



NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**OPERATIONALIZING DIGITAL THREAD THROUGH
MODEL-BASED SYSTEMS ENGINEERING METHODS
FOR HEAVY LIFT AND SALVAGE OPERATIONS**

by

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September 2021

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**OPERATIONALIZING DIGITAL THREAD THROUGH MODEL-BASED
SYSTEMS ENGINEERING METHODS FOR HEAVY LIFT AND SALVAGE
OPERATIONS**

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ABSTRACT

Challenges exist in determining out how to effectively integrate legacy analysis tools with Model-Based Systems Engineering (MBSE) tools to accomplish a digital transformation. In this study, we analyze the legacy Program of Ship Salvage Engineering (POSSE), an analysis-based tool that helps salvage engineers determine how critical a damaged ship situation is. Salvage engineers utilize POSSE to provide real-time assessments of complex salvage situations and to communicate with other commercial salvage software packages. The research focus of this study was to ask, “How can NAVSEA 00C accomplish a digital engineering transformation utilizing the legacy POSSE program for their heavy lift and salvage operations using MBSE methods?” This research used system modeling tools to model salvage operations by creating a digital thread from the systems model to the POSSE analysis tool. The main part of the approach demonstrated a working product integrating POSSE and Cameo Enterprise Architecture (Cameo). The study investigated the possibilities of operationalizing the digital twin concept in conjunction with the digital thread. The results of this study can help assess the advantages the Navy can realize by operationalizing digital threads and digital twins through MBSE.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANU	Authorized for Navy Use
Cameo	Cameo Enterprise Architecture
CDRL	Contract Data Requirements List
CNO	Chief of Naval Operations
CONUS	Continental United States
COTS	Commercial Off the Shelf
CURV	Cable Controlled Underwater Vehicle
DOD	Department of Defense
DON	Department of the Navy
DT	Digital Transformation
ESSM	Emergency Ship Salvage Material
FEMA	Federal Emergency Management Agency
ft	Feet
GO-GO	Government-Owned and Government-Operated
IME	Integrated Modeling Environment
ISEA	In-Service Engineering Agent
MBSE	Model-Based Systems Engineering
MDSU	Mobile Diving and Salvage Unit
MS	Microsoft
MSC	Military Sealift Command
MSFSC	Military Sealift Fleet Support Command
NAVSEA	Naval Sea Systems Command
NAVSEA 00C	Office of the Director of Ocean Engineering Supervisory of Salvage and Diving
NDI	Non-Developmental Item
NOSC	Navy On-Site Coordinators
NRT	National Response Team
OCONUS	Outside Continental United States
ODASDSE	Office of the Deputy Assistance Secretary of Defense for Systems Engineering

OHS	Oil and Hazardous Substance
PEO	Program Executive Office
PMS	Planned Maintenance Schedule
POSSE	Program of Ship Salvage Engineering
ROV	Remotely Operated Vehicle
SCA	System Certification Authority
SEALOGS	Sealift Logistics Commanders
SM	SurgeMain Units
SME	Subject Matter Expert
SMP	Ships Motion Program
SUPSALV	Supervisor of Salvage and Diving
SWISS	Shallow Water Intermediate Search System
SysML	Systems Modeling Language
U.S.	United States
ULSTR	Ultimate Strength Program
UML	Unified Modeling Language
USFF	United States Fleet Forces
USN	United States Navy
USNR	United States Navy Reserves
USTRANSCOM	U.S. Transportation Command
VADM	Vice Admiral

EXECUTIVE SUMMARY

This study was conducted in response to a United States Navy (USN) need to look for ways to implement digital engineering to expand the naval superiority by innovating, delivering new capabilities, and creating new and improved ways to conduct business operations. In many ways, the Naval Sea Systems Command (NAVSEA) enterprise is testing new technologies using outside-the-box thinking methods to expand the advantage. The new *Warfare Centers Strategic Plan for 2021–2025* (Naval Sea Systems Command 2021c) has brought to fruition a shift in the NAVSEA’s priorities to transform its digital capabilities.

Within the NAVSEA enterprise, the Office of the Director of Ocean Engineering Supervisor of Salvage and Diving (SUPSALV), the 00C Salvage division (NAVSEA 00C) oversees salvage operations that consist of salvage, towing, deep ocean search and recovery operations, and oil pollution abatement (Naval Sea Systems Command 2021b). One of the major tools used for computational analysis for ship salvage engineering when a ship is damaged is a legacy program called the Program of Ship Salvage Engineering (POSSE). This program is an analysis-based tool that helps the salvage engineer determine how critical the damaged ship situation is. Salvage engineers utilize POSSE to provide real-time assessment of complex salvage situations and to communicate with other commercial salvage software packages.

There currently exists a need to determine out how to effectively integrate existing legacy analysis tools with Model-Based Systems Engineering (MBSE) practices to accomplish a digital transformation (DT). This thesis identifies a technological opportunity to fill in the gap currently seen in digital transformation and MBSE within the USN, specifically in Heavy Lift and Salvage operations. The purpose of the thesis will be to find ways to incorporate the data provided from POSSE and utilize a digital thread to incorporate that same data into a MBSE systems modeling tool, specifically, Cameo.

Key outcomes described in this thesis are as follows:

- Demonstrate an integrated process that supports digital engineering transformation utilizing the legacy POSSE program.
- Integrate the Cameo Enterprise Architecture tool and the POSSE analysis tool to create a consistent digital thread from the systems model to the analysis results.
- Illustrate a working digital thread process scenario for a simulated diving and salvage operation.

The development of this model-based methodology requires knowledge about the system tools that will be used to create a digital thread. First, there needs to be a Cameo ship system modeling structure created that can set a context that a POSSE ship analysis will follow. The context is set through the implementation of a use case scenario for an oil tanker. The use case scenario describes a real-world situation that SUPSALV would have to act on and the data that was identified in POSSE was the most important for the analysis that was transferred. To have the full scope of the ship model structure, a block definition diagram, a use case diagram, and activity diagrams were created. These diagrams represent the overall oil tanker within its digital environment to allow the information to exist in the systems model to implement part of a digital thread.

Second, a ship was developed in POSSE to identify all key components of the ship structure. The oil tanker is defined by the ship characteristics, requirements, hull structure, various spaces, weight, draft, and other key parameters to create a realistic oil tanker to use in the scenario to help with the digital thread of information.

The result was that a digital thread was successfully demonstrated between POSSE and Cameo. This was predominantly done via data transfer from Cameo that triggered the salvage engineer to obtain the data for POSSE. Once the data was input to POSSE, the salvage engineer returned analysis data to Cameo via Excel spreadsheets to the MBSE engineer. This thesis outlined a path toward the integration between Cameo and POSSE, which was the goal established.

The thesis study also found that there is a lot of room for additional in-depth analysis of digital modeling tool applications that can address the needs of the salvage engineers in SUPSALV. Due to limitations with time constraints of the process, the digital thread was established, but was not able to be expanded in the details of the ship capabilities in a dynamic analysis that is typical for a damaged oil tanker situation. It is recommended that more complex simulations be created utilizing SUPSALV standard operating procedures that will enable effective model creation within US Navy standards and guidelines based on historical data of operations.

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I. INTRODUCTION

A. PROJECT OVERVIEW

This study was conducted in response to a United States Navy (USN) need to look for ways to implement digital engineering to expand naval superiority by innovating, delivering new capabilities, and creating new and improved ways to conduct business operations. In many ways, the Naval Sea Systems Command (NAVSEA) enterprise is testing new technologies using thinking outside the box to expand the advantage. The new *NAVSEA Campaign Plan to Expand the Advantage 3.0* has brought to fruition this shift in the NAVSEA's priorities to transform to digital capabilities.

The transformation of our digital capabilities will affect every aspect of our enterprise. We will modernize our virtual infrastructure and improve our interconnectedness to enhance our One Team experience. We will expand our digital capabilities and external partnerships around evolving and future technologies to develop innovative and relevant solutions. New digital tools and technologies will also give us the opportunity to reconceptualize our business models (Naval Sea Systems Command 2021a, 4).

Within the NAVSEA enterprise, the Office of the Director of Ocean Engineering Supervisor of Salvage and Diving (SUPSALV), the 00C Salvage division (NAVSEA 00C) oversees salvage operations that consist of salvage, towing, deep ocean search and recovery operations, and oil pollution abatement (Naval Sea Systems Command 2021e). The use of computational analysis tools is a critical part of diving and salvage operations. One of the major tools used for ship salvage engineering when a ship is damaged is a legacy program called Program of Ship Salvage Engineering (POSSE). This program is an analysis-based tool that helps the salvage engineer determine how critical the damaged ship situation is. Salvage engineers utilize POSSE to provide real-time assessment of complex salvage situations and to communicate with other commercial salvage software packages (Naval Sea Systems Command 2021j).

This research project integrates POSSE with model-based systems engineering (MBSE) tools to create a digital engineering implementation to assist SUPSALV to transform their specific processes into a NAVSEA digital engineering environment.

B. BACKGROUND

As outlined in the *NAVSEA Campaign to Expand the Advantage version 3.0*, in the commanders' message, the Commander of NAVSEA, Vice Admiral (VADM) William J. Galinis states: "As a nation and as a Navy, we are being challenged in ways we have not been in many years. The renewal of the Great Power Competition with China and Russia has fundamentally changed the conversation with respect to the strategic defense of our country and allies" (Naval Sea Systems Command 2021a, 2). With his intent the NAVSEA Strategic Framework 3.0 outlined what the Navy as a whole, needs to do to expand maritime advantage and deliver on the Chief of Naval Operations (CNO) properties. One of the three priorities is to transform digital capabilities.

It is understood that to transform digital capabilities within the USN, it will require an enterprise mindset across every facet of how the Navy conducts business. To complete an effective digital transformation, the Navy will need to develop and integrate its current and future capabilities to "a wide-range of capabilities to improve performance, unlock new opportunities, drive innovation, deliver new efficiencies, and inform analytic-based decision-making" (Naval Sea Systems Command 2021a, 10). The key aspect to focus on to achieve the desired results is to build on the digital engineering capabilities that will integrate the tools, products, and the all-around infrastructure required to improve all engineering practices in the areas of design, maintenance, and operations.

As described in *A Design of Maintaining Maritime Superiority version 2.0* (United States Chief of Naval Operations 2018), the United States (U.S.) is constantly battling to maintain maritime superiority. With the passing of time countries like China and Russia have been adding elements to their national defense systems that are reducing the U.S. Naval superiority gap. The U.S. needs to adapt to this new reality and needs to correct the gaps that are currently being presented. It is crucial that the USN modernize its combat systems and Fleet to a digital centric environment to maintain competitiveness in an

uncertain future where competitiveness Naval superiority is at stake. “Digital technologies have the potential to be force multipliers, putting data at the center of our decision making and transforming how we innovate, deliver new capabilities, and conduct business operations” (Naval Sea Systems Command 2021c, 4).

C. PROJECT OBJECTIVES

The thesis objective is to demonstrate how to effectively integrate existing legacy analysis tools with MBSE tools to accomplish a digital transformation. This thesis will identify a technological opportunity to fill in a gap currently seen in digital transformation and MBSE within the USN, specifically in the Heavy Lift and Salvage operations. Key outcomes described in this thesis are:

1. Demonstrate an integrated process that supports digital engineering transformation utilizing the legacy POSSE program.
2. Integrate the Cameo Enterprise Architecture tool and the POSSE analysis tool to create a consistent digital thread from the systems model to the analysis results.
3. Illustrate a working digital thread process scenario for a simulated diving and salvage operation.

D. STAKEHOLDERS

There are many stakeholders that can benefit from this thesis project. These include but are not limited to the USN, shipyards, vessels in distress, and the Department of Defense (DOD). The Fleet is our most important asset, and when the digital transformation occurs within the Navy stakeholders like NAVSEA Enterprise, USN, United States Navy Reserves (USNR) SurgeMain (SM) units, and the DOD, it will help maintain Naval superiority against adversaries.

E. SUMMARY

This thesis aims to demonstrate how to effectively integrate existing legacy analysis tools with MBSE tools as a specific example of how to accomplish a part of a digital transformation. This will allow the USN to maintain and control its current maritime

advantage. Digital transformation can occur by innovating, delivering new capabilities, and creating new and improved ways to conduct business operations through digital engineering.

F. THESIS OUTLINE

This thesis is composed of six chapters. The first chapter provides an overview of the project, the background emphasis of why the topic was chosen, outlines the project objective to be achieved, the stakeholders that this thesis could be applied to, and a chapter summary. Chapter II identifies the literature review of the Navy Salvage and Diving background on what each specific branch does within NAVSEA 00C. Chapter III talks about the digital engineering transformation, first introducing the term, followed by how the warfare centers came to have the digital transformation guidance starting from the Department of Defense, down to the Department of the Navy, and finally the Warfare Center Strategic Plans. Chapter IV introduces the terms of model-based systems engineering, digital twin concept, digital thread and talks about the tools that will be used within the use case scenario. Chapter V goes directly into the use case scenario where the Cameo model and the POSSE model are built, followed by talking about the scenario outcome and the limitations it presented. Finally, on chapter VI, discusses the conclusion and the recommended areas of further studies from this thesis.

II. NAVY SALVAGE AND DIVING, SUPSALV

A. INTRODUCTION

The purpose of this chapter is to give a brief history of Navy salvage and diving within military capabilities. Furthermore, it aims to show how the USN Salvage and Diving community is organized.

B. BACKGROUND

Since the early 19th century, the USN divers have performed salvage and repairs of ships, construction work, and military operations. Although in its beginnings, the divers were for the most part “skin divers,” also known as snorkel and fin type diving, and swimmers. The Navy has significantly increased operation requirements and capabilities that have required the diving community to adapt to new and growing changes. Within the U.S. code of law, the Title 10 was created to outline the roles and reasonability’s of the armed forces. The Salvage Facilities Act (10 U.S.C. 7361–764) was created in the Title 10 and authorizes the Secretary of the Navy to provide the required salvage facilities, to include all equipment, gear, and tools that are utilized to prevent, or minimize damage to the environment created by vessels that are public or privately owned.

Navy salvage and diving operations allow “for the maintenance of a national salvage capability for use in peacetime, war and national emergency” (Salvage and Recovery Program 2021). Within the scope of the OPNAV instruction salvage operations are defined as unique tasks, which require specialized equipment and systems, as well as highly trained personnel. The scope of this thesis will in part be aligned with the operations of emergency vessel tows.

The U.S. Navy salvage forces integrate Mobile Diving and Salvage Unit (MDSU) units, Military Sealift Command (MSC) assets, and the Supervisor of Salvage and Diving (SUPALV) Navy teams composed on government and military personnel. These entities’ main function is to remove hazards as a side effect of navigation that can be found in foreign and domestic coastal waters, they provide support to repair and tow damaged vessels, recover sensitive items that should not fall into the adversaries’ hands (such as

black boxes, radar equipment, and equipment that gives the U.S. a warfighting advantage), and recovery any type of objects from the ocean depths.

NAVSEA 00C or SUPSALV, is part of the Navy's salvage forces but are not part of the operational chain of command. This specific branch of salvage is directly tasked by the CNO to serve as operational control. Also, SUPSALV is the Technical Authority (TA) for all USN diving operations. It tests and authorizes all current equipment being utilized by the salvage forces (Naval Sea Systems Command 2021g). Furthermore, as described on the website, it oversees exercising and maintains all salvage and diving contracts in the USN to supplement the Navy's salvage, search, and recovery capabilities when required.

The USN with collaboration of the MSC provide enhanced the end user with the ability to tow or salvage vessels in distress. Further reading of the MSC handbook (United States Navy 2020), the reader can learn that the MSC was created to support the logistics mission readiness of the U.S. forces across the globe. The mission support can happen in peace time missions such as mission aid support, as well as in war time to help deployed combat vessels to stay forward deployed and in the fight. MSC is under the umbrella of United States Fleet Forces command (USFF) and has a fleet of around 50 to 60 government assets that are applied to Navy-unique matters. Within the MSC handbook it identifies the MSC as the operational Navy Component Commander to the U.S. Transportation Command (USTRANSCOM), which "provides coordination of air, land, and sea transportation to for the Department of Defense" (MSC Handbook 2020-2021). The Military Sealift Fleet Support Command (MSFSC) was created to help enhance the USN capabilities to have the proper personnel in the MSC government owned vessels, to train in the vessels, and to equip and maintain them. Within the combatant command support, the sealift helps provide "efficient and cost-effective transportation for the DoD and other federal agencies during peacetime and war" (MSC Handbook 2020-2021).

C. NAVSEA 00C

NAVSEA 00C or SUPSALV (as it is known in the Fleet), is part of the NAVSEA Enterprise. Currently the Headquarters for SUPSALV is located inside the Washington Navy Yard in Washington, DC area. The main function of SUPSALV team according to

its website is to oversee all aspects of the USN salvage and towing capabilities (Naval Sea Systems Command 2021b). As the website mentions, the responsibilities SUPSALV owns and maintains can identify in the following categories:

- Provide oversight of all the ocean engineering missions
- Salvage operations for USN and private own operated vessels, planes, materials, and any other objects that need to be salvaged from the ocean.
- In water ship repairs if a vessel is damaged to do a collision
- Is the technical authority in all contract matters of salvage and towing
- Overall authority for USN diving equipment maintenance, diving related material procurements, and diving safety.

1. 00C1 Business Management

The business management division deals with SUPSALV's unique financial and contract requirements (Naval Sea Systems Command 2021d). When a new contract needs to be created, this division tracks the financial and contractual documentation through the funding approval process until its fulfilled. They make sure to fund all logistical support and ensure budget requirements are being met for the SUPSALV team.

2. 00C1 Logistics Branch

The logistics branch is also part of NAVSEA 00C1. The website describes it as a logistics perspective this branch deals with all the management and logistics support of the SUPSALV team (Naval Sea Systems Command 2021d). They make sure that technical documentation like manuals, that all the data management is properly stored and looked after, as well as inventory all materials and products the SUPSALV team utilizes, stores, and manages.

The logistics team works closely with the financial team to ensure that all requirements and resources are being met through the cost, schedule, and performance metrics of the stakeholders. Within the scope of work of the logistics branch, the team makes sure that all data packages, material, and technical manuals are available to the

SUPSALV on site team. They also serve as custodians for all controlled records and data received via archives.

3. 00C1 Procurement Branch

The procurement branch is responsible for managing all contracts that include but are not limited to cost-plus-award-fee and firm fixed price (Naval Sea Systems Command 2021d). The team also manages an indefinite-quantity of response vehicles that are utilized for the emergency response team. These contracts that are outlined are in support of salvage, undersea, diving, search and recovery operations, and hull cleaning of the assets. In an environmental perspective the contracts that pertain to oil pollution and hazmat response are also worked and created in this team. As described on the website current NAVSEA 00C contracts include a wide variety of contracts such as ship salvage operations performed outside continental U.S. (OCONUS) and continental U.S. (CONUS), undersea operations, diving services, oil pollution, and hull cleaning services.

4. 00C1 Financial Branch

The Financial Branch is responsible for the current and future budgetary and financial planning and execution functions for NAVSEA 00C. As the website describes (Naval Sea Systems Command 2021d), the responsibilities include formulating of future budget requirements, earn value management, fiscal year budget execution, reporting to Program Executive Offices (PEO) and tracking of all the appropriated funds. Responsibilities outlined on the website within the financial branch include to receive funds from the PEO based on Congress funding of the fiscal year, obligating contracts to ensure that proper planning and execution of the funds are allocated in a timely manner, tracking, de-obligating of funds not utilized in a contract, and return the unused operational funds that were not used in the scope of the specific task intended for.

5. 00C2 Salvage Operations Branch

As outlined on the SUPSALV website (Naval Sea Systems Command 2021e), the Salvage Operations Division oversees the current worldwide commercial contracts for salvage operations that involve emergency towing, deep ocean search and recovery

missions, and oil pollution in the world's oceans. The operations branch of NAVSEA 00C provides the salvage technical assistance that is needed to successfully conduct mission in the Fleet and other federal agencies like the Federal Emergency Management Agency (FEMA). As described on the website, NAVSEA 00C2 owns, maintains, and operates the emergency ship salvage material (ESSM) system, which is the largest inventory of salvage equipment and pollution cleanup equipment that is fully maintained by the operations branch at SUPSALV. When extra resources are needed due to manning or asset shortage the SUPSALV team relies on MSC and civilian contracts to meet the Navy's mission. Some of the salvage assets used in the missions based on a MSC and civilian contractors are T-ARS 50's, and T-ATF 166 vessels.

The SUPSALV website also describes the assets the division uses in the search and recover process for deep-water missions. These systems are used when actual human capabilities cannot suffice due to pressure, atmosphere, or depth do not allow human resources. Some of the assets used are Cable Controlled Underwater Vehicle (CURV) III Remote Operating Vehicle (ROV), Deep Drone 7200 ROV, Magnum ROV, and the Orion Search System. These systems use digital capabilities that allow the personnel above in the salvage vessels complete the mission of recovering objects from the depth of the ocean. These capabilities can reach up to 20,000 feet (ft) (Naval Sea Systems Command 2021e).

One of the most important tools used by the operations branch is called POSSE. POSSE is a salvage response tool that provides the salvage expert a way to analyze data of a ship when it is subjected to any type of integrity damage. Based on the description from the website the program can evaluate technical details like structural integrity of the vessel, the drafts and trim based on water coming in the vessel or oil leaving the vessel, it calculates stability, forces, and reactions. These calculations are completed via a computerized model.

6. 00C25 Environmental

The environmental section in SUPSALV's website, (Naval Sea Systems Command 2021f), demonstrates that SUPSALV is the worldwide pollution response division. SUPSALV serves as the DOD representative on the National Response Team (NRT). The team is responsible for providing an Annual Oil and Hazardous Substance (OHS) Report

that is directly notifying the CNO of any oil or hazardous material missions. This report is saved and track in the “OHS Spill Tracking System that includes the Navy On-Scene Coordinators’ (NOSC) reporting” (Naval Sea Systems Command 2021f). This description of the system on the webpage “helps provide technical assistance in developing NOSC response plans” being undertaken. These systems aides the tasking of SUPSALV oversees the maintenance and distribution of the worldwide equipment inventory that is used in the response to major Navy pollution incidents. SUPSALV is the lead and works side by side other Federal agencies to develop plans as a mitigation strategy for pollution, research the latest spill response technologies for lessons learned, and conduct training exercises on a regular basis to maintain proficiency. The team responds to any environmental national emergencies and is the DOD eyes and ears on the NRT.

7. 00C3 Diving Program

SUPSALV’s Diving Program Division serves as the U.S. Navy and DOD diving technical authority. This division has information on the website (Naval Sea Systems Command 2021g) that provides stakeholders the service required to complete tasks from cradle to grave. The team oversees all the policies, procedures, and diving equipment that is used in scenarios such as research and development, developmental prototyping testing, and through USN acquisition processes. This division is the direct support agent across the Fleet to provide any assistance within the technical issue support. The team procures and maintains diving equipment that is used across the USN enterprise.

The website also describes the dive program as technical authority is the source of information in publishing the dive standards and procedures, in charge of providing advisory messages to the Fleet, and provide technical expertise when it comes down to technical manuals and instructions of the USN. Any questions related to diving within the DOD and sub agencies, this division serves as the point of contact both military and commercial manufacturers.

8. 00C4 Certification Division

Information provided on the SUPSALV website, (Naval Sea Systems Command 2021h), outlines the certification division as the System Certification Authority (SCA) for

all the USN diving programs. The SCA provides a quality review of equipment that is design, fabricated, tested, operated, and maintained by the USN. The team is composed of highly systems engineers, certifying technicians, administrative personnel, and the SCA. The main function of the team is to address safety concerns regarding system design and hardware in use by the Fleet.

In accordance with the website, during the design phase, the certification team reviews the design calculations, analyze the hazard implications, see what material compatibility there is amongst other systems, system drawings, and are a key instrument in the quality assurance process. During fabrication and testing process, the certification team reviews all procedures and records from the system to ensure that the hardware belonging to the system is following the design. After the initial certification, the team will conduct periodic surveys of certified systems to ensure that all the protocols and procedures regarding safety while operating are being met.

9. 00C5 Underwater Ships Husbandry Division

Underwater Ship Husbandry Division (UWSH) based on the website, (Naval Sea Systems Command 2021i), is instrumental to develop techniques and procedures to aide in the performance of waterborne ship repairs activities to reduce the need for drydock repairs and extending the time between drydockings. By doing the waterborne ship repairs the Navy minimizes the amount of ship time spent in drydock. The objectives of the UWSH Program outlined by the website are to improve the Fleet's readiness with ship repairs while maintaining low maintenance costs associated with drydockings.

The UWSH division relies on technical experts to be the on-site subject matter experts that provide training and technical expertise to Fleet anywhere operations are taking place.

D. SUMMARY

When it comes to USN diving, NAVSEA 00C or SUPSALV is the Navy's technical authority concerning salvage operations, diving operations, underwater ship husbandry support, equipment testing and certification, as well as overseeing all USN and Marine

Corps diving operations. Not only is SUPSALV the technical authority for diving operations within the Fleet, but it plays a key role in ocean preservation with regards to ship waste. Also, they provide aide support missions across the globe.

III. DIGITAL ENGINEERING TRANSFORMATION

A. INTRODUCTION

The purpose of this chapter is to provide a brief explanation of Digital Engineering within the USN and the DOD. Within the DOD Enterprise there is an ongoing effort to define processes of digital transformation to address the needs of the warfighter. This effort extends to all the branches within the DOD and their respective sub-commands.

In the search for adopting new strategies to achieve a greater performance of Naval vessels and the affordability to create, develop, and maintain an affordable Navy to meet its current and future needs, the DOD decided to create a digital computing enterprise. These strategies will allow the U.S. to modernize its defense systems capabilities and prioritize our methods to keep up with the rapid advancements in the military systems. With the use of digital programing and computing, the new technologies are conducting engineering in an integrated sophisticated virtual environment that increases performance amongst all the DOD helping to create a unified front against the adversaries.

Within the DOD, the DON Enterprise adopted the digital systems engineering transformation in mid-2020 as a response to the DOD's adoption of strategies. The main difference is that in the DOD set out a guidance on goals that were to be achieve through the enterprise, while the DON set out to review these strategic goals to turn them in to strategic objectives across the DON enterprise, thus achieving a greater performance and the affordability the Navy and Marine Corps need.

The DON Enterprise has a specific guidance set for the Naval Surface Warfare Centers (NAVSEA). The USN talks about how the warfare centers scoped it down to mission specific within fleet maintenance, and in-service engineering agent (ISEA) perspective. In 2021 the NAVSEA Enterprise set forth guidance for the *Warfare Centers Strategic Plans* that go from 2021 through 2025. In this guidance the main priorities are to deliver ready combat systems power, to be able to transform current efforts to digital capabilities, and build educated and competent teams to compete and expand the advantage (Naval Sea Systems Command 2021c). All the strategic priorities were set forth thanks to

the guidance provided within the DOD's goals that we needed as a military nation to maintain military superiority. This chapter will demonstrate the thought process and the benefits of a digital engineering transformation within the USN.

B. BACKGROUND

Digital engineering transformation was created in response from the DOD and DON need to create new designs, deliver a combat ready system in a shorter amount of time, sustain current combat systems Navy vessels, sensors, and offensive and defensive weapons. This need set forth goals and guidance's into a digital information strategy that impact the entire enterprise. The goal of the digital engineering transformation is to be able to respond quickly to changing operational requirements and threat environments. Specific programs need to ensure to deliver under restrictive budgets and quickly changing delivery schedules. The *Digital Engineering Strategy*, the *Digital Systems Engineering Transformation Strategy*, and the *Warfare Center Strategic Plan* were created for the Navy and Marine Corps military branches to set guidance's within their respective organizational structures.

In 2018, the DOD released the guidance on *Digital Engineering Strategy* that would set forth the playing field of how to properly guide the planning processes, develop instrumental components, and would pave the way to the implementation of digital transformation though the entire DOD Enterprise (Department of Defense 2018). The DOD needs to acquire strong engineering practices that will enable to develop new and improved weapon systems were the starting point of the nation needs to maintain the edge against our adversaries worldwide. In previous years, the nation had adopted a linear development process to achieve complex weapons systems. As outlined in the guidance, it was created to provide the means of going away from the document intensive and stove-pipe engineering processes that added unnecessary constraints to the systems life cycle. With development revolutionizing all major industries, the nation needed to catch up to speed with the digital technology era. The approach outlined in this document adopts a model-analyze-build methodology that enables the DOD to create prototypes, test, and experiment

on safe environments that virtual environments provide to run extensive research prior to delivering new capabilities to the warfighter.

The *Digital Engineering Strategy* intent was not to be descriptive, but to provide room for all DOD entities to meet their needs. It was intended to be a living document that encompassed the cooperation of the federal government, the industry leaders, as well as academia personnel. It provided guidance on planning, developing, and implementation of digital engineering transformation initiatives across the DOD. The *Digital Engineering Strategy* was composed of five different strategic goals that outlined what a military nation must align to succeed and maintain military superiority. Based on the Strategic Goals that were identified in the *Digital Engineering Strategy* (Department of Defense 2018) was to meet the following areas of interest:

- Formalize the development plan to integrate models to aide in the program decision making across the enterprise.
- Provide an overall source of truth.
- Incorporate current innovational capabilities to maximize engineering practices.
- Establish an infrastructure that allows effective collaboration and communication across stakeholders.
- Transform the current DOD culture that supports digital engineering.

In response to this strategy, the DON developed *the Digital Systems Engineering Transformation Strategy* that shifted from a system engineering that relied heavily on document-centric activities to a digital-centric environment. The transformation strategy supports regular applications across the DOD enterprise and encompasses “access to digital models and data applied in a model-based systems engineering approach” (United States Navy and Marine Corps 2020). The MBSE improves the quality and consistency of the systems delivered to the warfighter across all the programs life cycle. This includes changes in acquisition practices, overall training processes, and data modeling accessible via secure environments.

The NAVSEA Warfare Centers developed a strategic plan that would allow the DON's Digital System Engineering Transformation Strategy to be developed, maintained, and flourish from a bottom to top approach. NAVSEA Warfare Centers are the heart of the world's greatest Navy. The enterprise is a key contributor to maintaining and protecting America's global interests. This plan outlines what individuals must do as mission priorities, strategic goals, and what values they must achieve to expand the advantage.

C. DIGITAL ENGINEERING STRATEGY, DOD 2018

The *Digital Engineering Strategy* was developed to provide support to the needs of the DOD in providing critical capability to the warfighter in a timely manner. This strategy was created to aide in the planning, through execution of the digital engineering transformation that spans across the DOD enterprise (Department of Defense 2018). Furthermore, it was based on an interpretation perspective vice being a step-by-step guide to provide different DOD components with the necessary tools to create an effective digital engineering strategy that works for their respective branches. The Office of the Deputy Assistance Secretary of Defense for Systems Engineering (ODASDSE) developed the strategy workflow that can be seen in Figure 1.

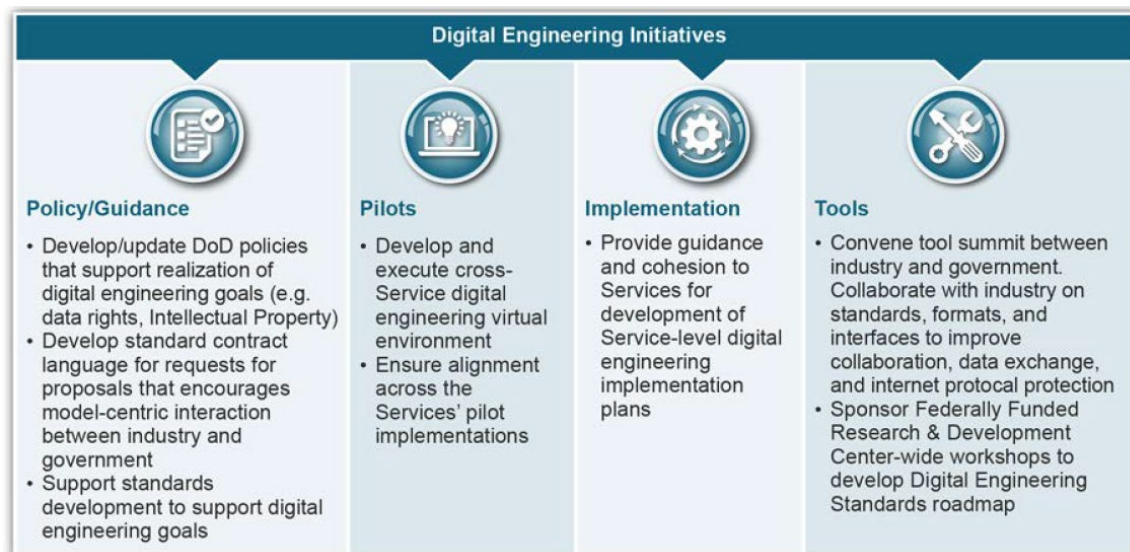


Figure 1. ODASD(SE) Digital Engineering Leadership Role. Source: Department of Defense (2018).

The guidance provided by the ODASDES is to enable the Leadership at any command with the necessary information to accomplish the mission. The main digital engineering initiatives are Policy/Guidance, Pilots, Implementation, and Tools. They have set forth policies that directly align with the digital engineering efforts which allow for specific language to be used when creating contracts, proposals, and work integration across multiple platforms. Also, they made virtual programs and implemented services that will help with the integration of a pilot implementation program. They provided guidance on how to implement plans across digital engineering. Finally, the ODASDES created an initiative which outlines the tools, in which the federal government and industry experts can come together and share ideas on how a digital engineering roadmap can be created and maintained.

The digital engineering strategy that the DOD developed is composed of five different goals outlined in Figure 2.



Figure 2. Digital Engineering Goals. Source: Department of Defense (2018).

a. Strategic Goal #1: “Formalize the development, integration, and use of models”

During the early phases of the life cycle process, the use of models provides the end user with the ability to explore possible solutions to a problem via virtual exploration. This process helps the life cycle process because what is learned in the virtual environment can be successfully replicated in its physical counterparts. This can be in the form of virtual

testing prior to incorporating it in actual sustainment support. A physical representation of what a formalized application modeling tool is through the life cycle phases can be seen in Figure 3 (Department of Defense 2018). The authoritative source of truth represents an example of the different models that can be used to develop, integrate, and use through the life cycle process. The intent in converting the system in the virtual environment is that they will be able to adapt through the life cycle process of the system and can be used or redeveloped to meet the needs of the system.

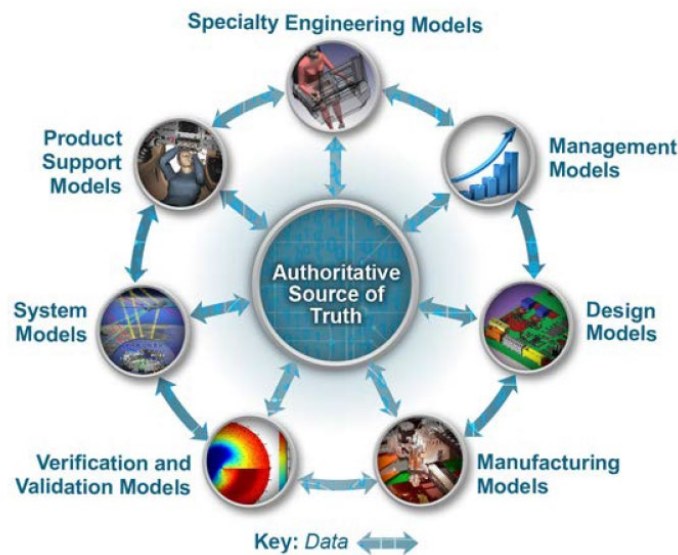


Figure 3. Models Connected via Authoritative Source of Truth. Source: Department of Defense (2018).

b. Strategic Goal #2: “Provide an enduring authoritative knowledge source”

The second goal was created with the thought that the source of truth needed to be transparent for all stakeholders across the Enterprise (Department of Defense 2018). The organizations within the DOD would be able to access the same information and analyze all the information gathered from the development and use of the digital models created in the first objective. The purpose of this goal based on the document, is to move away from static non-used artifacts and create a model that can be utilized and to share a current and historical background of the technical baseline of the system. It serves as a firsthand

account of the process and policies that have been developed and used through the life cycle. An example of this authoritative knowledge source can be seen in Figure 4.

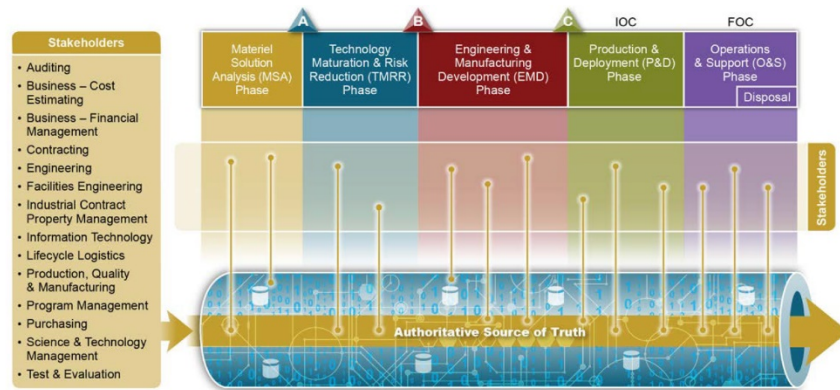


Figure 4. Authoritative Source of Truth. Source: Department of Defense (2018).

As seen in Figure 4, when the authoritative source of truth is used appropriately it provides real accountability that can be traced from cradle to grave in the life cycle process. Any changes made to the system have been noted and identified to help maintain the technical baseline. The goal is to provide the end user with the most accurate data that is known at the time of delivery.

c. Strategic Goal #3: “Incorporate technological innovation to improve the engineering practice”

The third goal that the DOD outlined was to be able to design and enable the organizations within the DOD the ability to maintain technological superiority by using methods outside the box to help in the innovation and use of advanced technologies (Department of Defense 2018). At this phase of the Digital Strategy, the user can start incorporating the end-to-end digital engineering enterprise. Once the first two goals are completed, the DOD organizations will have the ability to make decisions with more information at their disposal, as well as making decision in a more efficient way. Using a digital enterprise multiple DOD organizations can leverage the lessons learned and data that has been gathered though process improvement, research and development, and other

technological advances that can be shared for the common goal of acting in an autonomous ecosystem.

d. Strategic Goal #4: “Establish the supporting infrastructure and environments for the Digital Engineering practice”

The fourth goal is to build an infrastructure and environment that will support all digital engineering needs. Often, the infrastructure and environment that we had in 2018 were stovepipe in nature and were difficult to manage because there was no integration of resources. By creating this digital strategy, the DOD’s goal was to revamp their infrastructures and environments so that the information is consolidated, and its environment trusted. The infrastructure that needs to be created by the DOD needs to have the following core elements based on the *Digital Engineering Strategy* (Department of Defense 2018):

- Provide secure networks that align with digital engineering process.
- “Provide hardware and software to perform digital engineering”.
- Develop and implement methods that create processes that support a digital engineering environment through the life cycle process.
- Secure IT infrastructure.
- Protect intellectual property.

e. Strategic Goal #5 “Transform the culture and workforce to adopt and support Digital Engineering across the life cycle”

The fifth and final goal takes a systematic approach that allows to plan and support a digital transformation within the DOD organization (Department of Defense 2018). One of the key aspects is to have the workforce’s perspective in what the actual day-to-day challenges are so the DOD can grow their culture by means of sharing the values, beliefs, and the ability to work as a cohesive team. The *Digital Engineering Strategy* document outlines that the most difficult thing to do in an organization like the DOD is to promote a cultural change. Some ways to implement the change in culture is by taking deliberate steps within educational training, clear communication of intent, and leading by example within

the continuous improvement capabilities. This goal is the most important because it is completely dependent on everyone in the organization to have a culture of innovation and a thirst for continuous improvement with everyone's values, attitudes and beliefs transforming the culture and seeking to expand the advantage by a digital engineering approach.

Furthermore, the strategy states that when creating this transformation in the culture, there needs to be clear policy, guidance, specification, and standards to ensure that across the DOD organizations there is consistency and discipline. The DOD counts with many standards within the digital engineering enterprises, but none cover the range of models and data required for a full integration of all organizations within the DOD. It requires strong leaders who will seek to encourage their subordinates to accept and embrace the changes of a digital engineering transformation and to build the knowledge and communication within the entire DOD.

f. Measurable benefits

Digital engineering “will enable stakeholders to interact with digital technologies and solve problems in new and ground-breaking ways” (Department of Defense 2018, 11). Utilizing models has been performed for a long time; however, digital engineering utilizes the use of the same model across the life cycle of the system, allowing it to adapt to situations and help build form an already created system model. Based on information in the engineering strategy the reader can learn that transitioning to digital engineering addresses a long-standing challenge that related to the complexity and uncertainty of a rapid changing environment when “deploying and using U.S. defense systems. By providing a more agile and responsive development environment, digital engineering will support engineering excellence and provides a foundation to fight and win the wars of the future” (Department of Defense 2018, 11).

Expected benefits described in the *Digital Engineering Strategy* from a digital engineering environment are the following:

- Create an informed decision-making process by having greater transparency.

- Provides the opportunity to communicate efficiently across multiple agencies.
- Increased flexibility and adaptability on the design process of a system.
- Creating confidence of the system design that performs as it was tested.
- Allow room for more efficient engineering and acquisition processes.

D. DIGITAL SYSTEMS ENGINEERING TRANSFORMATION STRATEGY, DON 2020

The DON is committed to create new designs, deliver a combat ready system in a shorter amount of time, sustain current combat systems, and Navy vessels that transform within the rapid change of operational and threat environments considering cost, schedule, and performance metrics. The U.S. Navy and Marine Corps *Digital Systems Engineering Transformation Strategy* (United States Navy and Marine Corps 2020) was developed in mid-2020 in response to the DOD's guidance of the *Digital Engineering Strategy* created in 2018. This document outlined the response to the DOD needs to change into a digital engineering enterprise. Furthermore, it encompasses provisions and access to the digital engineering models and data applications that relate to a model-based systems engineering approach within the USN and the Marine Corps. "An integrated digital approach that uses authoritative sources of systems' data and models as a continuum across disciplines to support life cycle activities from concept through disposal" (Department of Defense 2018, 3).

According to the *Digital Systems Engineering Transformation Strategy*, The Department of the Navy (DON) embraces Digital Engineering to maximize agility, interoperability, reusability, and scalability across the DON. This Navy and Marine Corps Digital Systems Engineering Transformation Strategy specifies activities necessary to enhance engineering acquisition practices within our enterprise. Our strategy aligns with Department of Defense *Digital Engineering Strategy* goals, shifts how we work from traditional document-centric activities to digital-centric activities, and informs designers, developers, managers, and technical authority stakeholders with continuous access to authoritative data (United States Navy and Marine Corps 2020, 2).

Based on the *Digital Systems Engineering Transformation Strategy* the “Digital Engineering is key to managing the development and delivery of increasingly complex and interconnected warfighting systems” and to enhance the desired capabilities that the warfighter needs at that point in time. Through time the DON system engineering processes have normally been performed through a document focused program. What this means is that everything created needed to have documentation that could be trace back via processes and procedures. The document also outlines that over time, digital engineering has become a vital role in the new culture of excellence within the DON. The main concepts are basing the documentation process through digital models that used in the analysis process through the production. The use of digital models helps with cost, schedule, and performance metrics because you can use the same model through the lifecycle process of the capabilities and systems.

The use of digital models creates a virtual environment where you can identify technical discrepancies early in the process. Developing a digital model is based on the priority level of the system being adapted, the performance specifications that will be measured and tested, and most importantly the ability to maintain digital artifacts that can be used, modified, and created through the lifecycle process. This process helps identify possible solutions in a shorter amount of time with less cost implications. The approach becomes dynamic in nature which allows the creation of follow up documentation easier and with minimum time constraints (United States Navy and Marine Corps 2020).

Through the *Digital Systems Engineering Transformation Strategy* developed for the USN and Marine Corps, the reader can observe how it aligns with the DOD *Digital Engineering Strategy*, from June 2018. The results *from the Digital Systems Engineering Transformation Strategy* are described below for each of the strategy's objectives:

a. Objective #1: “Formalize the development, integration, and use of models”

DON observes the need to understand system behaviors to identify supporting functions in an effective way through a modeling process (United States Navy and Marine Corps 2020). Ideally, the process will start early in the acquisition lifecycle to establish

performance requirements. The focus for the first objective is to allow the performance specification to lead the way in the modeling process, contrary to earlier processes where they would use a writing performance process.

During the transition from writing performances approach to a digital driven approach found in the *Digital Systems Engineering Transformation Strategy*, the team will be able to (United States Navy and Marine Corps 2020):

- Trace the system requirements in order to ensure stakeholders needs are met.
- Model the system functional behavior(s) that will demonstrate the desired capabilities from a stakeholder's perspective.
- Create a functional system hierarchy that is derived from the model built.
- Create and analyze performance requirements of each element in the model taking into consideration external factors following all standards and policies.
- Develop requirements to verify the performance requirements.
- Review and approve the program compliance methods used in the Digital Engineering framework.

Furthermore, the document outlines the next steps in meeting these requirements as:

1. Deliver advantages to the Fleet in both short term and long-term acquisition operational readiness.
2. Design and process beta projects across the functional areas.
3. Utilize an integrated modeling environment that supports all the programs and capabilities across the Fleet.
4. Review and incorporate changes within the requirements and acquisition policy processes that are centered in a digital approach of the program.

b. Objective #2: “Provide an enduring authoritative knowledge source”

One of the most important parts of Digital Engineering is the interactive way to publish, store, curate, tag, and secure models in a way they can be found easily, are documents that are trusted and that the person who is authorize can have the documents when they will utilize them. If a person has a need to know, they should be able to perform the designated duties that apply to the specific model being reviewed, approved, or changed. In this instance, there is a designated person who will serve as a technical authority that grants the specific accesses based on the requesters need to know and functionalities needed. The models need to be in the network and should be controlled to maintain the model’s integrity. The data within the network must be well defined so the team who is working the model can have clear information (United States Navy and Marine Corps 2020):

Furthermore, the document outlines the next step in meeting these requirements as:

1. Develop an authoritative source of truth that will allow access to the model to implement a digital transformation data environment.
2. Establish policies and procedures to maintain a technical baseline.
3. Identify a specific point of contact that will manage the mapping efforts in the digital transformation model.
4. Document the best practices processes to assess the standards and strategies.
5. “Identify common reference models for use across the Naval enterprise, for acquisition, technical analysis and development effort”.
6. Establish security guidelines that are specific to each programs model.

c. Objective #3: “Incorporate technological innovation to improve the engineering practice”

Through the *Digital Systems Engineering Transformation Strategy*, the reader can observe how the NAVSEA Enterprise will utilize the digital enterprise to introduce a model-based approach that will be able to connect a virtual environment that can conduct life cycle activities from cradle to grave. Digital Engineering was designed to increase

understanding among the concepts that integrate systems together. This implementation reduces testing time and supports the decision-making process. Also, in this document demonstrates that by incorporating the digital engineering approach early in the lifecycle process the team reduces the risk of having discrepancies when it comes to requirements when building a new concept by using the information learned through the authoritative knowledge source.

As time goes on the Fleet's missions are becoming more complex that require a system of systems environment. The Navy will need to expand their combat capabilities and look for innovative ways to integrate the systems through their lifecycle processes from cradle to grave. As shown in Figure 5, the digital engineering process provides an overall understanding from cradle to grave perspective, using an authoritative data reference (United States Navy and Marine Corps 2020).

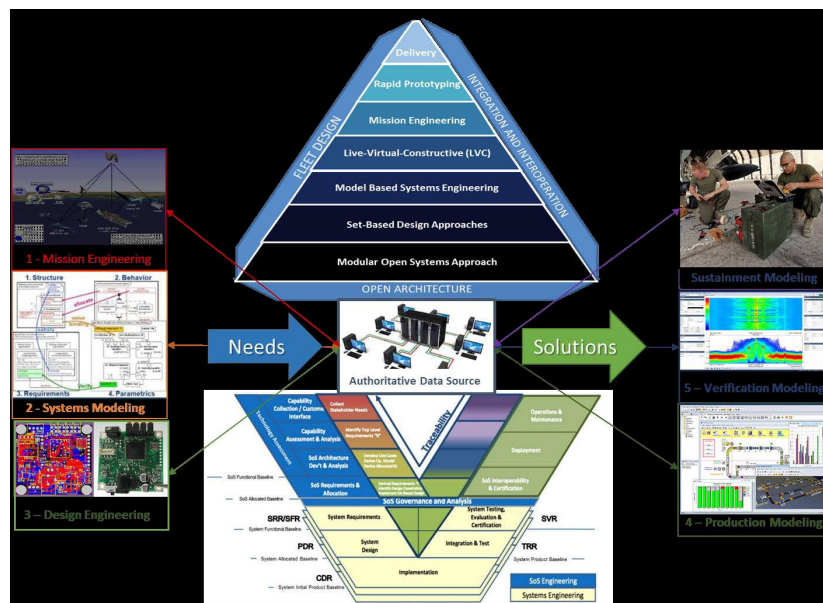


Figure 5. Role of Digital Models Connecting Systems of Systems Analysis, Standards, and MBSE. Source: United States Navy and Marine Corps (2020).

Further steps are presented within this strategy to meet the requirements is to (United States Navy and Marine Corps 2020):

1. Implement user approaches that are designed to resolve data capabilities.

2. Implement metrics processes to determine the outcomes of the digital solutions of the missions.
3. Utilize models as evidence that can be used in the Systems Engineering Technical Reviews (SETRs).
4. Leverage the use of artificial intelligence to have models that work in an autonomous way.
5. Establish a system model that allows the development of constraints that apply across all systems in the model.
6. Ensure accurate data is available in a digital format to leverage with future technology capabilities.

d. Objective #4: “Establish the supporting infrastructure and environments for the Digital Engineering practice”

In the objective #4 of the *Digital Systems Engineering Transformation Strategy* shows that an integrated modeling environment (IME) is established to provide a virtual infrastructure that supports specific objectives of a digital engineering environment. The environment is primarily data driven that allows multiple users from across different parts of the world to collaborate within the same system model. This environment must have accessible networks that are fully compliant with DOD digital engineering safety and requirements compliant (United States Navy and Marine Corps 2020).

“Key tools sets must be provided within the IME to support MBSE processes using Systems Modeling Language (SysML) and Unified Modeling Language (UML)” (United States Navy and Marine Corps 2020, 14). The languages must be government compliant to design and create specific Contract Data Requirements List (CDRL) tasks and items. Specific authentication policies are created to make sure that only the personnel who should have access are the ones that granted access to the modeling environment that is being utilized. In this document, it is describing that to maintain security protocols, the system administrator will ensure that everyone that logs into the IME will be vetted and cataloged to specific things that they are doing with the system model. Within IME Naval engineering process, you have the MBSE system models that outline the requirements of the digital

model, the team will have the ability to recreate operational threads to ensure that proper documentation is occurring, and you can test the platforms and cyber models within this environment. All the models must be in the lifecycle process between the conceptual design and up to the test and evaluation phases.

The next step to meet these requirements outlined in the strategy is to (United States Navy and Marine Corps 2020):

1. Identify the technical point of contact for Systems Command Technical Authority that will outline the documentation required to incorporate the digital engineering principles.
 2. Implement a constructive environment that can be utilized both in a live and virtual manner to support the integration process capabilities of the system desired.
- e. Objective #5: “Transform the culture and workforce to adopt and support Digital Engineering across the life cycle”*

To successfully implement a digital engineering environment, based on the *Digital Systems Engineering Transformation Strategy*, (United States Navy and Marine Corps 2020), *is that* each part of the enterprise needs to create an environment of change within its management. It takes leader with a vision to plan and support everyone in the workforce to enhance their skills and experiences to create a change and allow the digital engineering to thrive. The advances in the digital engineering environment opens the possibilities to become an avid subject matter expert in fields that were not needed before, thus allowing growth to happen in the enterprise. The digital engineering workforce needs to align together to bring new personnel in, to allow a safe environment where development is welcomed, and train the correct people on the right tools.

Also outlined in the strategy is that one of the major challenges the DON currently faces is the ability to identify the correct personnel that will be involved in the digital engineering process. Once the personnel are identified then they can proceed in providing the correct training environment depending on what function the personnel will be

performing. Training is a key component to be successful in a digital engineering environment.

The next step to meet these requirements outlined in the strategy is to (United States Navy and Marine Corps 2020):

1. Develop specific guidelines that reflect all components of digital engineering and MBSE.
2. Allow the workforce to fully integrate itself into the development of a digital engineering workforce.
3. Create a workspace for the digital engineering leaders where they can encompass on the lessons learned, notify of the progress being performed, and share the stories of success.

f. Measurable benefits

The DON expects Digital Engineering transformation will help capitalize savings on current sustainment capabilities and future design processes of the programs in a funding and time perspective over the entire systems life cycle. It will allow to enable future expandability and upgradeability while reducing work, streamlining processes, and reducing overall inventory. Furthermore, digital engineering will help identify the amount of funding required to develop key solutions that will impact the entire DON enterprise.

Digital engineering efforts based on the *Digital Systems Engineering Transformation Strategy* are focused on (United States Navy and Marine Corps 2020):

- Delivering lethal capabilities un a short among of time.
- Improve the decision process to allow for shorter times to deliver capable concepts to the Fleet.
- Deliver combat system capabilities at a more affordable price.
- Spread way to design and sustain warfighting capabilities across the workforce.

Results of this strategy help with making an informed decision when NAVSEA is looking into the options of an investment decision. The teams will be looking for greater interoperability systems and architectures within the return on investment of the capabilities. Future program plans and budgets should emphasize specific programs or locations to where the Digital Engineering will be more efficient. Metrics should focus on being able to complete the mission on time, that cost savings are well documented, testing new capabilities are performed sooner, capabilities get to the Fleet in a shorter amount of time, and build advanced future digital capabilities that will help expand the advantage.

E. WARFARE CENTERS STRATEGIC PLAN, NAVSEA 2021–2025

The NAVSEA Enterprise follows the guidance from the Strategic Plan (Naval Sea Systems Command. 2021c) which outlines the five strategic goals presented in the DON Systems Engineering Transformation Strategy. The overall picture that the warfare centers are looking for is divided in its three priorities:

1. Deliver combat power – As a warfare center the ISEA, Logisticians, and all management are focused in providing advance warfighting capabilities to the Fleet that are up to date and innovative in nature to assure that the Nation is combat-ready in all aspects from ships, submarines, combat systems and even a cyber environment. This Naval superiority can be achieved by looking into the capabilities in the future, creating a work environment where strategic thinking, innovation, technical excellence, workmanship, and safety are embedded into everything they do. The purpose of this is to have effective execution of tasks that will achieve on-time delivery and combat ready systems within the budget stipulated.
2. Transform digital capability – When looking for a force multiplier the digital transformation capabilities provide just that. It helps with a quicker response due to its innovative ways of delivering new capabilities while creating effective business operations. These digital capabilities will help the enterprise look beyond current capabilities, with the implementation of

a virtual infrastructure that the DOD can share with other internal and external resources.

3. Build competent teams – The purpose of this priority is to be cognizant that to succeed as a team you need to make sure that you provide the most training opportunities to your most junior personnel, as well as maintain skill trades within your mid-level to senior management personnel. Employee retention is key to building a team and fostering a culture of innovation.
4. The *Warfare Centers Strategic Plan* has five different goals that the team must accomplish in order to be successful and maintain Naval superiority.
5. Workforce and leadership development – What makes warfare centers strong and innovative are the people who day in and day out got out of their way to complete the Navy’s mission. To achieve this goal they need to hire, train, and develop the skillsets within the science, technology, engineering, business, logistics, and administrative that will be able to handle anything that the mission requires.
6. Mission-aligned strategies at the division level – The second goal is to make sure that pursuit of excellence in the mission, the Warfare Centers need to start thinking about space and the information and data domains. The mission relies heavily in the warfare center’s ability to safeguard the technical success of the Navy’s ships, submarines, and combat systems. The possibility of delivering key options and services that the Fleet needs is what keeps the Nation safe from its adversaries.
7. Technical innovation and excellence – To provide unique value to the Navy, the warfare centers must invest in a modernized infrastructure. Also, they must design, develop, and maintain solutions for urgent operational situations that improve the Fleet’s readiness. The teams also need to build relationships and bring in partners from industry and academia to cooperate within the DOD and DON to create an innovation culture.

8. Business excellence and improvement – The warfare center’s ability to maintain business excellence is as critical as maintaining its technical competencies. With a strong foundation of business capabilities, processes, and policies the warfare centers will be able to strive for an efficient, innovative, and adaptable business practices that allow the Navy to maintain course in being the maritime superiority.
9. Right culture and values – To be an effective team, the warfare centers have taken proactive measures to create a culture that is inclusive, engaging, and cultivating trust. One way to meet this goal is to instill diversity and inclusion into everything they do.

F. SUMMARY

Since 2018 when the DOD set the guidance to start shifting toward the Digital Engineering capabilities, the branches across the enterprise set out to research and proactively work on a plan to meet the strategies expectations. The DON came out with the expected goals to be achieved within the Department and clear guidance was provided to set out to the Fleet. In 2021 the Warfare Centers adopted the guidance provided by the CNO through the *NAVSEA Campaign Plan 3.0* and the *Digital Systems Engineering Transformation Strategy* from the DON to achieve a digital transformation and expand the advantage. In this thesis, the digital transformation will explore the possibilities of model-based systems modeling tools that integrate with current Navy tools used in operational capabilities.

IV. MODEL-BASED SYSTEMS ENGINEERING METHODS AND TOOLS

A. INTRODUCTION

The purpose of this chapter is to provide a general overview of the MBSE process, how it is implemented with digital thread and digital twin. Furthermore, this chapter describes the tools and methods that are used throughout this thesis.

B. BACKGROUND

In recent years, there has been an increase in demand to transform the DON through a digital transformation process. This demand is being met by enabling a data-driven decision-making process that can be incorporated in all the levels of planning, operations, and sustainment, as well as future resources to upgrade the combat system tools that will be required to maintain Naval superiority. This process helps the stakeholders understand everything about the system and the tools on what is going according to plan, what needs to change, and what are the gaps that need to be addressed to use resources to their maximum extent. In this decision-making process the stakeholders will be able to understand via performance metrics of their specific system, what they need to change to maximize efficiency and reduce maintenance time and costs to maintain the tool.

In today's warfighting capabilities, the stakeholders have put in an emphasis in the systems acquisition process. They are investing a MBSE to aid in the improvement of communication, rapid decision-making process, and oversee advance systems capabilities that could adapt to unforeseen events that may potentially be catastrophic, ahead of time by looking constantly at how the system is behaving. Furthermore, the MBSE process works with the systems acquisition structure because it is meant as a concept to be reused through the life cycle of the system. The MBSE sets forth the efforts and processes or digital thread processes. Digital thread is defined in Goal 2, Figure 3, as the communication framework that will allow different sources of data to flow and be able to integrate the data of the system across the systems life cycle process.

Through MBSE processes, the Digital Twin (DT) processes have been identified as a possible candidate that will allow stakeholders to analyze, modify, or create models that can be used throughout the systems life cycle. One of the reasons why DT is being leveraged in the development process is due to the unique ability to be considered as a separate system. The stakeholders can plan, modify, or act through a DT version of the system to test its vulnerabilities, look for ways to increase efficiency, and observe how the system would react to certain combat system changes. The DT version will be operated in parallel to the current MBSE processes that are done to the specified combat system tool.

1. Model-Based System Engineering (MBSE)

Within the DOD Systems Engineering, the MBSE field is an application that supports system requirements in a digital model. As outlined on the Digital Systems Engineering Transformation Strategy, (United States Navy and Marine Corps 2020), this model encompasses the design of a model that allows for specific verification and validation to take place tailored to the system that is being developed. When the team applies MBSE process they can grasp a better understanding of the capabilities the system needs, and it documents the behavior it could have while the performance metrics are being analyzed. The document further explains the main function of the digital models is that the team can see the systems and subsystems of the models which allows a better understanding of the potential future capabilities of the system in a military environment. When analyzing the systems models the team can identify possible inconsistencies in the system ahead of time and that allows time to fix the discrepancies before they go to the test and evaluation phases. Understanding the discrepancies in the model the team can assess and redirect efforts into improving the capabilities before it is implemented.

MBSE provides a technical framework to integrate complex model strategies to help expand the advantage. In modern day military it can be observed how stakeholders are looking into the acquisition programs and how the MBSE process is being brought in the beginning stages of the system acquisition pipeline to aid in the development of the systems design. This concept that is used in the design will be implemented and modified

through the life cycle process of the system to allow for a smother process of verifying system requirements that will comply with mission requirements. One of the key aspects that makes MBSE desirable within the DOD is its possibility of transitioning from document process-based acquisition program to a coherent modeling tool that will describe the system and help aid in the communication strategies among all stakeholders.

Since 2003 the MBSE process has been defined by the DOD directive 5000.01 (USD (A&S) 2003) to be utilized as the commonly used source of information for a formal process to identify top level requirements of a systems and their subsystems. MBSE seen in the DOD directive has three concepts that align with the DOD's intent on digital transformation:

- The use of models to represent an abstract reality to eliminate part of the complexity of a system. This allows a stakeholder to identify system requirements definitions and provide a decomposition. The purpose of this concept is to sufficiently represent the system and at the same time confirm the actual representations of the models.
- The use of systems thinking where the system being considered is thought of as a part of a bigger system. This assists with the demonstration that the concept of the design will be able to meet all system requirements put in by the stakeholder. In the modeling process of the systems thinking you can observe how the system is designed, understand the systems context, and the stakeholders will be able to model the system the way it should operate within a larger system.
- The use of system engineering principles through the life cycle of the system that will take into consideration the reliability, the processes, and procedures of the system to maintain the systems performance.

2. Digital Twin

Within the scope of this thesis the DT process has been identified as an approach that will be incorporated through the MBSE process. The DT is defined by the article *Demystifying the Digital Thread and Digital Twin Concepts* (Leiva 2016) as an analytical

framework that provides the ability to operationalize systems early on the systems models that will analyze, validate, and will be able to modify an already fielded system. One of the mayor benefits of this approach is that work performed already by the system during the development process can be used through the systems life cycle. The stakeholders can plan, modify, or act through a DT version of the system to test its vulnerabilities, look for ways to increase efficiency, and observe how the system would react to certain combat system changes. The DT version will be operated in parallel to the operational system. The operational system will provide data points that will be transferred over to the DT to analyze and determine the overall health of the system. This process will help determine if there should be a change in parameters to effectively field new updates or changes to the system. Currently there is no specific DT method that could apply to multiple systems and there is not defined process to implement DT.

“The idea of model reuse is the fundamental goal in the vision for fielding low-cost DTs to aid decision making, something that is consistent with the goals and objectives of modern DOD acquisition and engineering policies” (Friedenthal, Moore, and Steiner 2015).

One of the difficulties presented through the DT process is that building specific models can add to the development time as well as the overall costs of the systems. Depending on what the systems will be, the stakeholders need to be aware that to get a return on investments it must be performed early in the life cycle process. The process of building DT is a process that currently is being performed on a specific system base case, currently you do not have the ability to use it in cross functional systems due to the complexity of each system of systems. Often, the DT is being implemented after the systems are already operational, not being able to yield full efficiency of the time and effort that needs to be incorporated for a complex systems model.

To maximize the return of investment in a DT process the stakeholders would need to start in the development phase of the system. By implementing DT in the development phase, the stakeholders will be able to see many of the questions that result in a time reduction if it was in the operational phase. Being able to see the problems before the

system is operational helps in the overall life cycle process. Also, DT will set the tone when it comes down to establishing specific objectives and requirements of the operational system. When applying DT early in the development of the systems process, the stakeholders will be able to identify failures in the modules, identify possible stresses to the systems, and identify reliability issues that could be of concern.

The benefits expected from having a DT for each independent system based on the article *Demystifying the Digital Thread and Digital Twin Concepts* (Leiva 2016) are:

- Will create the environment where a team can assess current and future capabilities possibilities for a specific system through its entire lifecycle.
- Aide in outlining performance deficiencies in the beginning process of the system design.
- Optimize all working capacities of the lifecycle process though a digital version of the model.
- Opportunity to improve future design capabilities of a system through the model.

3. Digital thread

Digital thread is defined in Operationalizing Digital Twin through Model-Based Systems Engineering Methods (Bickford, Van Bossuyt, Beery, et al 2020) as the communication framework that will allow different sources of data to flow and be able to integrate the data of the system across the systems life cycle process. Many resources define it as having the correct information, in the right location, at the correct time. Digital thread is used across a system from cradle to grave. Its function is to serve as authoritative source of truth with the ability to access multiple sources of data, integrate lessons learned, transform capabilities, and analyze all information that is accumulated thought the systems life cycle.

C. TOOLS USED

1. Microsoft Products

The following Microsoft products were used in the aid of this thesis:

Table 1. Microsoft Programs Used

Program	Description
Microsoft Word	Software used for document creation and editing
Microsoft Excel	Software used for data visualization, analysis, and calculations
Microsoft Power Point	Software used to present project briefings and outlines
SharePoint	Used for file sharing and storage

2. Program of Ship Salvage Engineering (POSSE)

The SUPSALV website (Naval Sea Systems Command 2021j) describes how the POSSE program is used by SUPSALV salvage engineers to perform analysis scenarios required to determine a vessels survivability. This tool is used specifically by the USN as a response software to enhance the engineer’s ability to perform engineering assessments in real time. Some of the capabilities that POSSE provides are the ability to determine the ships stability and can show the engineers what are the effects of a damage vessel in a specific section of the hull. The program can determine the draft and trim, it can calculate how the vessel will react when flooded or oil starts outflowing due to a damage compartment, and it can determine the ships survivability when damaged calculating the amount of fluid that can be dispersed due to tides. The tool was created based on a need for the Navy to go from paper and calculator to automated assessments. Currently the POSSE program can be compatible with commercial program tools such as HECSALV, CARGOMAX and GHS (Naval Sea Systems Command 2021j).

The program POSSE, based on the SUPSALV website (Naval Sea Systems Command 2021j), is known for being able to do real time “numerical integration of hull and compartment offsets to calculate volumes” of the ship based on liquids like oil, fuel,

fresh water, and void spaces that become compromised. It calculates forces such as weight, buoyancy, and reaction that are iterated to obtain equilibrium. On occasions the “hull girder deflections can be calculated based on hull girder inertias,” depending on what the salvage expert wants to learn and investigate. POSSE includes features such as (Naval Sea Systems Command 2021j):

- Non-grid ground definition – This feature allows the salvage engineer to evaluate the effects a Navy vessel is undergoing in multiple points of the ship. A representation of this feature can be seen in Figure 6.

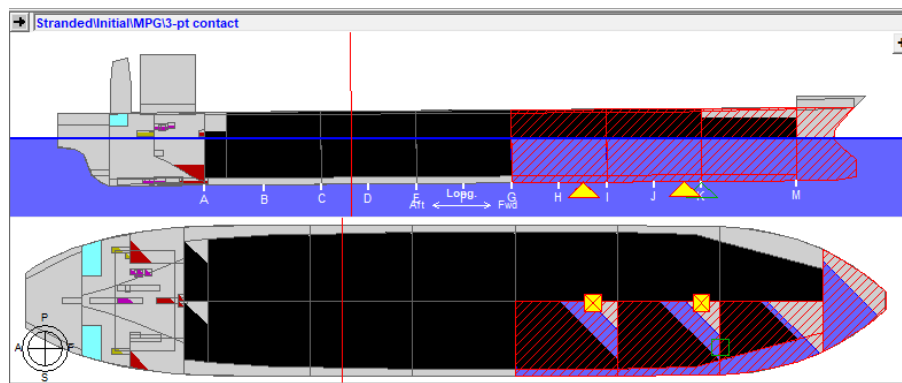


Figure 6. POSSE Ground Definition (Non-Rigid)

- Tide/Lighting Sequence (TLS) – This feature “allows the salvage engineer to calculate and display real time data of the tide height, ballasting/deballasting/ transfer of liquid” on ships that have no damage. For example, a ship that needs to transfer water in the portable water tanks so they can execute a proper ammo loading to the Navy Vessel (Naval Sea Systems Command 2021j). The TLS also shows the transfer of oil/water overflow from damage tanks or compartments. Furthermore, the salvage engineer can calculate ground reaction, bending moments, shear forces and hull distress. Depending on the status of the vessel and what the salvage engineer needs to make sure that the vessel can have maximum survivability. An example can be seen in Figure 7.

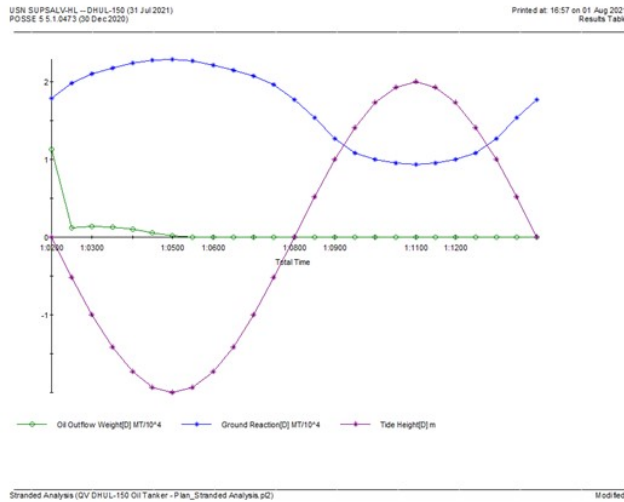


Figure 7. POSSE Tide Sequence Representation

- Hull axis rotation – This feature demonstrates a hull of a model that is capsized and will analyze the parbuckling processes.
- Multi-function interface – The feature allows the salvage engineer to interface the U.S. Navy Ships Motion Program (SMP) and the Ultimate Strength Program (ULSTR) to determine the wave bending moments that occurs in both the fully operational vessels and the damages ones. This feature can also evaluate the residual strengths.
- Windows-based operation – This feature allows the salvage engineer to have the data that was provided from the POSSE program to be converted into a 32-bit Windows application.

3. Cameo Enterprise Architecture

Cameo Enterprise Architecture from Dassault Systems (Dassault Systems N.d.) is a MBSE environment tool that provides robust and intuitive ways to define and track every aspect of systems model. The modeling language used is SysML and the software creates various system diagrams. This environment helps system engineers run analysis that impact the decision-making process, as well as validate all requirements. Also, it is used

as a metrics tracking system and as a checker for the model's consistency that identifies solution to needs like "improved project results, program accountability, resource management, success metrics, and efficiency" (Dassault Systems N.d.).

Benefits for using Cameo based on the Cameo Enterprise Architecture website (Dassault Systems N.d.) are as follow:

- Provides tailoring – Cameo provides the ability to customize the domain specific language that is used to execute validations of a system.
- Parallel development – In Cameo the team can utilize the MagicDraw Teamwork Server to work as a team of developers in the same model. This allows for creative ways to save time, create development strategies, test, and simulations of a project in an easy and accessible way.
- Configuration management – A control system that was implemented in the tool was the MagicDraw Teamwork Cloud that allows anyone who accesses the system model online to instantly obtain the newest version available. If multiple users are using the model at the same time, they can work in parallel and update the entire model. This tool allows the design to be in one specific location of the network and reduces the possibilities of losing data and causing confusion.
- Security – The Cameo tool provides multiple levels of security depending on the access level the project owner wants to administer.
- Interoperability – One of the benefits of utilizing this modeling tool is being able to have multiple outside source tools like Rational, Doors, Rational RequisitePro, and CSV files to communicate within each other. This provides a greater level of interoperability with other widely used system modeling tools. The main thing about these tools is that they need to utilize the UML and XMI standards as a requirement to be in the base line modeling tools.

- Serve as requirements manager – Cameo is used to create, modify, and track requirements across the combat system. The use of SysML requirements model is the most common when managing traceability between the requirements. As requirements manager the user can create custom schemes to support systems requirements, the user can define requirements and verify that they are met through matrices.
- Provide traceability for gap analysis – The modeling tool provides the ability to trace elements that are unknown through the system when in a specific view. This traceability helps discover, specify, and navigate specific elements in the overall system being implemented. The system modeler is used to find dependencies within the overall system.
- Provide reports – The tool contains a report wizard that allows the user to build and analyze reports that are normal texts, RTF, HTML, XML, and Microsoft (MS) products such as Word and Excel 2007. The reports have the ability to notify the user if the validation checks on the model are correct or have any errors that could potentially cause a failure. Utilizing active validation, it provides feedback and suggest solutions in real time.
- Solve parametric models – Within the SysML language, certain mathematical expression blocks are created representing a network of reusable constraints. These blocks represent the physical properties of the system to determine cost, schedule, and performance metrics. One of the tools that is used to solve dynamic constraints in system simulations is the Cameo simulation toolkit. This tool tracks and maintains all dependency parameters that the user identifies within the system model. Another tool used is the paramedic plugin that allows trade studies to determine the best alternative to the systems model design. Using the paramedic plugin allows the user to compare models without modifying the original model. The most used input values are MS Excel spreadsheets or sensors.

D. SUMMARY

During this chapter, the concept of MBSE was presented to provide an overview of the capabilities that the process can add to the warfighter. By understanding early in the lifecycle process what are the discrepancies and critical deficiencies of the systems are, the team of engineers can work to reduce the risk and allow for further modifications in a virtual environment prior to going to the test and evaluation phases. From a Program Office perspective, it provides a better grasp of cost, schedule, and performance metrics. Conducting extensive testing in a virtual environment and utilizing this environment through the lifecycle process as a guidance tool, the technical experts can help save costs and reduce risk, ultimately creating more efficient systems and systems of systems.

Furthermore, this chapter outlined the use of tools that will address the processes and procedures to be able to incorporate data from the POSSE engineering tool and Cameo Enterprise Architecture. By utilizing the MBSE concept and utilizing digital thread, the team of engineers can use the information being output from POSSE and transfer that data via digital thread to Cameo providing results on the fundamental question of how the USN can implement MBSE and digital thread to enhance their warfighting capabilities.

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V. DIGITAL ENGINEERING USE CASE SCENARIO, ANALYSIS AND RESULTS

A. INTRODUCTION

To successfully implement MBSE capabilities using a digital thread there is a need within the USN to describe the process to ensure proper reproduction of results. The intent of this chapter will be to outline the MBSE process used between POSSE and Cameo Enterprise Architecture to demonstrate the capabilities of a virtual environment via the digital thread. The chapter will identify the main components used to achieve the results.

B. DIGITAL ENGINEERING USE CASE SCENARIO

The scenario used in this thesis is based on a double hull oil tanker. The scenario consists of an oil tanker that ran aground on a reef just outside the coast of Florida. Within the Cameo Enterprise Architecture, a digital model representation pertaining to the parameters of the oil tanker is assumed to exist, acting as the authoritative source of data basis for the scenario analysis. The system model provides the ship characteristics to POSSE, which then uses the values as inputs to complete the scenario-based analysis. The system model engineer determines the proper parameters that the salvage engineer needs as inputs to POSSE. Using a digital thread implementation, the salvage engineer will retrieve the desired analysis input data from Cameo and complete an analysis. Once the analysis is complete the salvage engineer sends the damage analysis back to the system model engineer to incorporate it in Cameo for archiving, thus providing the digital thread needed to prove that the procedure has been completed as an example of a digital engineering MBSE integration with USN physics-based analysis tools.

C. DESIGNING A CAMEO SHIP STRUCTURE

For the purposes of this thesis Cameo Enterprise Architecture was used for the digital system model. When constructing the model within Cameo the systems requirements, characteristics, and the functions of the model represent the oil tanker. The model acts as the digital twin representation of the oil tanker that will be transferred to

POSSE to allow for an accurate analysis when the information flow starts going from one program to the other.

It all starts with the outline of the architecting process of the oil tanker. Any systems architect can develop the physical system hierarchy in some specific way. The system will have a sub-level system composed of different elements that will have a specific requirement or function within the overall system of systems that can help achieve the mission.

The first step in creating a simple working model in CAMEO to represent the digital twin is to create a ship system model and an outline of a process that represents the scenario for an oil tanker. The model was designed to have a ship structure and behavior relationship. As identified in Figure 8, the model is linked between each section to determine relationships.

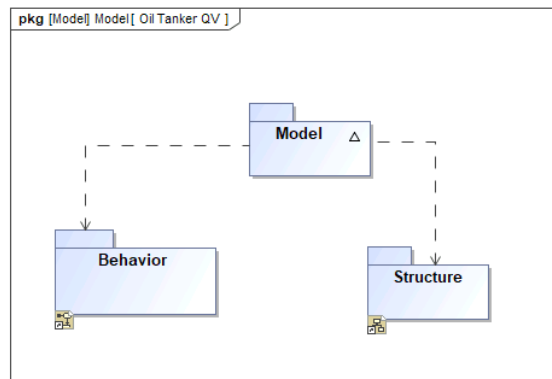


Figure 8. Cameo Model Identification

To visualize a hierarchy of system elements a ship decomposition was created based on the Ship Work Breakdown Structure (SWBS) normally utilized by NAVSEA, in this case for SUPSALV to use as the source of the ship structure. Figure 9 identifies the complete ship decomposition hierarchy of a vessel typically used by naval architects. In Cameo the SysML profile was used to create the SBWS. The SWBS, Figure 9, shows a high-level overview of the oil tanker subsystems which could be developed to the

subassemblies and components based on future capabilities from a ship. For the purposes of this thesis, a two-level hierarchy was deemed sufficient.

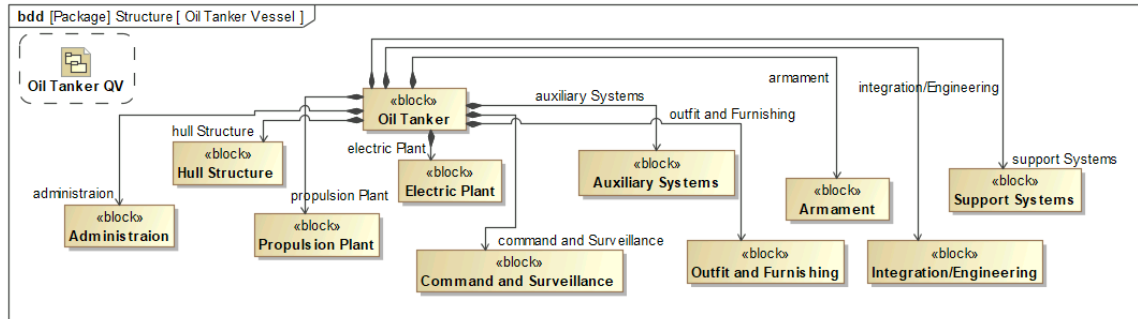


Figure 9. Ship Work Breakdown Structure in Cameo

The main function of the SWBS is to define the hierarchical structure of the ship systems that form the basis of the authoritative source of data in a digital modeling environment. It outlines the physical architecture of the subsystems that fully define an oil tanker. Figure 9 is used as the baseline of the design of the oil tanker and will incorporate up to level two requirements of the system to analyze the data within.

The SWBS was modeled utilizing a block definition diagram within the structure section of the model. At a high level, the block definition diagram makes a complex system understandable by breaking down the components into logical parts where engineers and personnel with working knowledge of Cameo can understand a specific system or subsystem components as a separate element versus looking at all the subsystems at the same time. For the purposes of this thesis, the breakdown structure identified needed to incorporate the pre-loading conditions of the oil tanker prior to being grounded and every thirty minutes until the vessel receives help. For the salvage engineer to be called out to the mission, the Cameo model needs to flag a need to call for assistance of the vessel. In Figure 10, there is an activity diagram that outlines the process of identifying when there is a need to call the salvage engineers.

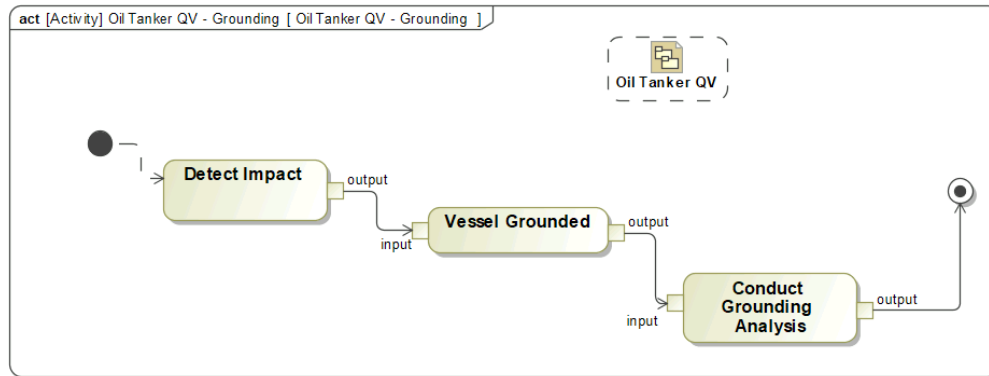


Figure 10. Activity Diagram for the Oil Tanker Grounding Incident

In the activity diagram presented in Figure 10, the scope is limited to a ship, which during the route to unload the cargo, was grounded. In Cameo it is represented by the system detecting an impact, followed by a grounding. By detecting the grounding, a flag was set to the model engineer to do a grounding analysis and to verify if it was satisfactory or not. The model engineer would then manually contact the salvage engineer and would transfer the model specifics to the salvage engineer to outline in POSSE to determine the stability of the oil tanker.

D. DESIGNING A POSSE OIL TANKER

The design process to develop the POSSE oil tanker starts with identifying the ship characteristics and requirements that the vessel needs to have to build a working model. Once the ship model is created the follow-on step will be to create a process where a typical salvage response analysis will be required for a salvage engineer perspective. In the use case scenario, the characteristics and requirements would be provided from the information stored in the Cameo model.

The first thing to do in the POSSE model is to determine the technical specifications for the oil tanker that will be used as the model. Utilizing the specifications outlined in Table 2 will allow for any type of analysis that will be performed to be developed quicker for different analysis types.

Table 2. Oil Tanker Technical Specifications

Particulars Name	Measurements
Length Overall	280.46m
Length Between Perpendiculars	264.00m
Breadth, Molded	24.00m
Depth, Molded	48.00m
Design Draft	16.80m

Once the technical specifications are created the salvage engineer will create the longitudinal references that will be used across the vessel. For this case the vessel reference planes are Aft perpendicular at 0m, at Midship at 132m, and at forward perpendicular at 264m. the numbers established in the reference planes allows to form a reference for the double hull tanker. The reference plane will aid in the definitions of the axis setting where the X, Y, and Z planes will determine the aft perpendicular, the baseline, and the center of the vessel, as seen in Figure 11.

Units	Axis Settings			Headings
	X	Y	Z	
Reference Type	Reference Plane	Reference Plane	Reference Plane	
Reference Plane	AP	BL	CL	
Plane Name	Sections	Waterlines	Buttocks	
Long Positive String (< 8 characters)	Fwd	Above	Stbd	
Short Positive String (1 character)	F	A	S	
Long Negative String (< 8 characters)	Aft	Below	Port	
Short Negative String (1 character)	A	B	P	
Direction Strings Visible?	YES	NO	YES	
Positive Values Entered Are	Fwd	Above	Stbd	
Angle Name	Trim	Heading	Heel	
CG Name	LCG	VCG	TCG	
FS Name	FSI	FSv	FSt	
Moment Name	Lmom	Vmom	Tmom	
Short Axis Name (< 4 characters)	Long.	Vert.	Trans.	
Long Axis Name (< 12 characters)	Longitudinal	Vertical	Transverse	
Stability Item (KM, GM, etc) Suffix	l	v	t	

Figure 11. X, Y, Z Axis Settings

The following step in creating a POSSE model is to create the specific frame table to establish longitudinal data within the longitudinal distances provided above. Defining the ship from Aft to Forward of the vessel, the definition of frames and spacing changes autogenerate the spaces regarding interior frames, as seen in Figure 12.

Reference Planes			Frame Table			
* Name	Long.		From Reference			Edit Frames...
	m-AP		Name	AP	MS	FP
AP	0.000			m	m	m
MS	132.000F		A	45.500	-86.500	-218.500
FP	264.000F		B	66.000	-66.000	-198.000
			C	86.000	-46.000	-178.000
			D	102.500	-29.500	-161.500
			E	119.000	-13.000	-145.000
			F	135.500	3.500	-128.500
			G	152.000	20.000	-112.000
			H	168.500	36.500	-95.500
			I	185.000	53.000	-79.000
			J	201.500	69.500	-62.500
			K	218.000	86.000	-46.000
			M	251.000	119.000	-13.000

Figure 12. Defining the Frame Reference

Once the frames have been defined, the draft marks of the vessel need to be identified. This is the beginning process of identifying the physical aspects that the vessel needs. The next step will be to identify the strength locations of the vessel. In this case the frames are identified as A through H and the location of the frame are in m-AP from the Table 3.

Table 3. Strength Locations

Frame designation	Location of the Frame (m-AP)
A	45.50F
B	66.00F
C	86.00F
D	102.50F
E	119.00F
F	135.50F
G	152.00F
H	168.50F
I	185.00F
J	201.50F
K	218.00F
M	251.00F

After defining the frames of the vessel, the salvage engineer will begin the process of outlining the geometry and hull for the vessel. The hull is defined by using offsets withing the POSSE program to offset the station locations to create a plane view of the

hull. Within the hull geometry the first thing one must do is determine the plate thickness of the structure, for this use case scenario is 22mm thick. Afterwards, the spaces need to be determined to take into consideration the spaces and volumes the vessel will have which will be used in the scenario once the compartments are compromised. The spaces are determined by the offset that was used to define the actual hull shape and volume. An example of station one is shown in Figure 13.

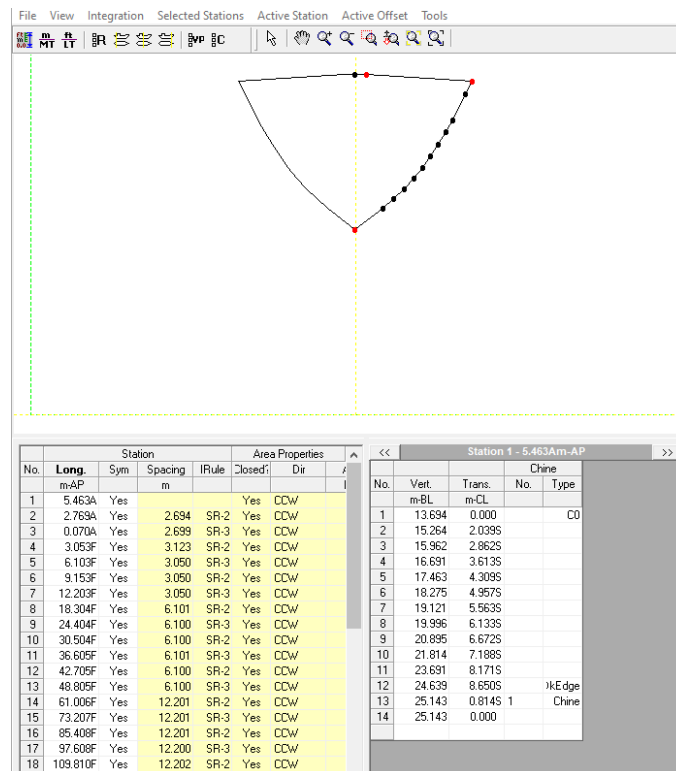


Figure 13. Example Offset for Station 1

The end product of defining the hull is seen in Figure 14.

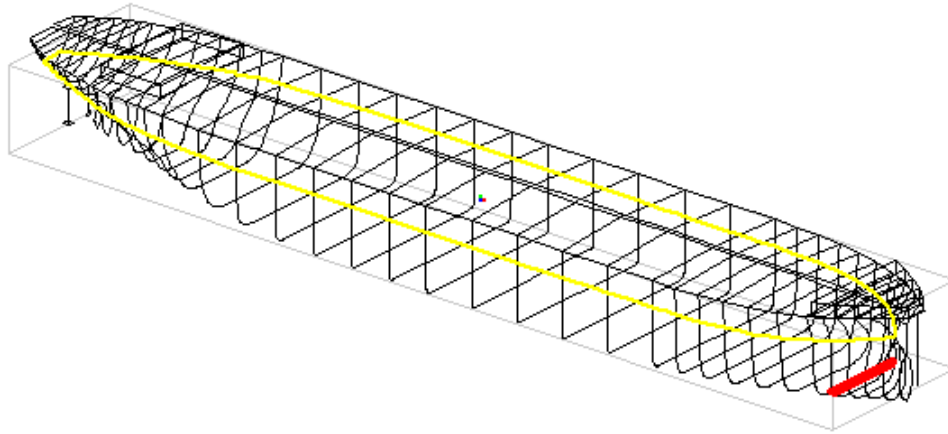


Figure 14. Hull Structure Defined

Once the hull spaces have been identified the next step is to define internal compartmentalization to generate the geometry of the volumes and boundaries of each specific space based on if it is a tank, a void, or an operational space. The compartments can be created the same way the hull was constructed. Utilizing the technical specifications created at the beginning of the exercise for horizontal, vertical, and transverse plane are used in simplifying the volumes that are being generated. The compartments groups that are created are that hold liquids like salt water, fuel, oil, freshwater tanks, and the unassigned compartments that are generally either voids or are compartments that allocate some operational equipment used for the vessel. Depending on the number of compartments within the group, and the number of spaces in the compartment the capacity within is also calculated in this step as seen in Figure 15.

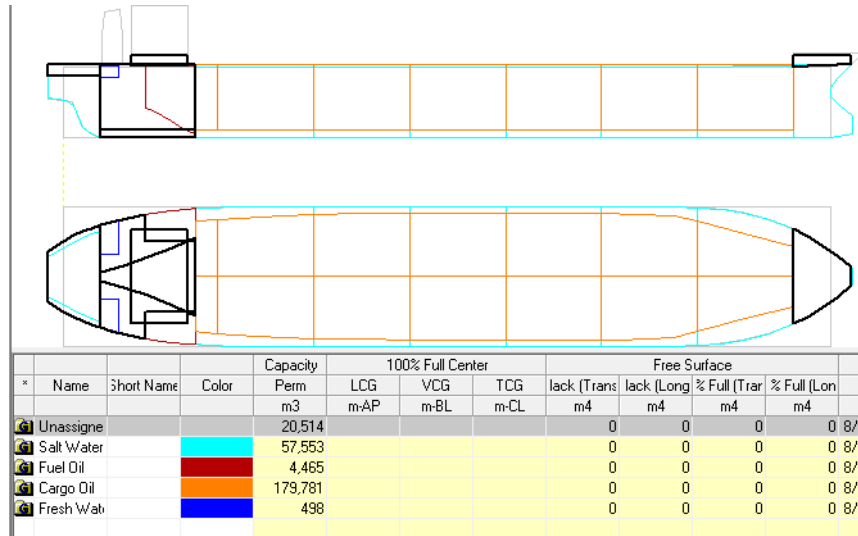


Figure 15. Compartment Spaces

After the compartments are identified, the following step will be to identify the bulkheads. For this example, there are two specific bulkheads that are outlined in port and starboard side. An example of the bulkhead is shown in Figure 16.

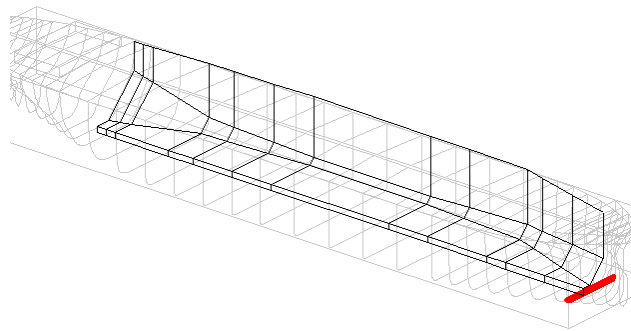


Figure 16. Bulkhead Portside

After creating the bulkhead, the rest of the compartments need to be completed. The compartments that need to be completed are the saltwater tanks, fuel tanks, oil tanks, freshwater tanks, and the undesignated spaces. Note that each type of tank has a different density and permeability as shown in Table 4.

Table 4. Defining Density and Permeability of Tanks

Type	Group Name	Density	Permeability
Salt water ballast tanks	“Salt Water”	1.025 MT/m ³ 0.0286 LT/ft ³	1.0
Fuel oil tanks	“Fuel Oil”	1.0 MT/m ³ 0.0279 LT/ft ³	1.0
Cargo oil tanks	“Cargo Oil”	1.0 MT/m ³ 0.0279 LT/ft ³	1.0
Fresh Water Tanks	“Fresh Water”	1.0 MT/m ³ 0.0279 LT/ft ³	1.0
Void spaces	“Unassigned”	1.0 MT/m ³ 0.0279 LT/ft ³	1.0

The next step of the process is to create the actual loads based on the dimensions of the oil tanker. Things to take into consideration are the overall weight of the ship as well as the weight that will be distributed across the platform. There are two specific types of weight the salvage engineer needs to know: the constant weight and the tank capacity weight. The constant weight is the overall weight that the vessel has in the structure, the specific elements inside of the vessel such as empty tanks, cables, wires, equipment, systems, and other miscellaneous equipment. In the tank capacity the salvage engineer inputs the data of things like weight of the fuel, oil, salt water and other items that might be incorporated for transportation, this will need to be distributed evenly based on the vessel’s metacenter so that no off weight to one side could cause a tilt or affect the center of gravity.

The last step for the POSSE program is to create the tables for intact stability analysis which constitute of Hydrostatic tables, the Bonjean tables and the cross-curve tables to define the trim and stability of the vessel.

E. USE CASE SCENARIO OUTCOME

A use case provides the basis for the oil tanker grounding salvage scenario. An activity diagram was created to demonstrate the interaction between stakeholders to visualize the use case scenario analysis interactions and sequence, as seen in Figure 17.

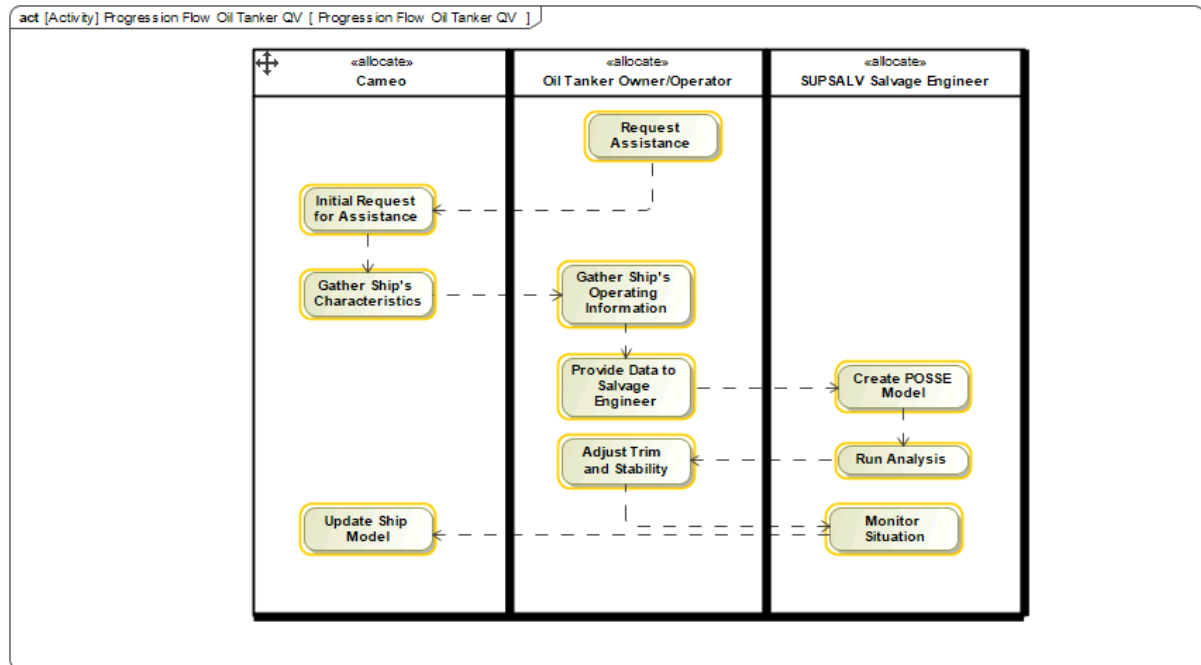


Figure 17. Process Flow Activity Diagram

The use case diagram, Figure 18, shows the stakeholders for this scenario, representing the interactions of the three stakeholders. Based on Figure 10, the activity diagram for the oil tanker grounding incident begins at the time when the vessel is grounded, Cameo (via the modeling engineer) is notified of the incident. Once notified, the vessel owner and engineers are apprised of the situation so the salvage efforts can begin. In reality, the notification event would also include communication to the relevant parties to create the contracts and agreements to put them in place so SUPSALV could start their planning process. The SUPSALV salvage engineer is then provided with the preconditions of the ship to start analyzing trim and stability of the ship. In turn the POSSE analysis outputs would be transferred to the Cameo model engineer to add the results to the model database.

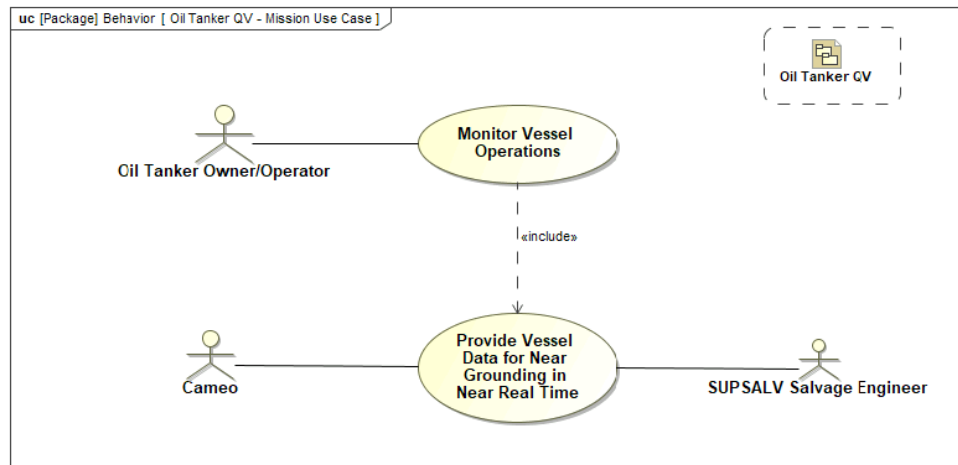


Figure 18. Mission Use Case

The SUPSALV salvage engineer conducts a stability analysis of the oil tanker to see what the damage is and if the structure can survive within the current parameters. From the SUPSALV perspective the most important thing for a salvage engineer to have to begin the analysis is the preexisting condition of the oil tanker immediately prior to departure. Key elements that the salvage engineer needs to know are the weight, draft, and the loading conditions such as draft marks, oil, fuel, or any liquid that can output and cause an environmental damage. The original values for the weights of liquids are outlined in the Figure 19. The original drafts and stability are outlined in the Figure 20.

Group	Weight MT	VCG m-BL	LCG m-AP	TCG m-CL	FSt m-MT
Lightship	22,849	12.960	123.550F	0.000	0
Cargo Oil	152,432	13.299	144.259F	0.000	264,795
Fuel Oil	2,256	13.137	38.754F	0.004S	2,735
Diesel Oil	170	17.986	25.059F	0.392P	88
Lube Oil	66	16.661	30.997F	7.355P	41
Fresh Water	498	22.596	15.807F	0.000	0
SW Ballast	0	--	--	--	0
Misc.	0	--	--	--	0
Constant	300	15.600	237.600F	0.000	0
Displacement	178,572	13.289	139.919F	0.003P	267,659
Deadweight	155,723				
Avail Deadweight	221	--SUMMER--			

Figure 19. Weights of Liquids Oil Tanker

Stability		Trim	
KMt	19.684 m-BL	Specific Gravity	1.0250
VCG (Upright)	13.289 m-BL	LCF Draft	16.781 m
GMt (Solid)	6.396 m	LCF	131.795F m-AP
FS Correction	1.499 m	LCB	139.947F m-AP
GMt (Corrected)	4.897 m	LCG	139.919F m-AP
GMt Required	0.150 m	TP1cm	115.7 MT/cm
GMt Margin	4.747 m	MT1cm	2,110 m-MT/cm
-Min 0.15 Gm-		Trim at Perps	0.023A m
		HeelAngle	0P deg
		Propeller Immersion	230 %
Drafts - Perps		Drafts - Marks	
AP	16.793 m	Aft	16.790 m
MS	16.781 m	MS	16.781 m
FP	16.769 m	Fwd	16.772 m

Figure 20. Draft and Stability Values Oil Tanker

In a real case, a salvage engineer needs to provide a status report every 30 minutes until help arrives on the scene of the incident, based on projections of the tides being plus or minus 2m. The salvage engineer then determines the outflow of the oil and inflow of saltwater to the damage compartments. For the purpose of this scenario, there are three compartments that are compromised on the starboard side, cargo oil tanks No1, No2, and No3 as seen on Figure 21.

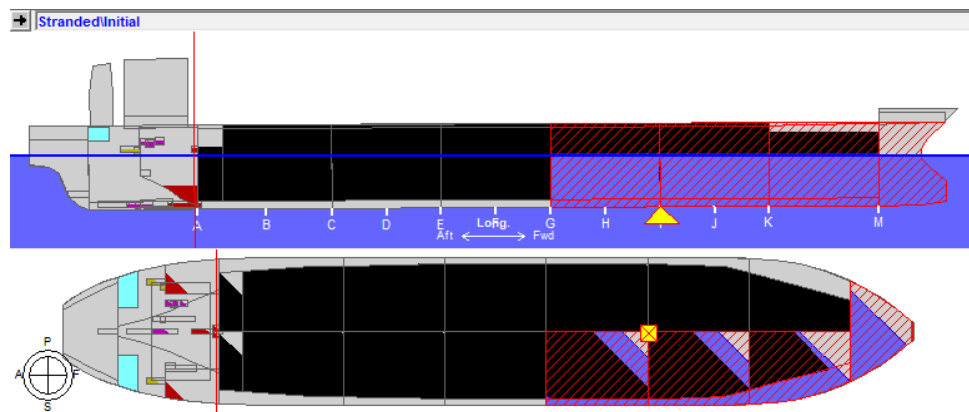


Figure 21. Compartments No1, No2, and No3 Compromised – Initial

The result at day two of awaiting help to be towed to safety is outlined in Figure 22. Note that to keep the vessel stable so it would not capsize, it was determined that the saltwater ballasts on the starboard side need to be used to offset the instability of the ship.

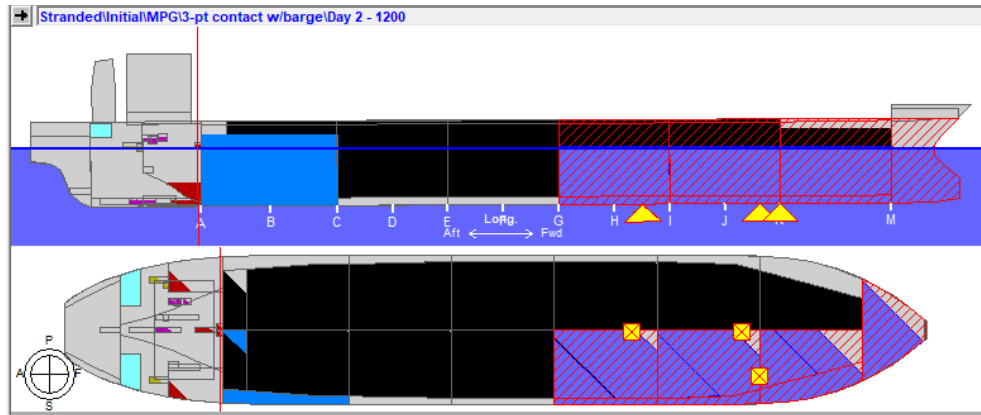


Figure 22. Compartments No1, No2, and No3 Compromised – Day 2 at 1200

The information that was gathered every 30 minutes was exported from an Excel file to send along the digital thread into Cameo. An example of what the spreadsheet can produce is shown in Table 5.

Table 5. POSSE Oil Tanker QV calculations

			Departure	Stranded	Day 1 - 0200	Day 1 - 0230	Day 1 - 0300	Day 1 - 0330	Day 2 - 0200	Day 2 - 0300	Day 2 - 0400
Marks - Aft	m		16.79	16.518	16.072	15.958	15.979	16.056	16.473	16.715	16.879
Marks - MS	m		16.781	16.689	15.334	14.989	14.702	14.475	14.836	14.277	13.885
Marks - Fwd	m		16.772	16.86	14.597	14.019	13.425	12.895	13.199	11.84	10.891
Heel Angle	deg		0P	0P	2S	0P	2P	4P	1S	3P	5P
Trim at Perp	m		0.023A	0.451F	1.947A	2.559A	3.372A	4.171A	4.322A	6.434A	7.905A
Tide Height	[D]	m	---	---	0	-0.518	-1	-1.414	-1	-2	-2.732
**Weight by Group											
Cargo Oil	MT		152,432	152,432	152,432	141,078	139,894	138,503	131,363	131,097	130,832
Fuel Oil	MT		2,256	1,195	1,195	1,195	1,195	1,195	1,195	1,195	1,195
Diesel Oil	MT		170	170	170	170	170	170	170	170	170
Lube Oil	MT		66	66	66	66	66	66	66	66	66
Fresh Water	MT		498	498	498	498	498	498	498	498	498
SW Ballast	MT		0	0	0	0	0	0	2,460	2,665	2,870
Misc.	MT		0	0	0	0	0	0	0	0	0
Constant	MT		300	300	300	300	300	300	300	300	300
Draft AP	m		16.793	16.464	16.308	16.268	16.388	16.561	16.997	17.495	17.837
Draft FP	m		16.769	16.915	14.361	13.709	13.016	12.39	12.675	11.06	9.932
Draft MS	m		16.781	16.689	15.334	14.989	14.702	14.475	14.836	14.277	13.885
GMt	m		4.897	4.915	3.216	3.128	2.866	2.703	2.857	2.665	2.444
KMt	m		19.684	19.691	19.949	20.059	20.187	20.316	20.201	20.54	20.845
LCB	m-AP		139.947F	139.996F	138.243F	137.589F	136.597F	135.549F	135.275F	132.398F	130.194F
LCF	m-AP		131.795F	131.855F	112.649F	112.714F	112.631F	112.525F	112.084F	111.830F	111.648F
LCF Draft	m		16.781	16.689	15.477	15.176	14.95	14.783	15.162	14.769	14.494
LCG	m-AP		139.919F	140.531F	142.960F	142.254F	141.513F	140.847F	140.721F	138.947F	137.636F

The POSSE salvage engineer sends this data to the Cameo model engineer to store it within the Cameo database. The Cameo model engineer in turn, would then add the specific files into the database, depending on how they have structured the data storage of

information. An example of the process as modeled is shown in Figure 23, with the Cameo model engineer accepting the spreadsheet of values taken from POSSE as part of the “Conduct Grounding Analysis” action, thus completing the digital thread.

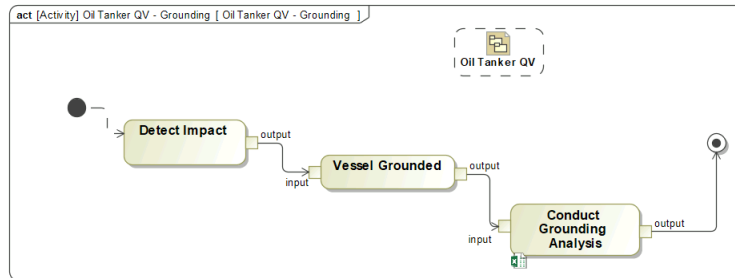


Figure 23. Cameo Data Entry for Use Case Oil Tanker Scenario

An example of the finished process is shown in Figure 24. The model can receive the data in many different file formats, including Word, Excel, and PDF.

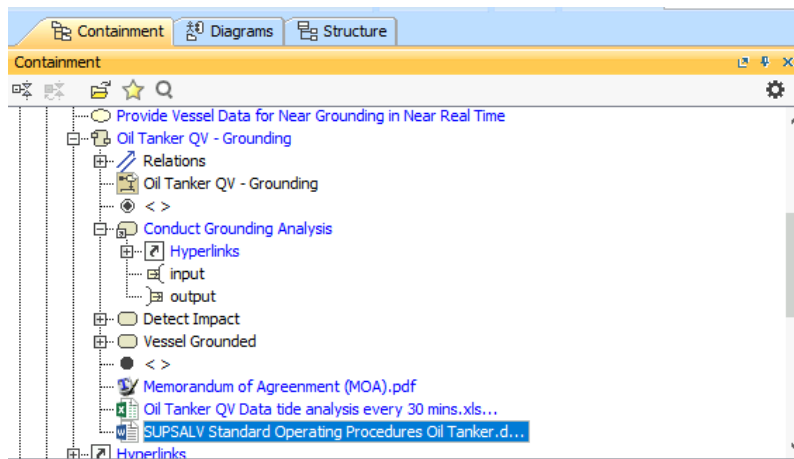


Figure 24. Cameo Embedded Documents Example

F. CURRENT LIMITATIONS

One current limitation of this simple use case scenario is in part the lack of a complete ship model in Cameo. With in-depth knowledge of the specific vessel that is modeled in Cameo, a ship systems engineer would be able to have a full operational digital

ship that can provide the depth of information required to for any type of external physics-based analysis. For example, by modeling a ship down to the component level, you could add information to the authoritative source of data that forms a comprehensive digital twin. For example, if planned maintenance scheduled (PMS) digital data were available, and a subsystem is not working, maybe a pump system that would be critical in a salvage operation, that would be noted to the salvage engineer to consider in their real-time situational analysis of a grounding event. Furthermore, the current use case scenario does model an integrated and automated data exchange where once the information is made available, the model can be added to or adjusted without the need of the model engineer to directly intervene as part of the process.

In this use case scenario, there were no requirements documented in the Cameo digital ship model. For future studies, if specific ships requirements were outlined, such as specific speed on impact, and fuel consumption from departure to initial contact, this could help provide a better picture of the scenario at hand. The departure statistics are the data used to determine initial damage in the scenario vice calculating distance from departure and the fuel rate of consumption up to that time.

G. SUMMARY

This chapter outlined a digital engineering process with a systems model in Cameo connected to SUPSALVs physics-based engineering tool, POSSE. The systems architecting process from POSSE was used in the definition of the processes Cameo oil tanker needed to be created. The information that built POSSE and its digital twin concept via Cameo were performed based on the same information provided on both tools in consideration of ships characteristics, utilizing a surrogate authoritative source of data or truth perspective. This process is intended to be integrated in the front end of the USN vessel engineering process to have the POSSE model and the digital model concept created at the same time before a damage assessment is required. By utilizing resources ahead of time, it can cut down on the process time across the analyses.

VI. CONCLUSION AND AREAS OF FURTHER STUDIES

The final chapter provides the conclusion of this thesis as well as areas of further considerations.

A. CONCLUSION

The goal of this thesis was to demonstrate a portion of the technical part of a digital engineering transformation, specifically for SUPSALV as a part of NAVSEA utilizing the legacy POSSE program.

First, this thesis demonstrated an integrated process that forms a potential basis for enabling a digital engineering MBSE approach for SUPSALV. A ship was modeled in appropriate perspectives, at the systems level in Cameo and at the detailed design level in POSSE outlining a specific approach needed for salvage engineering efforts in a digital engineering tool environment.

Second, this thesis demonstrated a digital thread between Cameo and POSSE. The most important part of implementing a digital thread between both engineering tools is creating a consistency between the digital models – the Cameo system model and the POSSE physics-based analysis model – so that you have a true bearing on what you will be sourcing from a Cameo system model data foundation to and from the POSSE salvage engineering tool.

Third, this thesis demonstrated a basic use case for a diving and salvage operation scenario via a digital thread implementation.

The digital thread implemented does have some real-life limitations, in that the information transfer and use is not implemented in fully integrated and automated sense. There is a human aspect of being able to complete the connection between each specific system tool as the humans provide the ability to reason about the model aspects to make decisions about what to do as the dynamic situation emerges and changes. Through the study it was evident that the system currently does not have the potential to be fully "autonomously" implemented such that the Cameo simulation can automatically conduct

communications and analysis with the salvage engineer experts. It requires a systems model engineer working on Cameo to be able to provide that message to a salvage engineer to run analysis within the POSSE system tool. This is something that could potentially improve over time as the digital transformation moves forward. A working digital process scenario was completed and successful regardless of not being fully automated.

The continued development of MBSE and digital twin will help provide the DON the ability to plan and implement the digital transformation processes and procedures not to just SUPSALV, but to the Fleet when it comes down to Navy's vessels, systems, systems of systems, and combat systems. This will greatly impact the way the Navy operates and conducts operations within the architecting processes.

B. RECOMMENDED AREAS OF FURTHER STUDIES

The process outlined in this thesis just scratched the surface about implementation of MBSE processes and digital engineering aspects that can provide value for the DON. It provided a basis for the creation of a digital thread, insights on the basis for a digital twin used for damaged operation incidents, and a foundation on what digital transformation capabilities could provide the fleet to expand the Navy's operational advantage.

To aid in the digital twin concept multiple models were built in SysML diagrams across Cameo. The models were based on working knowledge of the SUPSALVs ship's structure. Even though multiple types of models were used in this thesis, one key takeaway about this scenario is that it opens the door to a detailed version of a ship. For example, currently the USN SUPSALV team possesses POSSE representations of all class ships within the USN arsenal. This is key into having a functional digital twin in a digital transformation environment. This thesis can potentially be expanded in Cameo as a full ship representation on more than three levels of the structure, potentially a full working USN vessel with all the systems and systems of systems.

The development of the overall integration and implementation of SUPSALV analysis and responsiveness in both developmental and operational capabilities would allow for faster and more integrated data-based decisions that could also be used as a secondary check for salvage engineers. To expand on this thesis, it is recommended that

SUPSALV engineers take a proactive approach in determining the overall benefits to integrating Cameo with POSSE. Cameo can be used to keep information for future use as well as keeping documentation in a centralized database that can serve as both an authoritative source of data and a digital twin. For example, within the digital twin you could have specific planned maintenance schedule (PMS) requirements known so salvage engineers would know the current status as to, for example, when the last time specific systems from the damaged areas were last maintained.

The process could also provide all the preexisting conditions of ships in the USN inventory. For example, having a place to house the pre-existing conditions regarding oil, fuel, weight, saltwater tanks, freshwater tanks, and other liquids prior to an actual incident would be a game changer for the SUPSALV community. In a real-world scenario, it is very difficult for the SUPSALV engineers to have an accurate representation of the initial preconditions due to the fact that it is not tracked outside of the vessel's logs. When an actual vessel gets damaged, runs aground, or has any hull integrity damage, the salvage engineers must go with an average calculation of the hull type until any response can be received from the vessel in distress.

The creation of preexisting hull specific structures as an authoritative source of truth as a digital twin in Cameo would allow a rapid turnaround time when called upon a heavy lift and salvage operation since they would only need to account for the specifics of the POSSE real time calculations. By creating further models representing the systems and systems of systems would allow for further data analysis from POSSE.

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