Service	CQ.x
	Skill	Skill	CS.x

Measure	Measures of Effectiveness (MOE)		MOE.x
	Key Performance Parameters (KPP)		KPP.x
	Measures of Performance (MOP)		MOP.x
	Technical Performance Measures (TPM)		MOP.x
Cost	Cost	Cost	C.x
Location	Orbital	Orbital	LO.x
	Physical	Address, Geolocation	LP.x
	Virtual	IP Address	LV.x
Statement	Guidance	Mission	MI.x
	Standard	Joint Capabilities	JC.x
		Task	MT.x
Requirement	Originating	Performance Requirement	RP.x
		Operational Requirements	RO.x
	Derived	Functional Requirements	RF.x
		System (Physical) Requirements	RS.x
		Interface Requirements	RI.x
Risk	Risks		R.x
Time	Time	Event	T.x
		Milestone	T.x
		Phasing/Evolution/Forecast	T.x

Table 4 also shows a notions numbering schema. This schema will be discussed in Section C. The attributes describe the inherent characteristics or quality of an entity. It further describes the entity, enhancing its uniqueness. The attributes that apply to all entity classes employed in this research are: Text; Number; Boolean; Percent; Date Time; URI; Enumeration; and Geopoint. The definitions of these attributes are shown below (LML 1.4, 2022).

- **Text** - Text data type represents: a single character, single word, or multiple words.
- **Number** - Number data type represents any individual real number.

- **Boolean** - Boolean data type represents the two possible logical values “true” and “false”.
- **Percent** - Percent data type represents a special case of Number where the value is restricted to values between zero and one hundred.
- **DateTime** - DateTime data type represents a specific method of storing a given date and time value. Commonly stored as “YYYY-MM-dd hh:mm:ss”. Where “YYYY” is the four-digit year, “MM” is the two-digit month, “dd” is the two-digit day, “hh” is the two-digit hour (in twenty-four hours), “mm” is the two-digit minute, and “ss” is the two-digit second.
- **URI** – Uniform Resource Identifier (URI) data type represents a special case of Text where the value must be a URI. Examples of URI: “C:/Program Files”, “http://www.google.com”, and “test@test.com”.
- **Enumeration** - Enumeration data type represents a set of defined choices, where the selection of only one choice is permitted. An enumeration must contain at minimum two choices. All choices within the set must be of the same data type (having a set containing both Text data type and Number data type is not permitted). Also, within a set, a repeated choice is not permitted.
- **GeoPoint** - GeoPoint data type represents a longitude and latitude pair on the surface of a body.

C. THE CONCEPTUAL DATA MODEL

In Section B, an ontology was developed as a means to reduce seemingly disparate entities from various program data dictionaries to the atomic level as identified by a parsimonious set of entities. This ontology is an ERA(L) ontology where the relationships and attributes are defined. However, the ontology does not use the relationships *per se*.

As previously mentioned, prior attempts at developing an ontology, across the Naval Domain, have focused on individual modeling languages and specific MBSE tools. These attempts have convoluted the concept of the ontology and have often neglected the concept of relationships. However, engineers develop systems composed of elements that have relationships, so why not focus that the system and the relationships instead of solutions that are based in languages and tools.

The concept behind the System Design Language (SDL) schema discussed in Chapter 2 serves as the motivation for the CDM developed for this research. While the SDL schema is constrained by its language, the CDM is modeling language, presentation framework, and MBSE tool agnostic. The CDM is only constrained by the system itself.

The definition of a system is defined numerous ways within the Systems Engineering Domain. However, no definition captures the full extent of the real-world system. For MBSE to be successful, the full scope of the system should be modeled, most likely via different MBSE tools that represent a portion of the system. The purpose of the CDM is model the various aspects of the system, using the ontology entities and relationships to create a virtual representation of the system. In an ideal system model, each data type will be represented as many times as it is represented in the real-world – JUST ONCE – but

given the relationships can be viewed from several perspectives, thereby achieving concordance.

Figure 14 illustrates the format of the CDM. The entities are connected by a line that represents the relationships between the system entities, with the types of relationships annotated at each end of the arrows.

The CDM represents the most common relationships found within a system. However, as discussed in Chapter II, and shown in Figure 9, most entities are related to each other, thus approximates $22!$ or 10^{21} possible combinations. While the ontology represented by the research is based on the LML ontology, only 12 entities were used for a possible of $12!$ or 10^8 possible combinations. While only a fraction of these combinations are represented in the CDM, these relationships are extensible if needed to make the virtual representation of system model complete.

The CDM also represents a mapping of the virtual and not an architecture of that system. Each data element with the ontology is only represented once but can be decomposed to the *nth*-level, as needed to model the appropriate level of detail with the system.

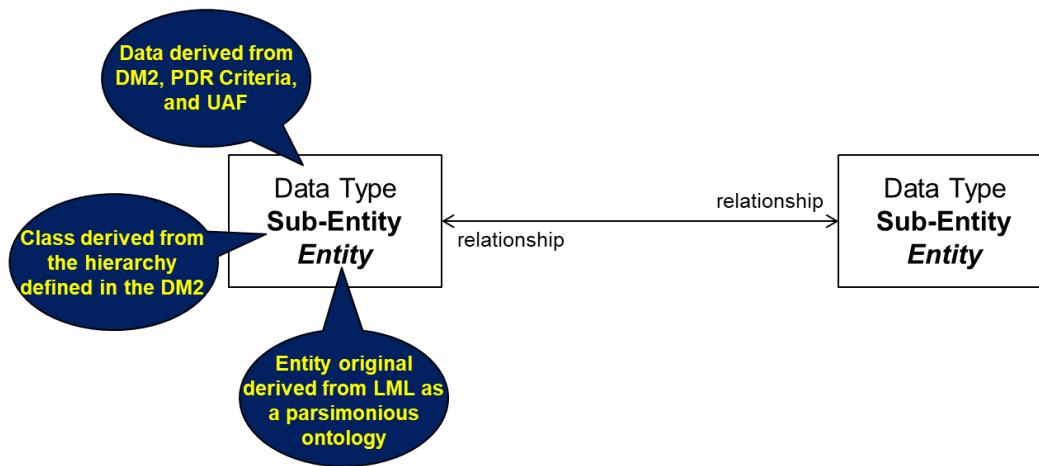


Figure 14. Conceptual Data Model Format

The CDM is a model of the system, but for readability, it is organized into seven viewpoints, and can be initiated with any of the viewpoints, depending on the perspective of the model. For example, new systems start naturally being with the Capabilities, Operations, and Requirements Viewpoint, and the identification of the capabilities that are derived from the mission. However, for system developments already on-going, the Systems and Services Viewpoint may be explored first. If the application involves the planning of system sustainment, the Logistics and Maintenance Viewpoint may be a logical place to begin. The viewpoints are discussed in the following sections, and are illustrated with an example in Chapter IV.

1. Capabilities, Operations, and Requirements Viewpoint

The purpose of the Capabilities, Operations, and Requirements Viewpoint is to lay the foundation of what the system needs to do from a formal guidance perspective, derives Missions, Capabilities, Operations, Functions, and eventually Requirements.

This viewpoint can be used to indirectly map data from a mission analysis to the derived specifications required to design and build the system. There are various different modeling languages, MBSE tools, and presentation frameworks that can be employed here. The Capabilities, Operations, and Requirements Viewpoint is shown in Figure 15.

Capabilities, Functions, and Requirements Viewpoint

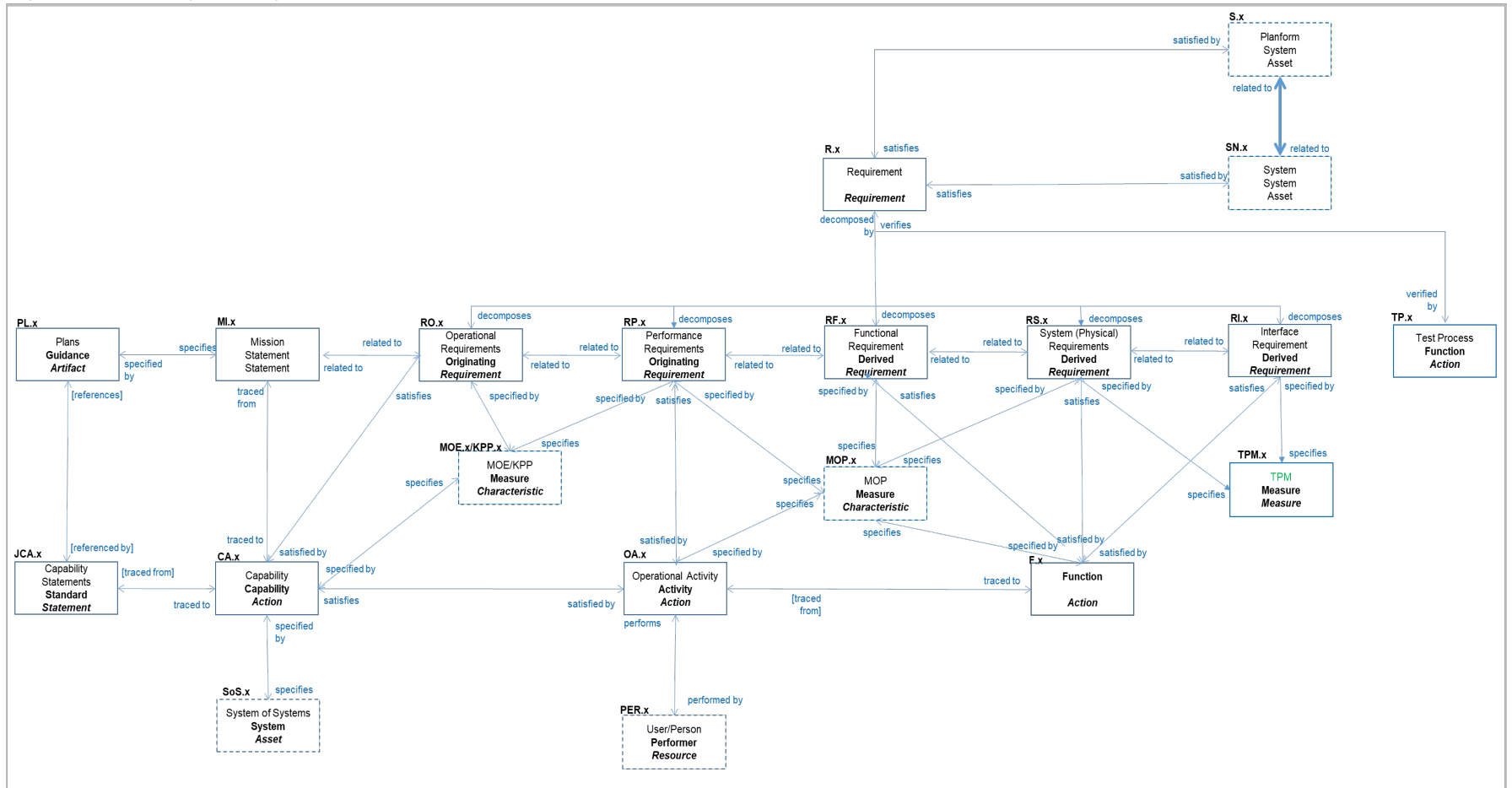


Figure 15. Capabilities, Operations and Requirements Viewpoint.

2. Systems and Services Viewpoint

The Systems and Services Viewpoint is one of the main focus of the CDM. As with any viewpoint, the Systems and Services Viewpoint can be entered at any point. Starting at the top of the viewpoint at Enterprise/Portfolio and working down, the system is decomposed to the lowest level to include the Hardware, Software, and Services data types. Since the ontology and CDM are modeling language, MBSE tool, and presentation framework agnostic, the modeling tools most efficient and effective to model that portion of the system can be used. A purpose, and strength, of the CDM is identify areas where data translations needs to occur.

A few areas of this viewpoint that warrant additional discussion are the System of Systems and Family of Systems, and Platforms, and Systems data types. The following definitions of the data types apply:

- System of Systems (SoS)- A set or arrangement of systems that results when independent, and task-oriented systems are integrated into a larger systems construct, that delivers unique capabilities and functions in support of missions that cannot be achieved by individual systems alone (Vaneman, 2015).
- Family of Systems (FoS) - a set of systems that provide similar capabilities through different approaches to achieve a similar or complementary effects. (DoD, 2008).

The main difference between a SoS and a FoS is the SoS is more operationally focused may include a wide variety of different systems. The FoS is more technical management focused where a fleet of the same type of systems is being managed. The system within the FoS may or may not be part of a SoS.

Continuing, the following definitions also apply:

- Platform – A system that is able to host other systems that have their own lifecycle and program. A platform exhibits the characteristics of a system.
- System - An integrated set of elements, designed to function together to achieve some defined objective.

Therefore, a platform can host a system, but a platform is not a SoS *per se*. Chapter IV illustrates these differences with an example. The Systems and Services Viewpoint is shown in Figure 16.

3. Program Management Viewpoint

Traditional program management includes cost, schedule, performance, and risks. These elements provide tremendous insights into the health and status of the system and the program that governs it. Figure 17 depicts the Program Measurement Viewpoint.

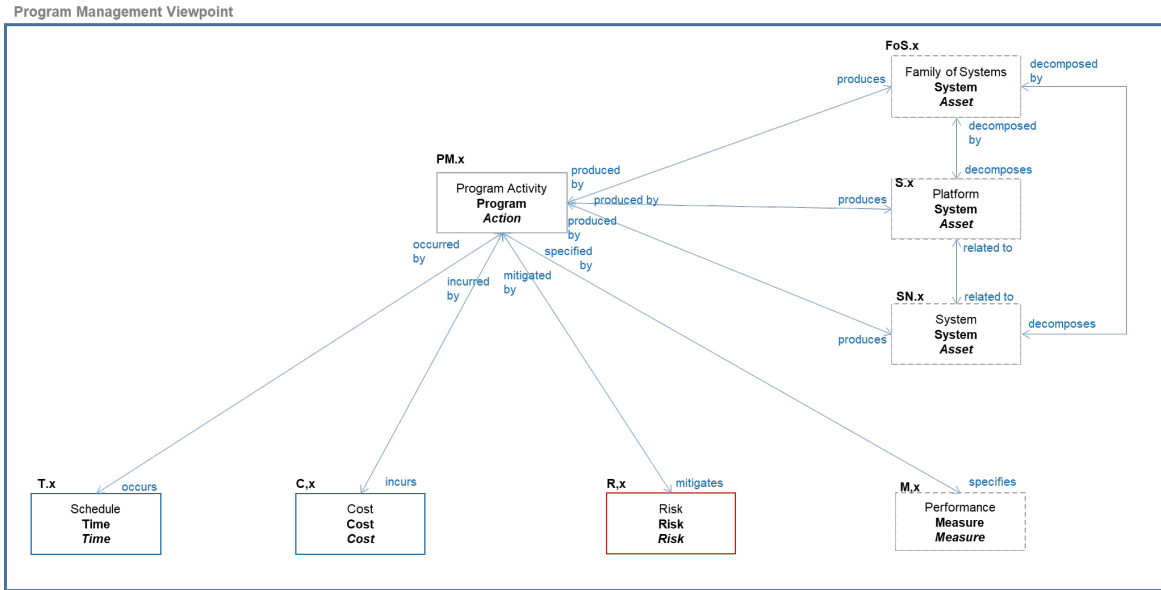


Figure 17. Program Management Viewpoint.

4. Measures Viewpoint

The Measures Viewpoint highlights the various measures within the system. While measures are often aligned to the “ilities” (reliability, maintainability, affordability, availability, performability, etc.). An exhaustive list of measures would subsume the ontology and CDM. Therefore, the measures are shown four levels: Measures of Effectiveness (MOE); Key Performance Parameters (KPP); Measures of Performance (MOP); and Technical Performance Measures (TPM). A definition of these measures is included in Table 3. Figure 18 shows the Measures Viewpoint.

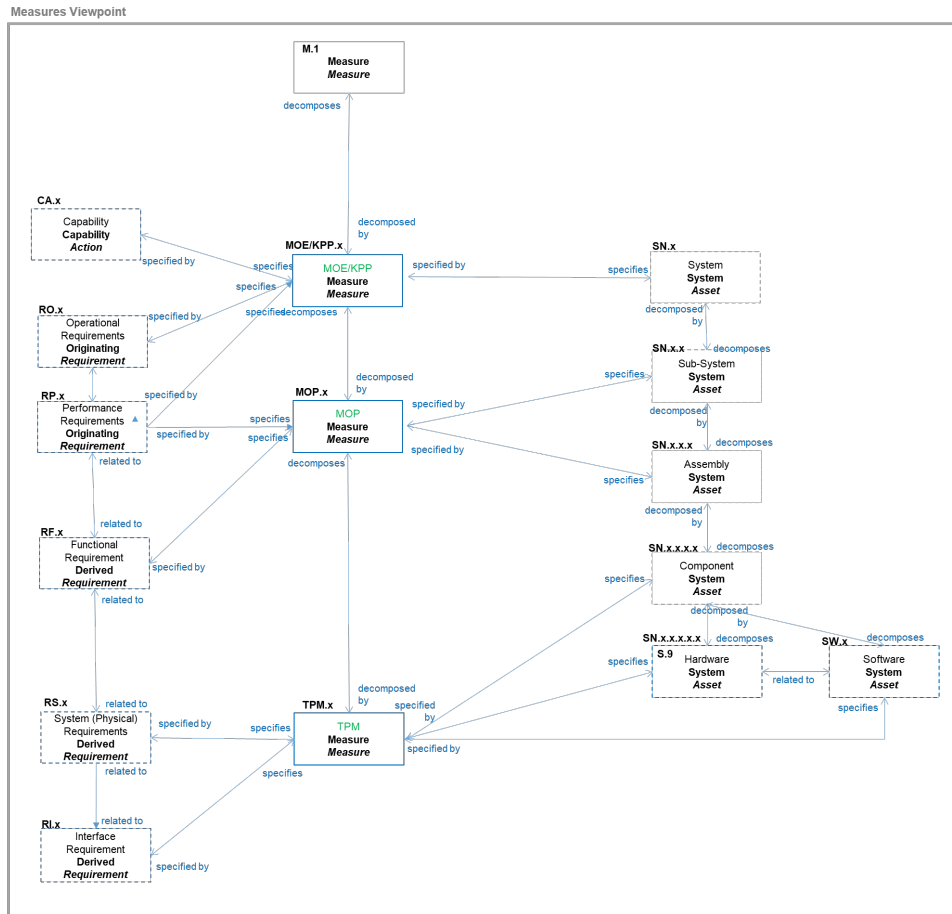


Figure 18. Measures Viewpoint.

5. Logistics and Maintenance Viewpoint

The purpose of the Logistic and Maintenance Viewpoint is to facilitate the operations and maintenance phase of the systems lifecycle. Understanding what type of system maintenance is required at various points in time, the test equipment, and logistics required is essential. Today that engineering planning is generally performed effectively, but is typically disconnected from the system planning during the early phases of the lifecycle.

The vision for digital engineering is for all engineering disciplines to migrate to a model-based environment, therefore the Logistics and Maintenance Viewpoint is included in the comprehensive definition of the system within the CDM. Figure 19 shows this viewpoint.

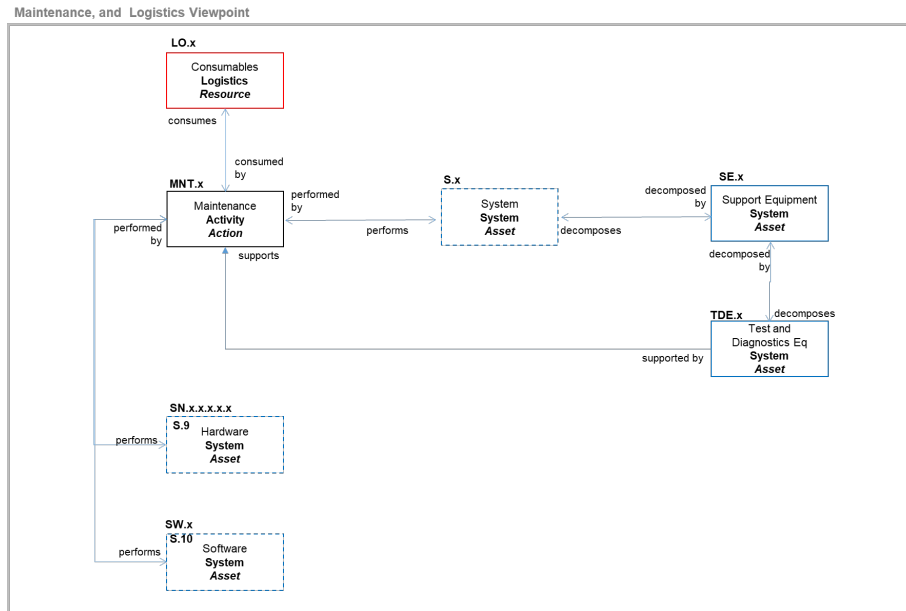


Figure 19. Logistics and Maintenance Viewpoint.

6. Manpower, Personnel and Training Viewpoint

The purpose of the Manpower, Personnel, and Training Viewpoint is included in the CDM to emphasize the importance of human system integration (HSI) as it relates to the system. When considering all aspects of the system, the type of skills the operators and maintainer require plus the training to gain and maintain their skills sets needs to be considered. Unfortunately, HSI is often omitted as the cost of system increase and schedules become more constrained. The Manpower, Personnel, and Training Viewpoint is shown in Figure 20.

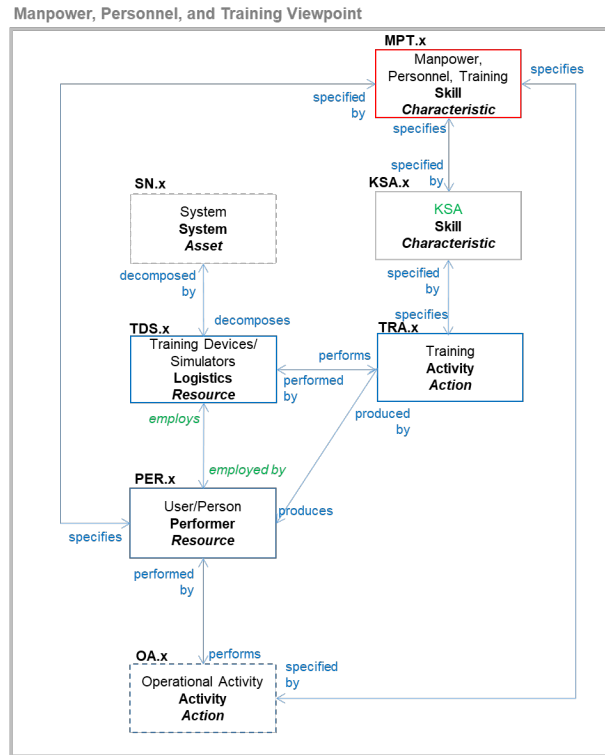


Figure 20. Manpower, Personnel, and Training Viewpoint

7. Location Viewpoint

The purpose of the Location Viewpoint is to identify where the system is located. This is important because the location of the system is currently, or will be in the future, will determine the environmental state that the system will operate in, and hence may influence its design and operations.

The location is identified as Geolocation which identifies the location on earth, Orbital which shows where space based systems are located, and Virtual which shows where data, applications, or services used by the system resides. The Location Viewpoint is shown in Figure 21.

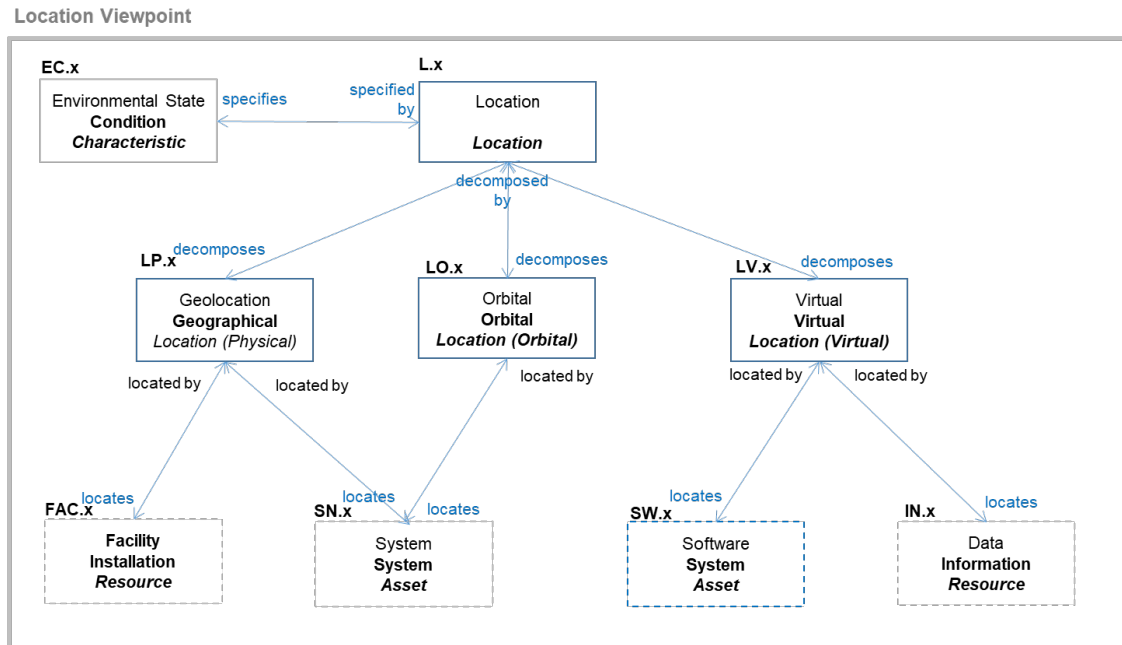


Figure 21. Location Viewpoint.

D. NUMBERING SCHEMA

The notional numbering schema is more than a means to identify where data resides within a model. It is key to satisfying Goal 2 of the DoD Digital Engineering Strategy, which states, “Define the authoritative source of truth” (DoD, 2018). Goal 2 further call for the establishment of governance of the authoritative source of truth.

The notional numbering schema (Figure 22) represents some initial thoughts that may be used in the governance of the authoritative source of truth. The notional numbering schema has four parts.

The first two parts of the numbering schema represents where the data resides in the model, and in analogous to a street address. The first part is the Data Type which identifies the type of data that is being represented by the entity. It can often be confusing what data is being displayed in a MBSE environment. The Data Type is analogous to a street name in an address.

The second part of the numbering schema is the Number itself. The entities shown in the CDM represent one level of the model of the virtual system. However, each entity can be decomposed to the n th level of decomposition. When examining large models is easy to get lost in the data, and these numbers assist with the understanding. If the Data Type is analogous to a street name in an address, the numbers are analogous the building number, the floor number, and the apartment number.

The third part of the numbering schema is if the data is authoritative or derived. Different organizations will use the same data in the portion of the virtual system they are modeling. But, who is really the authority of that data? For example, one organization may be

responsible for modeling the virtual system from an operational viewpoint. Modeling from the operational viewpoint may require data from the systems viewpoint. However, this data is derived, and that organization is not the authoritative source of the system data, and therefore they are not free to significantly change that data, or even answer question about that data. Only the organization with the authority should be able to change the data they are responsible for.

The fourth part of the numbering schema is organization who is the authority for data. If there is going to be an authoritative source of truth, there must me an authority, because” when everyone is responsible, no one is responsible.”

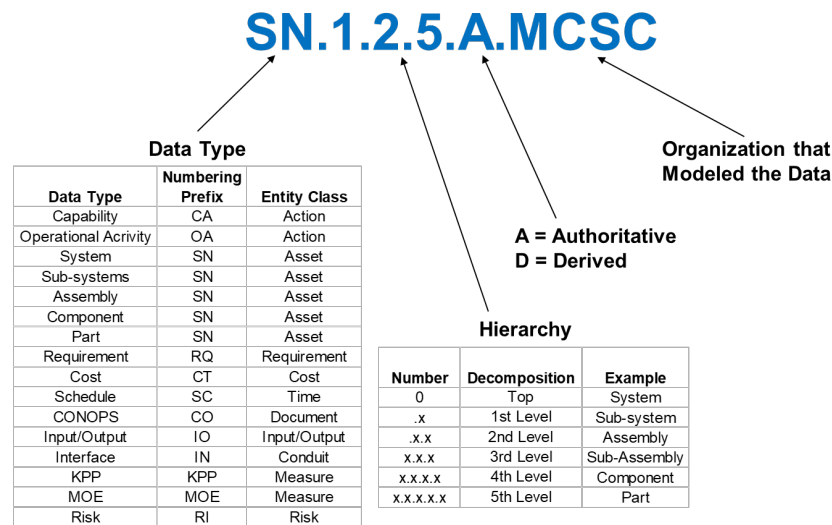


Figure 22. Notional Numbering Schema.

E. USING THE ONTOLOGY AND CDM AS A ROSETTA STONE

Thus far, Chapter III developed a parsimonious ontology that can be used to reduce systems to their atomic level, thereby being able to identify like system entities for disparate real-world systems. A CDM was also developed to illustrate how representative data types can employ the relationships associated with the ontology to develop a schema of the system. This combined approach is a significant departure from other ontological efforts because, is modeling language, MBSE tool, and presentation framework agnostic, thereby making the system the focus.

Another benefit of the ontology and CDM is that it allows for the identification of areas where data exchanges standards need to be developed. Given the three challenges to exchanging digital data, it is clear that data exchanges need to be at the entity level. The ontology and CDM can be used as a “Rosetta Stone” to exchange data between model entities where that data is developed in various modeling languages, MBSE tools, or presentation frameworks. This allows different organizations to execute a modeling strategy of their choosing while being able to share the data with other organizations employing a different modeling strategy. The spirit of DoD Digital Engineering Strategy (2018) Goal 4 is to be able to use various modeling approaches to develop a comprehensive system model.

Decisions on which modeling language, MBSE tool, or which presentation framework to use to base on organizational preferences or focus of the modeling effort.

For example, Figure 15 show the Operation Activity (OA.x) entity. Operational activities can be modeled in every modeling language, MBSE tool, and presentation framework. Each uses slightly different nuisances to model the entities to contribute to the development of the system model. Perhaps the Operational Activities are modeled in two different MBSE tools: one tool is based on SysML as the modeling language and uses the UAF as the presentation framework; and, the other is based in LML as the modeling language and uses DoDAF as the presentation framework. By applying this information to the CDM, a mapping between the entities can be determined as shown in Table 5.

While the previous example illustrates the Rosetta Stone when sharing data about the same entity, it will be more commonly applied when sharing data from different entity types. Each relationship within the CDM is potentially an area where an application programming interface (API) needs to be developed. The investigation and further discussions of APIs is beyond the scope of this research, but is discussed in the Chapter V as an opportunity for future research.

Table 5. The Mapping of Entities

Ontology			Presentation Framework		Modeling Languages	
Entity Class	Data Entity Type	Data Entity	UAF View(s)	DoDAF View(s)	SysML Diagram	LML Diagram
Action	Activity	Operational Activity	OP-PR – Operational Processes	- OV-5a – Operational Activity Decomposition Tree - OV-5b – Operational Activity Model	Activity Diagram	Action Diagram

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IV. THE ONTOLOGY AND CONCEPTUAL DATA MODEL APPLIED TO THE CORPS LAND DOMAIN

A. OVERVIEW

The purpose of this research, as stated in Chapter III, is to create an ontology along with a Conceptual Data Model (CDM) that will allow multiple users to work on the same model, using the same or different languages, tools, or presentation frameworks, and have the model be consistent and exchange data between all entities. To ensure both the ontology and the CDM were applicable to all systems, three interim test cases were utilized to verify the completeness during development. The test cases utilized were the Amphibious Combat Vehicle, Joint Air Domain Command and Control (JADC2) concept as well as the Marine Corps Enterprise Network (MCEN) architecture. All of these resulted in updates to the ontology. As a final use case and validation, this chapter will apply the USMC land domain construct, as articulated in Force Design 2030 (Congressional Research Service Insight, 2022), to both the ontology and the CDM.

B. TEN LAYER MODEL AND U.S. MARINE CORPS LAND DOMAIN

The final application to be demonstrated is the US Marine Corps force structure as it applies to the Land Domain. The principal document that was used as the overarching guidance for this domain was Force Design 2030 (FD2030). This document, and its annual updates, describe how the US Marine Corps envisions its transformation over the next decade. This transformation started with a top-level vision, an articulation of USMC missions and a brief description of the anticipated force transformation required to accomplish those missions. One of the elements described in this guidance was that of a Marine Littoral Regiment (MLR). This unit would be more agile and able to respond to the missions described in the document.

The methodology applied in this chapter was to decompose the FD2030 guidance as well as the MLR missions to pull a single thread from the highest overall missions through specific capabilities and systems, down to the lowest level components and assemblies. As can be seen in the descriptions below, and throughout this chapter, the system utilized is the Marine Air Defense Integrated Future Weapons System (MADIS). To help illustrate the process that was used to break out and map the Land Domain, the 10-Layer model (Vaneman, 2022) will be utilized. The 10-Layer model contains a descriptor of the 10 layers of force structure and how they relate to the 4 Layers of capability structure. This illustration will serve as an overview of the decomposition that was performed and utilized to demonstrate the ontology as well as the CDM and is shown in Figure 23.

		USMC Land Domain Example	References
Enterprise Capability Level	10. Strategic Objectives and Policies	Great Power/Peer Level Competitor	38 th Commandants Planning guidance
	9. Enterprise Mission Area	Expeditionary Advanced Base Operations	Force Design 2030
	8. Enterprise Mission Threads	Coordinated Air and Missile Defense Operations	Third Marine Littoral Regiment CONOPS
	7. Enterprise Mission Capabilities	Conduct Short Range Ground Based air Defense	Third Marine Littoral Regiment CONOPS
Mission Wholeness Level	6. SoS Mission Operations	Deny Hostile Air Munitions from targeting Exp Forces	Third Marine Littoral Regiment CONOPS
	5. SoS Mission Structures	Ground Based Air Defense SoS	Third Marine Littoral Regiment CONOPS
Program/ System Level	4. Platforms	Joint Light Tactical Vehicle (JLTV)	NIWC PAO
	3. Systems	Marine Air Defense Integrated Systems (MADIS)	Congressional Report
Allocated Sub-System Level	2. Sub-Systems	MK-2 360 Degree Radar and C2 System	Missile Defense Advocacy Alliance
	1. Assemblies and Components	Radar Receiver	PEO Land Systems

Figure 23. 10-Layer Model with USMC Land Domain.

It is important to note here that the information displayed in this figure is only a single thread of the entire decomposition of the USMC Land Domain. This single thread is being utilized to simplify, for demonstration purposes, both the ontology and the CDM that will follow in this chapter. Additional detail and some further decomposition of the Land Domain can be found in Appendix A. The application of the Land Domain to the 10-layer model, along with the references utilized, can be seen to the right of the model in figure 23. Layer 10 begins with the 38th Commander's guidance as he calls out the need for the US Marines to be a Great Power/Peer level competitor (Berger, 2019). Layer 9 is extracted from FD2030 and as previously stated, only one thread for each of the layers of the model will be depicted for this validation. For example, for the mission areas, layer 9, FD2030 calls out three; Distributed Maritime Operations, Littoral Operations in a Contested Environment, and Expeditionary Advanced Base Operations. For the example presented in this chapter, EABO was the mission area that will be depicted. FD2030 also calls out a reorganization of the USMC, of which one component is the Marine Littoral Regiment or MLR. Much of the remaining resources used are from MLR draft CONOPS (Arnold, 2022) and were used to decompose layers 8-5. As can be seen, this decomposes into the Mission thread of Coordinated Air and Missile Defense (layer 8), Mission Capabilities of Conduct short-range ground-based air defense (layer 7), System of Systems (SoS) Mission Operations of Deny Hostile Unmanned Air Systems (UAS) and Loitering munitions from targeting Expeditionary forces (layer 6), and SoS mission structure of Ground Based Air Defense System (GBAD) (layer 5). The MADIS system is mounted on a platform called the Joint Light Tactical Vehicle (JLTV) which is layer 4 (NIWC Public Affairs Officer, 2022). The GBAD SoS is comprised of multiple systems one of which is the Marine Air Defense Integrated Future Weapons System (MADIS) which is level 3 (Congressional Research

Service InFocus, 2022). There are two units or subsystems of MADIS, and the thread utilized in this verification is the MK2 360-degree radar and communication system (level 2) (Missile Defense Advocacy Alliance, 2020). Finally, level 1 consists of numerous assemblies and components of which a display panel will be utilized in this validation (PEO Land Systems, 2022).

This 10-Layer model and the decomposition of the USMC Land Domain as it applies to it, is presented here to show, from a high level, how this validation and subsequent description that follows in the ontology and Conceptual Data Model was applied. As you will see in the sections that follow, they contain much more detail than was presented here. It is important as well, to remind the reader that this overview of the USMC Land Domain presented in the 10-Layer model, as well as the data and example that will be shown in the ontology and CDM, is only one string of many in the decomposition of the USMC Land Domain. What one will be able to determine at the end of this chapter is that if all the various decompositions of the information depicted in this chapter were performed, the ontology, and the CDM, will apply to all of them, and the entire USMC land domain would be represented.

C. ONTOLOGY MAPPING

The ontology definitions need to be agreed upon prior to identifying the relationships between model entities. The data definitions can be mapped to the system's data dictionary. This exercise intends to populate the ontology and determine if all aspects of an acquisition program would be captured. The USMC is transitioning to becoming a "Mission Focused" acquisition organization. The logical place to start was with the high-level mission.

As previously mentioned, the Marine Air Defense Integrated Future Weapons System (MADIS/FWS) is the system that was selected to validate the ontology and CDM. To become familiar with the system, several acquisition documents were requested from the program office. These documents contained the data needed to populate the ontology and CDM fully. This applies to any acquisition program in all lifecycle stages. After reviewing the documentation, a different approach was used to populate the ontology and CDM. To preserve the ability to share this research outside of the DoD, no actual "Program Data" was used. The details that were included came from publicly available sources, guidance documents, and general knowledge of radar systems as well as command and control equipment.

When this is used in an acquisition environment, the "model" must adhere to the appropriate distribution statements and markings.

1. Artifacts

The first set of artifacts that were selected were high level guidance documents and are shown in Table 6. The strategic documents provided by the DoD lays out "what" needs to be accomplished. The DoN / USMC provides the "how" this will be accomplished.

Table 6. Artifacts.

Entity	Sub Class	Data Type	Number
Artifact	Guidance	2018 National Defense Strategy	STRT.x
		Directives	Dir.x
		2018 Defense Planning Guidance	DPG.x
		Commandant's Planning Guidance	PLAN.x
		Tactics, Techniques, and Procedures (TTP)	TTP.x
		Force Design 2030/CPG/DPG	Doc.x
		Marine Air Defense Integrated Future Weapons System (MADIS / FWS)	POR.x
	Governance		
		Regulations:	REG.x
		Policy	POL.x
	Agreement		
		Memorandum of Understanding (MOU)	MOU.x
		Memorandum of Agreement (MOA)	MOA.x
	Standard		
		Conduct Defensive Operations	JCA.x
		MCT 6.1.1.8.3 Conduct short-range ground-based air defense in support of Expeditionary Bases (GBAD) ** Capable of conducting Short Range GBAD in support of semi-fixed/limited mobility critical assets within the Joint/Coalition Integrated Air Defense System(s).	METL.x
		Required Operational Capabilities/Projected Operational Environment	ROC/POE.x
		The MADIS shall adhere to TEMPEST guidelines.	TS.x

The set of artifacts selected for this exercise includes several high-level strategies and planning guidance. In 2018 both the National Defense Strategy and Defense Planning Guidance were released. These artifacts shifted the focus away from the insurgent activities which had been underway in the Middle East toward the reemergence of long-term strategic competition by revisionist powers. (NDS, 2018). In alignment with those artifacts, the USMC Commandant released his Planning Guidance in 2019. This document serves as the authoritative document for USMC planning. This also serves as the roadmap describing where the Marine Corps is going and why. (Berger, 2019). The USMC will strive to integrate operationally with the Navy. The key warfighting concepts include Distributed Maritime Operations (DMO), Littoral Operations in a Contested Environment (LOCE), and Expeditionary Advanced Base Operations (EABO). The five priority focus areas documented are force design, warfighting, education and training, core values, and command and leadership.

Force Design 2030 was released in 2020 as a direct result of the Commandant's Planning Guidance introduced above. This provides greater detail on the specific capabilities,

missions, and threats that need to be addressed by the Marine Corps. The focus includes the following areas: Littoral Maneuver and Sustainment, Maritime Reconnaissance/Counter Reconnaissance, Long-Range Precision Fires, and Operations in the Information Environment.

The Program of Record selected for this research aligns well with Force Design 2030. The Marine Air Defense Integrated System (MADIS). MADIS will consist of two variants. The MADIS Mk1 includes a turret-launched Stinger missile, multi-functional EW capability, a direct-fire weapon, Electro-Optical Infra-Red (EO/IR) optic, and a shoulder-fired Stinger missile for dismounted operations. The MADIS Mk2 (C-UAS variant) includes a multi-function EW capability, 360-degree radar, direct fire weapon, EO/IR optic, and supporting C2 communications suite. The Mk1 and Mk2 form a complementary pair and are the basic building block of the LAAD Battalions' GBAD capability. (PEO LS, 2022) The Mk1 and Mk2 will be integrated onto the Light Tactical Vehicle (JLTV) Platform.

There are many different regulations and policies which would apply to any significant weapons system acquisition project. Each service has its acquisition policies which implement the DoD Acquisition regulations.

The standards that were selected are directly tied to supporting the EABO mission. The subclass artifact, which documents the tasks required to conduct short-range ground-based air defense (GBAD,) will soon reside in the Marine Corps Task List: Conduct GBAD in support of semi-fixed / limited mobility critical assets within the Joint/Coalition Integrated Air Defense System(s) (IADS) (Arnold, 2022). The final artifact selected for this effort is a standard normally included in systems that support the transfer of military data. "TEMPEST" certification via DoD and NATO ensures that the data is protected from outside forces. There are many more standards that support the mission execution; these are just a few that are tied to the one mission thread that is being traced through the ontology and CDM.

2. Actions

All action entities selected for this research are tied to the guidance documents mentioned earlier and shown in Table 7. The operational activity, "Coordinate Lethal Fires," is just one of the activities needed to support the mission. The operational activity will require trained Marines to carry out the mission. A training curriculum is necessary to ensure the operational training will produce trained Marines who will carry out the mission and maintain the systems involved in the mission.

The same operational activity traces to several different functions. The one selected for this effort is to "provide short-range ground-based air defense." For system to complete this operational activity, it must rely on a different acquisition entity to provide the GPS Location service. The functions will be decomposed into requirements which will be documented later. These requirements will be verified through a test process that includes developmental testing as well as operational testing. The GPS Location will also be verified through a test process to ensure it meets the requirements. Marine Corps Systems Command is responsible for procuring, testing, and fielding all systems to the USMC warfighter. PEO, Land Systems will manage the acquisition effort of the MADIS, and MCSC LCES will manage the acquisition of the JLTV.

Table 7. Actions.

Entity	Sub Class	Data Type	Number
Action	Activity	Coordinate Lethal Fires	OA.x
		Conduct Occupational Training	TRA.1
		Develop Training / Curriculum	TRA.2
		Conduct Maintenance on MADIS System	MNT.X
	Capabilities	Conduct short-range ground-based air defense	CA.x
	Function	Provide short-range ground base defense	F.x
		Destroy Low Flying Aircraft and Helicopters	SF.x
		Provide GPS Service to the MADIS System	SVC.x
		SOA Function	SOA.x
		Test Process (Perform DT / OT)	TP.x
		Test Process for "Service" (Service DT / Service OT)	TP.xx
		Perform tests & Diagnostics	TD.x
	Program	PEO Land Systems shall procure and field the MADIS MCSC Logistics Combat Element Systems (LCES) shall procure and field the JLTV	PM.x

3. Assets

The Enterprise that owns all assets that will support the mission selected for this research is the Marine Littoral Regiment. (MLR). Assets are depicted in Table 8. The System of Systems (Ground Based Air Defense) includes several entities essential to carrying out the mission. The entities selected for this project include the JLTV, which will host the MADIS. The representative decomposition identified for the MADIS is only a single subsystem from one of the two MADIS variants identified earlier. The MADIS MK2 includes radar and a command and control suite. One subsystem (the radar) can be decomposed into several assemblies. The radar receiver and radar transmitter can be decomposed further into sub-assemblies and components. The radar receiver will need to be observed by the operator. The component that fulfills that function would be a display panel consisting of a circuit

board. The radar sub-system will need software to track targets. This will be accomplished via a software tracking algorithm. The system can be broken down further where needed.

Table 8. Assets.

Entity	Sub Class	Data Type	Number
Asset	System	Enterprise (Marine Littoral Regiment)	ES.x
		System of Systems (SoS) – Ground-Based Air Defense (GBAD)	SOS.x
		Family of Systems (FoS) - Joint Light Tactical Vehicle (JLTV)	FOS.x
		Platform (JLTV)	S.x
		System (MADIS)	SN.x
		Sub-System (MK2 Radar System)	SN.x.x
		Assembly (Radar Receiver / Transmitter) (RR/T)	SN.x.x.x
		Sub-Assembly	SN.x.x.x.x
		Component (Display Panel)	SN.x.x.x.x.x
		Hardware (Circuit Board)	SN.x.x.x.x.x.x
		Software (Target Tracking Algorithm)	SW.x
	Service	Service (Global Positioning System Location)	SER.x

4. Resources

The USMC is the organization that provides the resources (Table 9) necessary to carry out the mission. The Marine is the warfighter who performs the tasks associated with accomplishing the mission. The MADIS system will be assigned to a unit within the MLR. The unit will be stationed on a Marine Corps base or installation where the equipment is stored and maintained. The ontology can map to each entity that will receive the MADIS. One unit that will receive the MADIS is the 3rd Littoral Anti-Air Battalion supporting the 3rd Marine Littoral Regiment stationed at the Marine Corps Air Station, Kaneohe Bay Hawaii. The Logistics resources are required to sustain the MADIS throughout the acquisition lifecycle. The test and diagnostic equipment are used to maintain the MADIS during operation. The MADIS VS is used by the Marines during the operational training activity.

Table 9. Resources.

Entity	Sub Class	Data Type	Number
Resource	Organization	USMC	ORG.x
	Performer	US Marine	PER.x
	Installation	Assigned Facilities: XXX Building	FAC.x

		Property	IN.x
		Site: Marine Corps Air Station Kaneohe Bay	IN.x.x
	Logistics	Consumables	LOG.x
		Support Equipment	LSE.x
		Test and Diagnostic Equipment (T&DE)	TDE.x
		MADIS Virtual Simulator (MADIS VS)	TDS.x
	Information	Data	INFO.x

5. Characteristics

The Characteristics are shown in Table 10 and described below. The mission can take place in any part of the world. From the extreme heat of the desert to the frigid temperatures in the artic. The environmental conditions are needed to facilitate design decisions. The MADIS needs the GPS signal always available to complete the mission successfully. There needs to be a mutual agreement between both parties on the Quality of Service before any detailed design can commence.

The skills needed by the operators and maintainers are directly impacted by the operational activity which ultimately supports mission success.

The Measures are key to mission success. The Measures of Effectiveness (MOE) and Key Performance Parameters (KPP) selected for this effort ties directly to tracking several targets to secure the ground base. The Measure of Performance (MOP) is tied to how well the radar tracks targets in the area. The Technical Performance Measures (TPM) provides details on how the data is portrayed to the user. There are many more measures that support this effort, only these were listed for the purpose of this example.

Table 10. Characteristics.

Entity	Sub Class	Data Type	Number
Characteristic	Condition	Environmental State	CE.x
		Extreme Heat (+150°F) to Very Low Operational Temperature (-45°F)	CC.x
		The GPS Signal shall be available continuously and provide updates every second.	CQ.x
	Skill	Manpower, Personnel, Training	CS.x
		KSA	CS.x
Measure	Measures of Effectiveness	The MADIS shall be capable of simultaneous Tracking of X targets	MOE.x
	Key Performance Parameter	The MADIS shall be capable of simultaneous Tracking of X targets	KPP.x
	Measure of Performance	Detect targets of x meter cross-section area	MOP.x

	Technical Performance Measure	The system display shall have a resolution of 1080p.	TPM.x
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6. Location

The location provides details on where the MADIS system will be deployed. The location chosen for this effort is tied to the 3rd LAAB stationed in Hawaii. The MADIS system does not have an orbital location or a virtual presence IP address. Since this ontology can be used for many different systems, those attributes may be needed. Location ontology can be seen in Table 11.

Table 11. Location.

Entity	Sub Class	Data Type	Number
Location			
		Location	L.x
	Orbital	Orbital	LO.x
	Physical	Maine Corps Air Station Kaneohe Bay	LP.x
		GPS Coordinates: 21°26'45"N 157°46'11"W	LP.x.x
	Virtual	IP Address	LV.x

7. Statements

The mission selected for this effort is EABO. As mentioned previously, there are many different aspects of the EABO mission. The EABO mission supports the Joint Capability “Conduct Defensive Operations”. One of the Marine Corps tasks that will support this effort is MCT 6.1.1.8.3 “Conduct Short-Range Ground-Based Air Defense in support of Expeditionary Bases (GBAD)”. Statements are contained in Table 12.

The requirements chosen for this effort provide value and utility to user. The originating requirement of availability specifies the amount of time the system will be functional. The system will provide force protection to fulfill its mission. One of the functional requirements needed to conduct ground-based air defense is to detect low-flying aircraft and helicopters. The system needs to be hosted by a platform, so the system weight should not exceed the payload capacity of the platform. The final requirement selected is tied to the need to integrate seamlessly with the Navy fleet and provide data to the AEGIS weapon system to give commanders additional firepower and protection.

Table 12. Statements.

Entity	Sub Class	Data Type	Number
Statement	Guidance	Scenario Steps	SC.x
		Mission (Expeditionary Advanced Base Operations)	MI.x
	Standard	Joint Capabilities (Conduct Defensive Operations)	JC.x
		MCT 6.1.1.8.3 Conduct Short Range Ground Based Air Defense in support of Expeditionary Bases (GBAD) ** Capable of conducting Short Range GBAD in support of semi-fixed/limited mobility critical assets within the Joint/Coalition Integrated Air Defense System(s) (IADS).	MT.x
Requirement		Requirement	R.x
	Originating	Performance Requirement The MADIS system shall Achieve an Ao of $\geq$ XX %	RP.x
		Operational Requirements The MADIS System shall provide Force Protection	RO.x
	Derived	Functional Requirements The MADIS system shall detect low-flying aircraft and helicopters	RF.x
		System (Physical) Requirements The MADIS system weight shall not exceed the payload capacity of the host platform.	RS.x
		Interface Requirements The MADIS system shall incorporate the equipment necessary to interact with the AEGIS Weapon System (AWS).	RI.x

D. CONCEPTUAL DATA MODEL

Now that the ontology has been applied to the USMC Land Domain, the next part of this verification is to see how the Conceptual Data Model relationships represent the Land Domain, using the applied ontology from section C. Keep in mind that the CDM in reality is one large, interconnected diagram as described in Chapter III. For illustration purposes, it has been broken into numerous sections and presented here.

1. Capabilities, Functions and Requirements

Figure 24 depicts the portion of the CDM that relates to the Capabilities, Functions and Requirements of a system. It is important to know that the entities depicted in the figures only represent one thread of the missions/capabilities/systems in the decomposition that will need to occur to fully decompose the entire USMC Land Domain. As can be seen, the top left box of this figure starts with the Commandants guidance so it starts with the highest level of the USMC Land Domain guidance and the mission thread that is being utilized in this example, EABO, will ultimately lead to just one system (MADIS) needed to perform that mission. To fully capture the EABO mission, the mission would need to be fully decomposed and that would result in numerous threads like the one depicted here. Additionally, to capture the USMC Land Domain, numerous missions, and their

decompositions would need to be performed. The example shown here in this chapter is presented to show that the CDM, as developed, can support the creation of all the missions and systems needed to fully represent the USMC Land Domain.

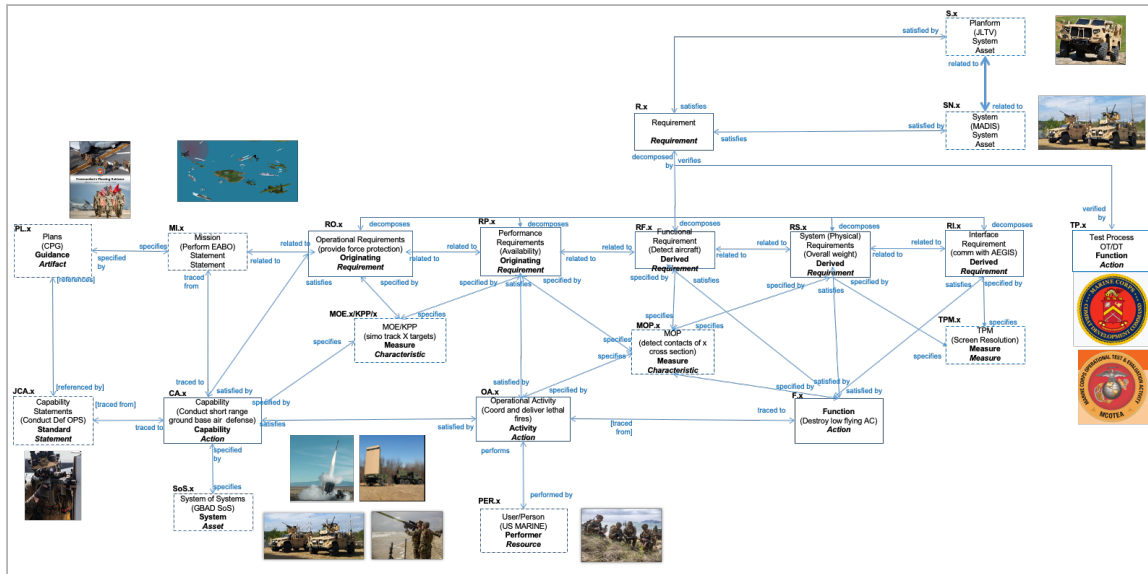


Figure 24. Capabilities, Functions and Requirements CDM

The specific data types that are represented in this CDM have been previously identified in Section C. This diagram begins with the overall plans represented in the CPG. It can be further decomposed into one of its missions, EABO. Additionally, it can be traced to the joint capability of Perform Defensive Operations. Those two areas decompose into the capability of Conduct Short-Range Ground-Based Air Defense. This capability is performed by the GBAD system and will have some associated required MOEs. In this case, simultaneously track x number of contacts was used as a representative. The mission and the associated MOEs decompose into some operational requirements (provide force protection). The capability of Conduct Short-Range Ground-Based Air Defense will also be decomposed into operational activities (Coordinate and Deliver Lethal Fires) which will also be decomposed into Functions such as the one selected in this example, Destroy Low Flying Aircraft. As can be seen in Figure 24, the operational activities will be performed by USMC personnel.

Continuing in the CDM, one can see that the operational activities and the functions will have associated MOPs to ensure they can adequately meet the operational activities and functions. In this case the MOP is Detect aircraft of X cross section. Following along in Figure 24, these functions are decomposed into functional, system, and interface requirements. In this example, these were identified as detect aircraft, overall weight of system, and communicate with the AGEIS system respectively. The MOPs, MOEs and operational activities also specify performance requirements (availability). This entire set of requirements now roll up into a set of requirements that defines the system. In this case the system is MADIS, which resides on a vehicle, the JLTV. Finally, this set of requirements is tested using test process, both DT and OT.

2. Systems and Services

The next portion of the CDM that will be demonstrated is the systems and services viewpoint. As can be seen in Figure 25, the connection between this viewpoint and the others depicted are the dashed boxes and there are many of them, mostly from the Capabilities, Functions, and Requirements viewpoint. The mission, EABO, and Capabilities, conduct short-range ground-based air defense, are directly from that viewpoint. The mission is performed by an Enterprise/Portfolio, in this case the Marine Littoral Regiment (MLR) which is a portion of the organization, the USMC.

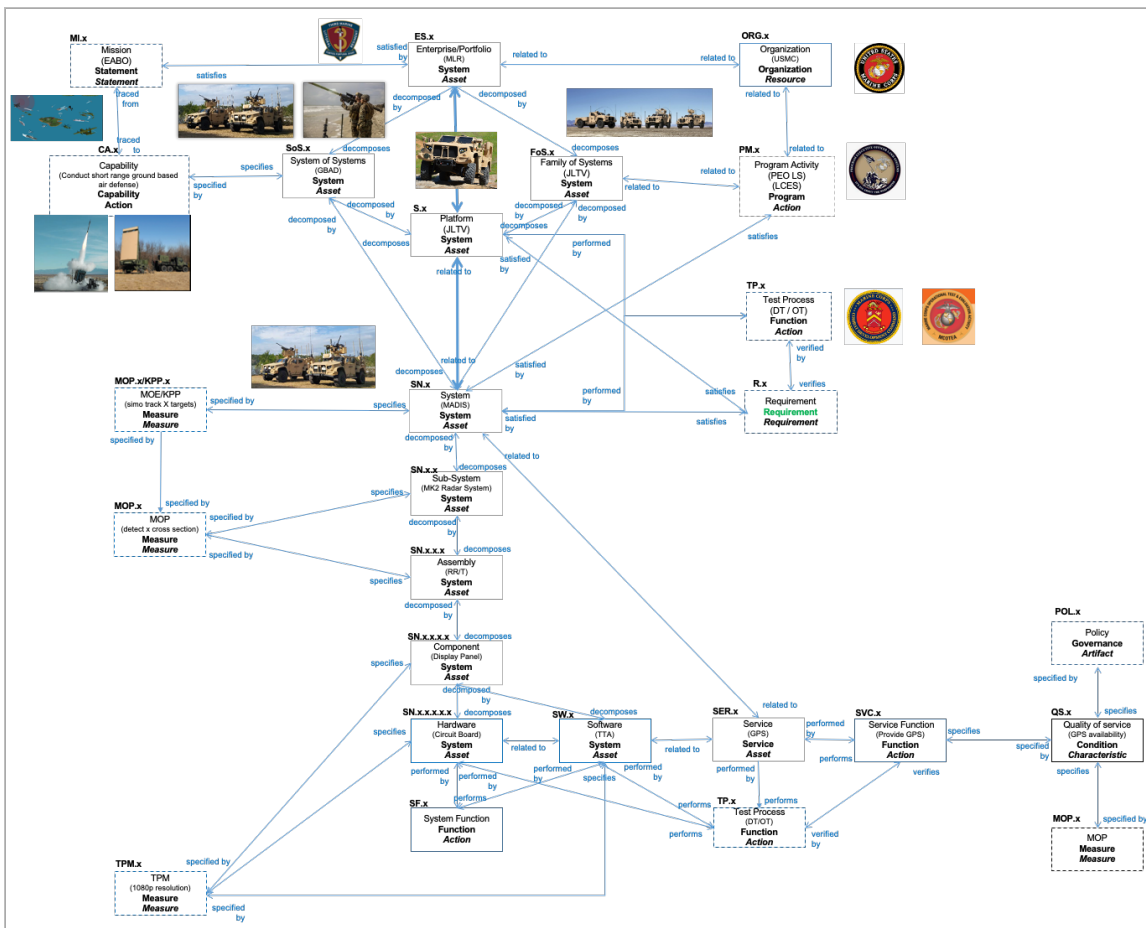


Figure 25. System and Services CDM.

The capability, conduct short-range ground-based air defense, would be performed by the system of system, the Ground Based Air Defense system, which is part of the MLR equipment, and is comprised of the Joint Tactical Land Vehicle (JLTV) and the MADIS system. The JLTV and MADIS are part of a family of systems that are procured by PEO LS and LCES program office.

The system requirements have already been defined as was covered in the previous section and define the MADIS system as do the MOEs/ KPPs (simultaneously track X targets). The MOP (detect targets of X cross-section) were also previously determined and relate to the sub-system (MK2 radar system) and the Assemblies (MM/T) which are both decomposed from the MADIS system. Further decomposing the system leads into components (display panel) which is comprised of both hardware and software, things like circuit boards and ITA

respectively. The components, including the hardware and software, perform the functions required for the system to meet its requirements. These components also have TPMs to ensure that the system can meet its MOPs and MOEs. Continuing the decomposition of the system, it can be seen that service and service functions may be required for the system to operate and that is the case with the MADIS system. This system requires GPS to accurately target aircraft. GPS also has its own policy and MOP to ensure quality. Finally, the entirety of the system and its components will need to be tested utilizing test processes and plans.

3. Program Management

The Program Management view of the CDM can be seen in Figure 26. The Program Offices and PEOs, in this case LCES and PEO LS, perform the program activities required to produce the JLTV Family of Systems, the JLTV Platforms, and the MADIS System defined in the previous viewpoints. These systems support the capabilities and missions required to support the guidance from the USMC. The program builds these systems to the specified performance measures, identifies and mitigates program risks, incurs and controls costs and creates and controls the time to build systems utilizing the programs schedules.

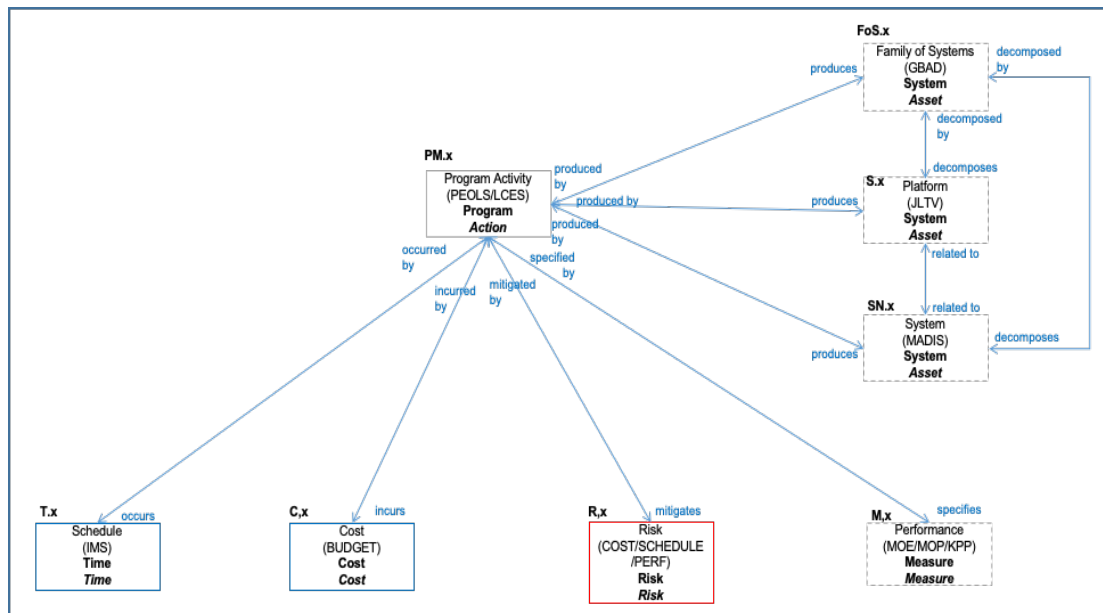


Figure 26. Program Management CDM.

4. Measures

The Measures view of the CDM is shown in Figure 27. As can be seen, this view is capturing data that has been defined in previous views but is important to capture as it is a key element to the system, the program management of the system, as well as the test procedures. Since this data has been previously discussed, it will be presented here for review.

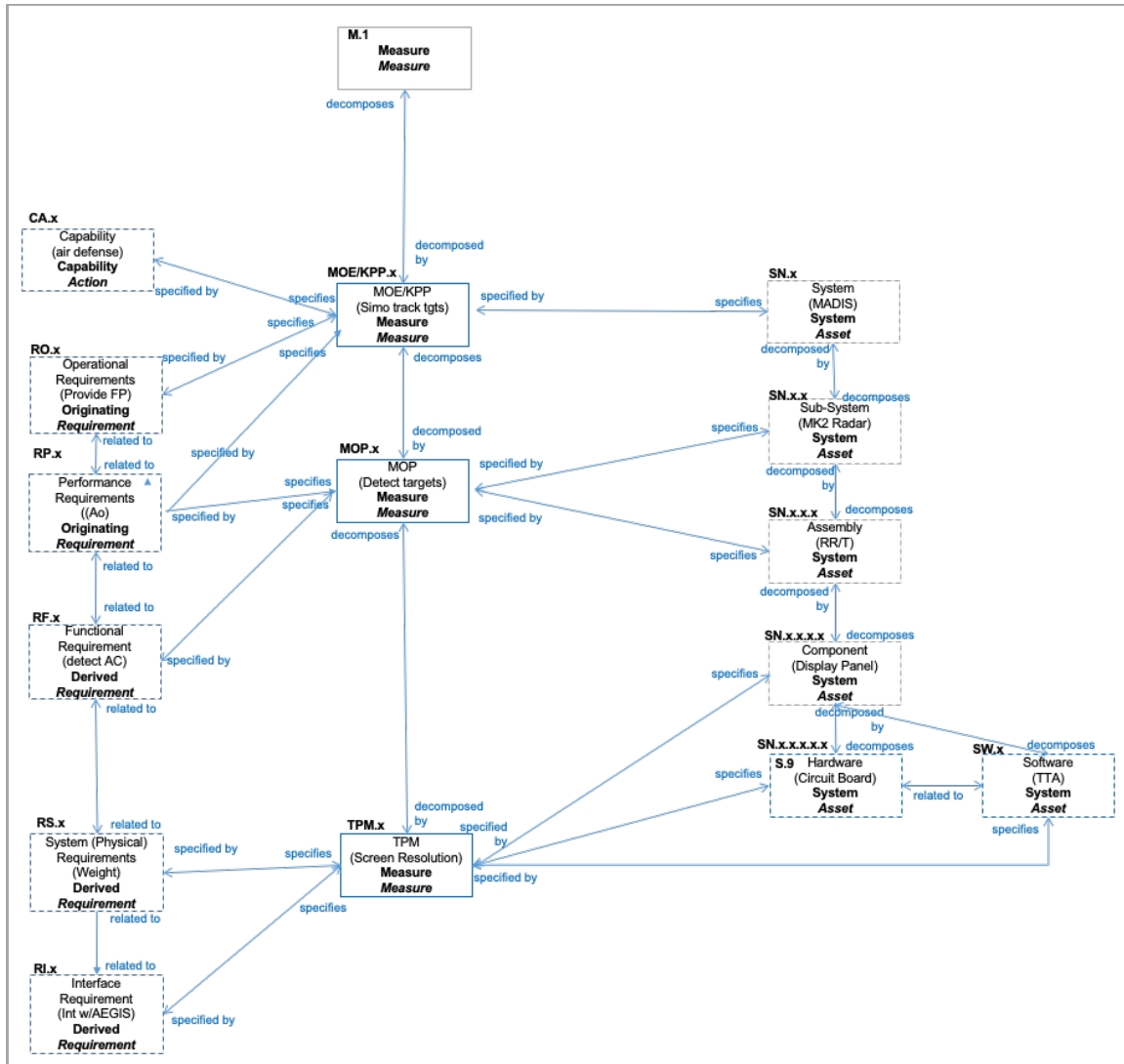


Figure 27. Measures CDM.

5. Maintenance and Logistics

Figure 28 depicts the maintenance and Logistics portion of the CDM. This segment is centered around the system that will require maintenance (MADIS). Prescribed maintenance activities will be performed on the MADIS system which will utilize consumable resources. The MADIS system may also have specific support equipment and test and diagnostics equipment to help support the required maintenance actions.

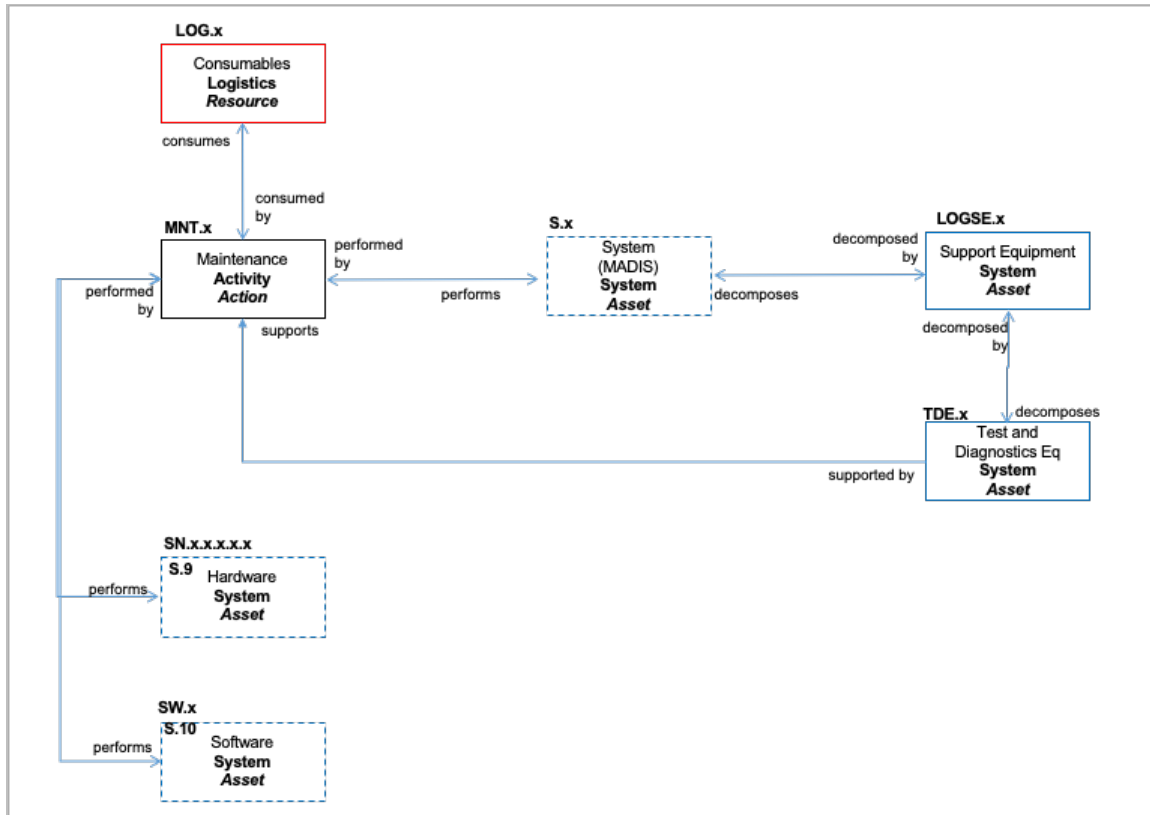


Figure 28. Maintenance and Logistics CDM.

6. Manpower and Personnel

Like the previous portion of the CDM, the Manpower and Personnel portion is centered on the system being utilized and the operational activities required to utilize the system. As can be seen in Figure 29, the User, a US Marine will perform both the operational activities needed to utilize the MADIS system as well as those to keep the system functioning. Those operational activities will require manpower with some specific skills as defined by the KSA's. To develop those KSAs and remain proficient at them, training will be developed and taught, and it may require the use of training devices or simulators. It is important to remember here that this training is for both the operators and the maintainers of the MADIS system.

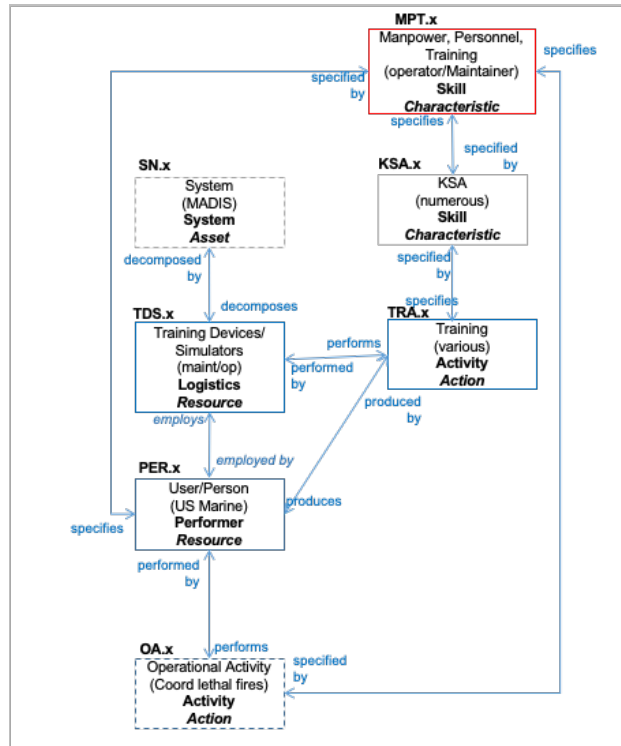


Figure 29. Manpower and Personnel CDM.

7. Location

Lastly, the Location portion of the CDM can be viewed in Figure 30. One can see again that the MADIS system is represented here and it will have a geolocation. That geolocation may be at a specific facility such as MCAS Kaneohe Bay, or it may be at a deployed, or training location. These locations will drive the environmental conditions that the system will need to operate in. This portion of the CDM contains some aspects that were not covered in this use case as the MADIS system does not have an orbital location or a virtual location. Some elements of other systems may contain these elements, which is why they are included in this view.

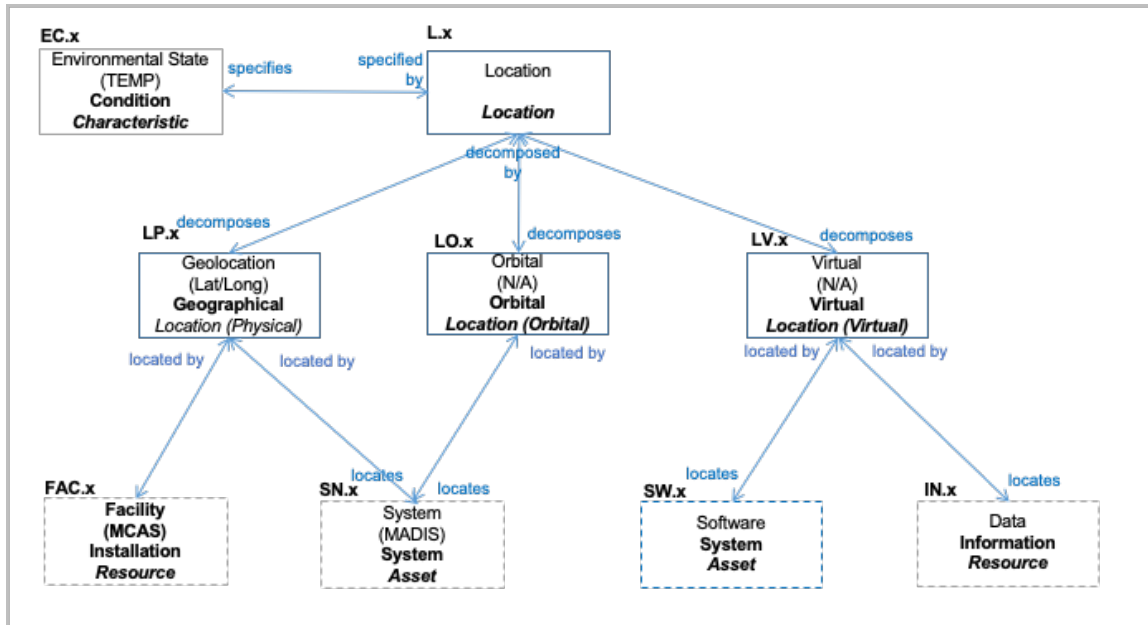


Figure 30. Location CDM.

Utilizing the ontology presented in section C, and the seven different views of the CDM presented here, one can see how the system entities relate up to the highest-level missions defined by strategic guidance as well as how they decomposed and are defined by the lowest levels of components. Utilizing a defined ontology and CDM allows separate organizations to create their respective portions of this model and each layer of the model should relate to the next.

E. SUMMARY

As mentioned in Chapter 3, the combination of the specific ontology and the CDM can serve as a “Rosetta Stone” to exchange data between model entities where that data is developed in various modeling languages, MBSE tools, or presentation frameworks. Section B described a 10-layer model of the decomposition of the example presented here of USMC Land Domain and Force Design 2030. Figure 23 pulls a single thread throughout this model using a specific mission area, mission thread, and mission capability. It goes on to select a single SoS mission, followed by a specific SoS, down to a platform, system, as well as subsystems and components. In the USMC this series of model creation and ownership resides at various levels starting with Combat Development and Integration (CDNI), Marine Corps System Command (MCSC), Program Offices, contractors as well as the multitude of subcontractors and government components. Utilizing a defined ontology and CDM will ensure that as this model is created, at the various levels, utilizing various languages and MBSE tools, the final product will have a consistent schema and fully represent the system. Even though there would need to be several more threads of the USMC Land Domain modelled to get the full set of missions, capabilities and systems, the viability of this approach is demonstrated in the USMC Land Domain use case presented in this chapter.

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V. SUMMARY, CONCLUSIONS, AND OPPORTUNITIES FOR FURTHER RESEARCH

A. SUMMARY AND CONCLUSIONS

This research considered four major areas for designing and analyzing an ontology that can be applied across the land domain.

Focus area 1 considered the importance of identifying a generic ontology that comprehensively represents the system across the lifecycle. As such, a parsimonious ontology that serves as the foundation of the land domain was described.

A conservation of entities principle was employed when identifying the entities within the ontology. Describing the system with fewer entities allows for a “common denominator of entities” to be used to describe the system. The entities within the data dictionary of individual programs and systems can be mapped to the ontology, thereby facilitating data exchanges to define the virtual model of the system. Chapter 2 discusses the research approach of using a parsimonious ontology. Chapter III expands on this basic approach.

Focus area 2 analyzed the relationships between entities defined within the ontology. System structure identified the elements of the system that connect and interact with each other to achieve the system’s purpose, and depicts how behavior will emerge within the system. A generic CDM was defined in Chapter III, and serves as the basis of a common terminology and structure. Chapter IV demonstrated the utility of having authoritative data within a defined structure, and validate the generic ontology and CDM using four example mission threads.

The Amphibious Combat Vehicle (ACV) mission thread was first, and was designed to demonstrate the concept as the ontology and CDM evolved. The second was the Joint All-Domain Command and Control (JADC2) mission thread which demonstrated the applicability of the ontology and CDM to dataset beyond those associated with the land domain. The Marine Corps Enterprise Network (MCEN) mission thread was designed to demonstrate the applicability of the ontology and CDM to a large data set. More than 17,000 data points from the most complex MCEN node were mapped to the ontology and CDM. This represents a one hundred percent mapping.

The fourth mission thread was a comprehensive analysis of Force Design 2030. Unlike the ACV, JADC2, and MCEN datasets, where the available data was provided, this research was able to define a data collection plan. While the MCEN mission thread demonstrated the ontology and CDM’s ability to map to a large quantity of data, the Force Design 2030 was designed to represent a large quantity of data mapped to the ontology and CDM.

Focus area 3 considered the ontology as a foundation for an authoritative source of truth. The CDM identified entities where the single source of truth resides, established data boundaries, and mapped interactions to allow for data exchange between models. This focus area highlights issues that need to be addressed by model governance policies. As discussed, a goal of Digital Engineering is to use the modeling language and MBSE tool that best models the perspective of the system being explored. It is envisioned that data from these various sources will be combined through a data exchange. While it is beyond the scope of this research to define data exchange standards, the CDM can be used to identify where those

data exchange standards need to be developed between entities. While data exchange standards are not defined, the “Rosetta Stone” allows for translations between modeling languages and presentation frameworks. This is significant because heretofore the focus has been on specifying a single tool to use for most applications. The strength of the ontology and CDM is that it is modeling language, MBSE tool, and presentation framework agnostic.

A universal numbering schema was developed in Chapter 3, to assist in managing the authoritative source of truth. This was a nascent attempt, but while this numbering schema does not address all questions that arise during model governance, it is a schema that can be further developed in future research.

Focus area 4 considered a design framework for a roadmap that will help MCSC transition from document-based systems engineering to a true MBSE-based Land Domain. When this research was formulated, focus area 4 made sense. However, as the research progressed it became apparent that this focus area was orthogonal to the core parts of the research. However, some effort was applied in developing a six-step process for transitioning to a MBSE environment, and is provided in Appendix A.

B. OPPORTUNITIES FOR FURTHER RESEARCH

This research has made great advances in defining a universal ontology and CDM. The following opportunities for further research were identified.

First, while this research applied the generic ontology and CDM to the USMC Land Domain, additional effort is needed to demonstrate its applicability to other domains. Validating the ontology and CDM with the Naval Operational Architecture, as well as other service component models such as the Army, is recommended. The success of this proposed research will enable the standardization of an ontology and CDM.

Second, for the ontology and CDM to be most effective, it needs to be implemented as a formal data exchange standard. An exploration of approaches that represent the complex knowledge about entities, the relationships between entities, and additional information needed to exchange data will provide a more holistic and comprehensive view to share data across various modeling languages, MBSE tools, and presentation frameworks.

Third, additional “model curation” research is needed. Currently there are few efforts exploring how system models will be governed in the future. Implementation of a universal ontology and CDM will require a more defined processes for “model curation.”

C. ENVISIONED BENEFITS AND IMPACTS

The envisioned benefits of the ontology and CDM are:

- Identifies a minimal set of entity classes and relationships.
- Elements within the data dictionary can be mapped to the ontology.
- Relations and attributes defined that entity class level, are applied to lower level (specific) data entity level.
- Identifies data boundaries.

- Identifies areas for data exchange standard need to be development.
- Identifies where the authoritative source of truth for each entity resides.
- Defines a universal numbering schema.
- Show how changes to data will “ripple” through the MBSE/DE environment.

This research has attracted a lot of attention. The MCEN Architecture Team has adopted the ontology and CDM as their architecture is transitions to a SysML-based tool. Various Army components and Navy commands have also followed this research very closely and are looking at how this ontology and CDM can be applied to their modeling efforts.

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APPENDIX A



Force Design 2030

- 2019 – 38th Commandant of the Marine Corps published his Commandant's Planning Guidance
 - Force Design is his #1 Priority
- 2020 – Force Design 2030 was published. The document provides greater details regarding the direction of the Marine Corps
 - The USMC needs to adapt to new warfighting concepts including:
 - Distributed Maritime Operations (DMO)
 - Littoral Operations in a Contested Environment (LOCE)
 - Expeditionary Advanced Base Operations (EABO)
 - Joint Warfighting Concept (JWC)
 - Stand-In Forces
 - Recon/Counter-Recon



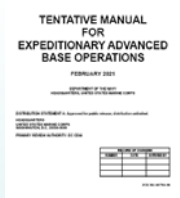
Commandant's Planning Guidance
2019 Commandant of the Marine Corps



Force Design 2030
Annual Update
May 2022



Littoral Operations in a Contested Environment
2017



TENTATIVE MANUAL
FOR
EXPEDITIONARY ADVANCED
BASE OPERATIONS
FEBRUARY 2021

FD2030 - Marine Littoral Regiment



- One of the outcomes of Force Design 2030 was the determination to create one Marine Littoral Regiment (MLR).
 - The MLR consists of:
 - Littoral Combat Team (LCT)
 - Combat Logistics Battalion (CLB)
 - Littoral Anti-Air Battalion (LAAB)
 - One of the Missions of the LAAB is to conduct “Ground-Based Air Defense”
 - The MADIS is utilized to ensure mission success
 - » The MADIS is integrated into the JLTV Platform

10-Layer Model

Strategic Objectives & Policies (Layer 10)	Enterprise Mission Areas (Layer 9)	Enterprise Mission Threads (Layer 8)	Enterprise Mission Capabilities (Layer 7)	SoS Mission Operations (Layer 6)
Strategic Objective: Provide U.S. Indo-Pacific Command (U.S. INDOPACOM) and the Commander, 7th Fleet with a fight-tonight, stand-in force capability to persist inside an adversary's weapon systems threat range, create a mutually contested space, and facilitate the larger naval campaign.	Mission Areas: • Distributed Maritime Operations (DMO) • Littoral Operations in a Contested Environment • Expeditionary Advanced Base Operations (EABO)	Mission Threads for EABO: • Coordinate Air and Missile Defense Actions • Support Maritime Domain Awareness • Support Operations in the Information Environment • Conduct Expeditionary Strike • Attack Enemy Maritime Targets	Support Coordinated Air & Missile Defense: • Conducts fires • Conduct reconnaissance • Conduct counter-reconnaissance • Conduct anti-air warfare • Conduct air control • Conduct airspace surveillance • Conduct short range ground based air defense • Provide forward arming and refueling points	SoS Mission Operations for conducting Short-Range Ground Based Air Defense: • Enable joint kill chains through multi-domain CSISR • Secure key maritime terrain • Provide ground based naval strike missiles • Support AAW and ASUW kill webs • Deny hostile UAS and loitering munitions from targeting Expeditionary Forces

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APPENDIX B



Digital Engineering Transition Planning Considerations

**How Do You Get to a Digital Engineering
Environment?**

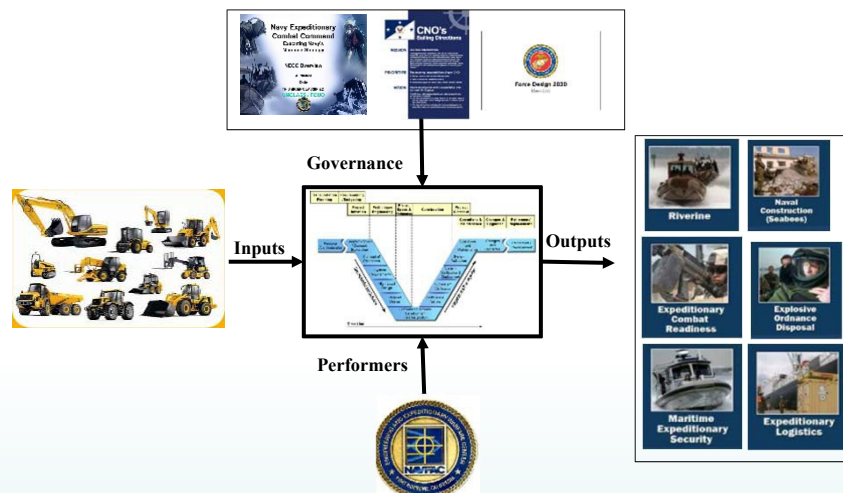
Understanding the Current Environment

Understanding the organization's mission and vision is important at the outset of a transition plan.

1. Understanding the Current Environment



Understanding the Current Environment



Many organizations jump right into MBSE/Digital Engineering tools without a fundamental understanding of "why"... what are you trying to get out of MBSE? What problem are you trying to solve?

Creating Your MBSE Vision

Understanding the mission and vision is important at the outset of a transition plan.

1. Understanding the Current Environment

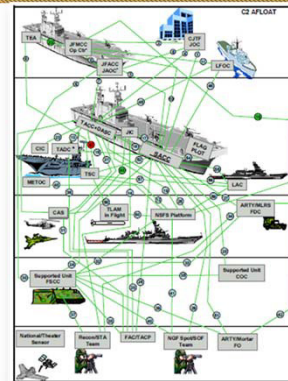
2. Understanding the MBSE Vision for the Organization



5

Envisioned Digital Engineering Environment Considerations

- 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.
- Formalize the Development, Integration, and Use of Models to form Enterprise and Program Decision Making
 - Formalize the planning for models to support engineering activities and decision making across the lifecycle.
 - Use models to support engineering activities and decision making across the lifecycle.



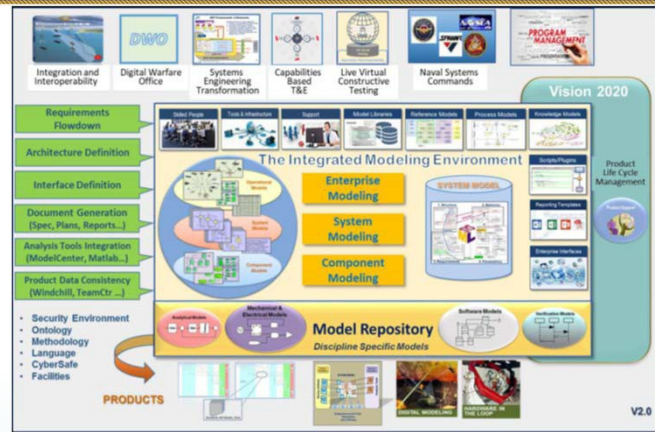
Goal 1: Formalize the Development, Integration, and Use of Models to form Enterprise and Program Decision Making

- 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.

Source: DoD Digital Engineering Strategy (2018)

6

Naval Integrated Modeling Environment Vision



Goal 2: Provide an Enduring, Authoritative Source of Truth.

- 2.1 Define the authoritative source of truth.
- 2.2 Govern the authoritative source of truth.
- 2.3 Use the authoritative source of truth across the lifecycle.

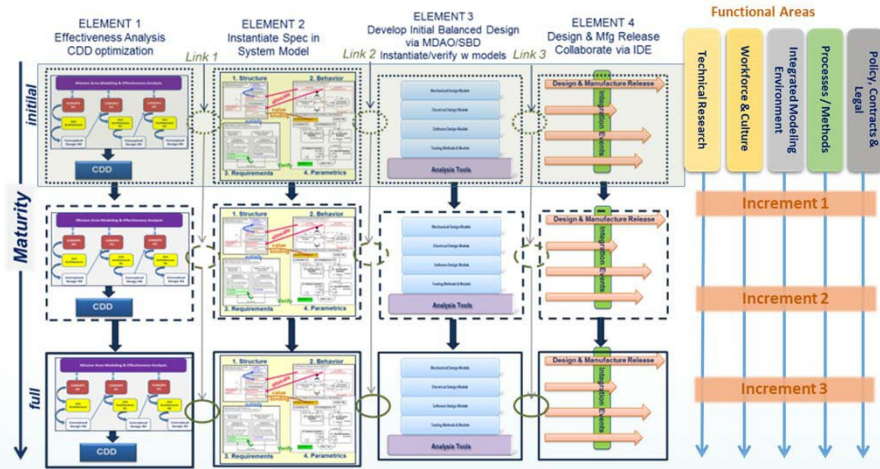
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Create Plan & Communicate The Vision



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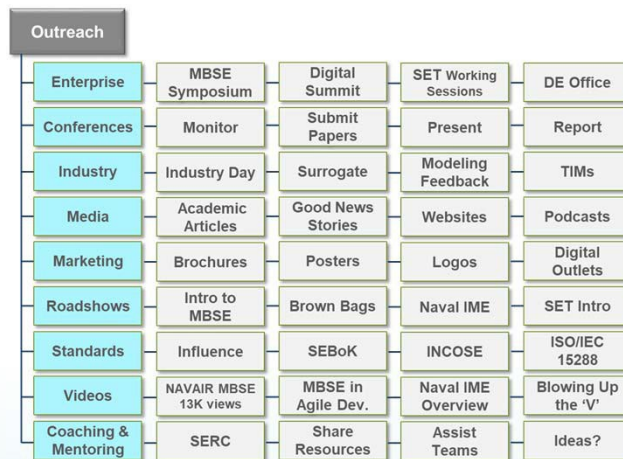
Creating an Implementation Plan



MBSE can be a great capability if deliberately implemented, and tailored for the mission, context, maturity of your organization.

9

Communication Approach



The systems engineering culture (both government and contractor) must change to focus on the virtual model of the system, and away from technical documentation.

10

Communicating the Vision



NAVAIR AIR-00 Digital Transformation - Speed to the Fleet Video (5 minutes): <https://youtu.be/ppTq1n2cTVY>
 SET - Systems Engineering with System Models: An Introduction to MBSE(1 hour): <https://youtu.be/171blNCgpCo>



Systems Engineering Transformation (SET) at NAVAIR website: <https://isee.nswc.navy.mil/navair/i.cfm/site/set#p=home>
 The *What, Why and How of SET* – Visit this site to understand what SET means and what it will take to implement it on your project.
 Naval IME Knowledge Base: <https://confluence.di2e.net/display/MBSEIME>
 Guidance for accessing the *tools, infrastructure, and support* for Naval Model Based Systems Engineering (MBSE) activities.



APAN.org – Create account, then request access to the sites below based the description and membership criteria listed.
NAVAIR Systems Engineering Transformation: <https://community.apan.org/wg/navair-set/>
 Sharing of *SET work in progress* with core SET team and collaboration partners across the DoD. Membership Criteria: U.S. Government and U.S. Government Support Contractors
SET Surrogate Pilot: <https://community.apan.org/wg/navair-set/set-surrogate-pilot/>
 Sharing information regarding the SET Surrogate Pilot – demonstrating the *'Art of the Possible' in MBSE*. Membership Criteria: U.S. Government, U.S. Government Support Contractors, and Industry Partners
NAVAIR MBSE Community of Practice: <https://community.apan.org/wg/navair-set/navair-mbse-community-of-practice/>
 The go-to place for *technical discussion and information sharing* for Model Based Systems Engineering. Membership Criteria: U.S. Government, U.S. Government Support Contractors, and Related Industry
 *public can view; must be member to contribute

Communicate, Communicate, COMMUNICATE!!!

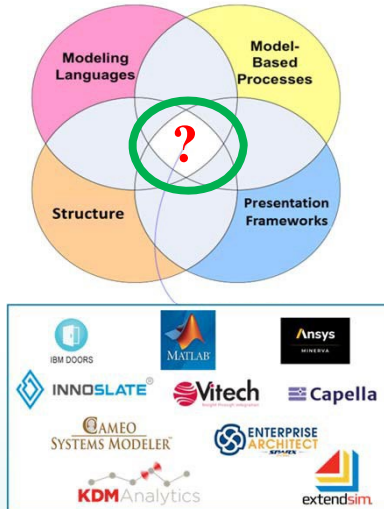
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Selecting the Proper MBSE Tools



12

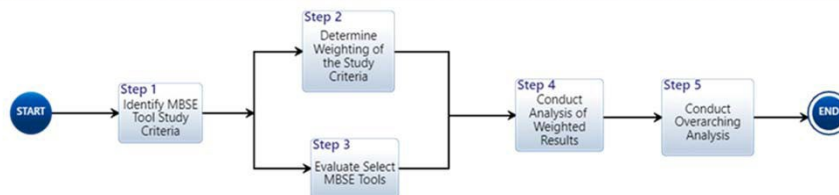
MBSE Tool Evaluation Process Questions



- What are the strengths and weaknesses of each tool WRT the weighted criteria associated with:
 - Modeling Languages
 - Structure
 - Model-Based Processes
 - Presentation Frameworks
 - Model Management

13

Digital Tool Evaluation Process Overview

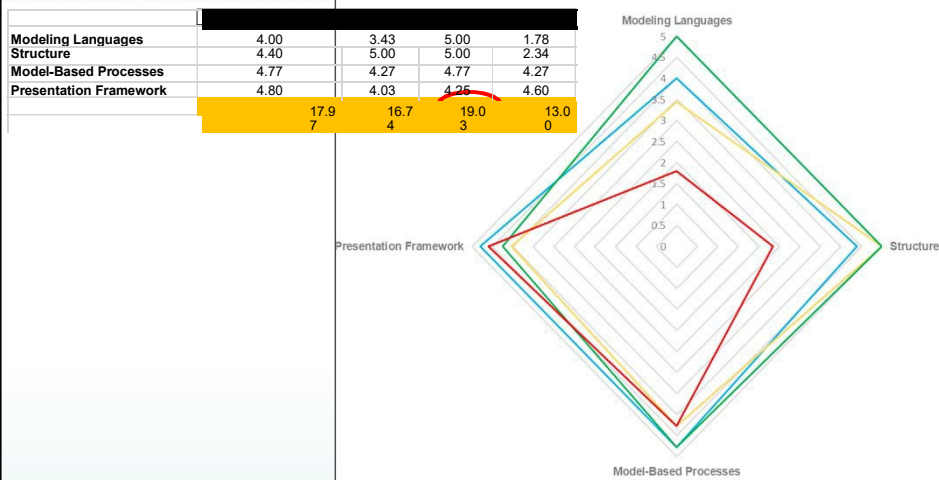


- Five step tool evaluation provides a fair and repeatable process that highlights the relative strengths and weaknesses of each tool.
- Allows each organization to identify the criteria that are considered important to their engineering processes.
- Weighted criteria provides insights into which criteria are the most important to the organization.

Goal 3: Incorporate Technology Innovation to Improve the Engineering Practice.

- 3.1 Establish an end-to-end digital engineering enterprise.
- 3.2 Use technological innovations to improve the digital engineering practice.

Digital Overall Tool Analysis



This tool evaluation approach highlights the relative strengths and weaknesses of each tool according to your organizations criteria and priorities.

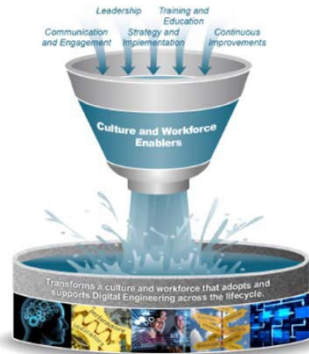
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Transitioning the Workforce



16

Cultural Changes



- Strategic and fiscal patience is required from MBSE/Digital Engineering implementation.
 - Initial resource investment can be high in terms of costs and time.
- Implementation includes not only the civilian and military workforce, but the contractor partners.

Goal 5: 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.*

Recommendations

- Assemble a cadre of change agents to tackle the MBSE/Digital Engineering implementation.
- Take the time to go through the transition planning process before adopting MBSE/Digital Engineering tools.
- Start small to prove and refine the concept.
- Partner with other organizations that are going through the same transition.
- Communicate Communicate Communicate

To succeed at implementing MBSE/Digital Engineering the DoD needs a deliberate effort to transform the workforce to promote a cultural change. - DoD Digital Engineering Strategy (2018)

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