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UNMANNED SURFACE VESSEL LIFECYCLE SUSTAINMENT ENGINEERING INVESTIGATION

Berger, Michael L.; Chan, Aaron; Gomez, Patricia; Kutsunai, Jonathan K.; Navarrete, Nathaly D.

Monterey, CA; Naval Postgraduate School

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NAVAL POSTGRADUATE SCHOOL

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SYSTEMS ENGINEERING CAPSTONE REPORT

UNMANNED SURFACE VESSEL LIFE CYCLE SUSTAINMENT ENGINEERING INVESTIGATION

by

Michael L. Berger, Aaron Chan, Patricia Gomez,
Jonathan K. Kutsunai, and Nathaly D. Navarrete

December 2023

Advisor: Douglas L. Van Bossuyt
Second Reader: Donald Muehlbach

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Unmanned systems are quickly evolving capabilities that U.S. military services are pursuing to meet military needs. The Department of the Navy requires unmanned surface vessels (USV) to be forward deployed to accommodate tactical and operational needs. These USVs will not generate cost-effective capabilities if they cannot be sustained effectively outside of continental United States (OCONUS), thus this report provides recommendations to be used in USV life cycle sustainment planning to ensure that USVs can accommodate the Fleet's tactical and operational needs. To ensure USVs are sustainable OCONUS, requirements were categorized according to mission needs, personnel, cost mitigation, training, and programmatic sustainability. Magic System of Systems Architecture was then used to generate a back-of-the-envelope model to output materiel availability (A_M) and operational availability (A_O) to verify the outputs of a more detailed ExtendSim model. Simulation and analysis concluded the primary factor affecting USV availability rates is the availability of corrective maintenance. Decreasing access to corrective maintenance facilities also initiated a cascading effect, leading to backlogs throughout the USV sustainment and deployment cycle. The finding concluded that corrective maintenance of USVs throughout their sustainment and deployment cycle should be prioritized.

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Michael L. Berger, Aaron Chan, Patricia Gomez,
Jonathan K. Kutsunai, and Nathaly D. Navarrete

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Lead Editor: Patricia Gomez

Reviewed by:
Douglas L. Van Bossuyt — Advisor
Donald Muehlbach — Second Reader

Accepted by:
Oleg A. Yakimenko
Chair, Department of Systems Engineering

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ABSTRACT

Unmanned systems are quickly evolving capabilities that U.S. military services are pursuing to meet military needs. The Department of the Navy requires unmanned surface vessels (USV) to be forward deployed to accommodate tactical and operational needs. These USVs will not generate cost-effective capabilities if they cannot be sustained effectively outside of continental United States (OCONUS), thus this report provides recommendations to be used in USV life cycle sustainment planning to ensure that USVs can accommodate the Fleet's tactical and operational needs. To ensure USVs are sustainable OCONUS, requirements were categorized according to mission needs, personnel, cost mitigation, training, and programmatic sustainability. Magic System of Systems Architecture was then used to generate a back-of-the-envelope model to output materiel availability (A_M) and operational availability (A_O) to verify the outputs of a more detailed ExtendSim model. Simulation and analysis concluded the primary factor affecting USV availability rates is the availability of corrective maintenance. Decreasing access to corrective maintenance facilities also initiated a cascading effect, leading to backlogs throughout the USV sustainment and deployment cycle. The finding concluded that corrective maintenance of USVs throughout their sustainment and deployment cycle should be prioritized.

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LIST OF ACRONYMS AND ABBREVIATIONS

A_M	Materiel Availability
A_O	Operational Availability
APB	Acquisition Program Baseline
ASUW	Anti-Surface Warfare
BOE	Back-of-the-Envelope
BSA	Battle Space Awareness
C4I	Command, Control, Communications, Computers, Intelligence
CBM+	Condition-Based Maintenance Plus
CDD	Capabilities Development Document
CM	Configuration Management
CMAV	Corrective Maintenance Availability
CMBD	Configuration Management Database
CNO	Chief of Naval Operations
ConOps/CONOPS	Concept of Operations
CRS	Congressional Research Service
DAS	Defense Acquisition System
DMO	Distributed Maritime Operations
DOD	Department of Defense
DON	Department of the Navy
DSOR	Depot sources of repair
EMI	Energy, matter, and information
EW	Electronic Warfare
FDNF	Forward Deployed Naval Forces
FOC	Full Operating Capability
FPR	Final Progress Review
FY	Fiscal Year
IMS	Integrated Master Schedule

IPR	Interim Progress Review
IPS	Integrated Product Support
ISEA	In-Service Engineering Agent
IRB	Institution Review Board
ISR	Intelligence, Surveillance, and Reconnaissance
IWS	Integrated Warfare Systems
JCIDS	Joint Capabilities Integration and Development System
JROC	Joint Requirements Oversight Council
KPP	Key Performance Parameter
KSA	Key System Attribute
LCS	Littoral Combat Ships
LCSP	Life Cycle Sustainment Plan
LUSV	Large Unmanned Surface Vehicle
MBSE	Model Based System Engineering
MIP	Master Integrated Program Schedule
MOE	Measure of Effectiveness
MOP	Measure of Performance
MPSF	Mission Package Support Facility
MRC	Maintenance Requirement Card
MS	Microsoft
MSOSA	Magic Systems of Systems Architect
MSSE	Master of Science in Systems Engineering
MTBF	Mean-Time Between Failures
MTBM	Mean-Time Between Maintenance
MTBPM	Mean-Time Between Preventative Maintenance
MTD	Maintenance Downtime
MUSV	Medium Unmanned Surface Vehicle
MOS	Military Occupational Specialties
M&S	Modeling and Simulation

NAVSUP	Naval Supply System
NIWC	Naval Information Warfare Center
NDAA	National Defense Authorization Act
NOSSA	Naval Ordinance Safety & Security Activity
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
O-Level	Organizational Level
OCONUS	Outside of Continental United States
OFRP	Optimized Fleet Response Plan
OMS/MP	Operational Mode Summary/Mission Profile
PEO	Program Executive Officer
PHD	Port Hueneme Division
PM	Preventative Maintenance
PMAV	Preventative Maintenance Availability
PMS	Planned Maintenance System
PoR	Program of Record
PV	Present Value
RMC	Regional Maintenance Center
SURNDEVRON-1	Surface Development Squadron One
SysML	System Modeling Language
TOS	Time-on-Station
TYCOM	Type Commanders
UAV	Unmanned Aerial Vehicle
USN	United States Navy
USV	Unmanned Surface Vessel
USVDIV-1	Unmanned Surface Vessel Division One
UUV	Unmanned Underwater Vessel
UVC	Unmanned Vehicle Carrier
UxS	Unmanned Systems

UxV	Unmanned Vessels
VLS	Vertical Launch System
WFC	Warfare Center
WSESRB	Weapon System Explosives Safety Review Board
XLUUV	Extra-large Unmanned Undersea Vehicles

EXECUTIVE SUMMARY

In 2007, the Department of the Navy initiated the integration of Unmanned Systems (UxS) to the fleet, including unmanned surface vessels (USVs) (Department of the Navy 2007). To ensure that USVs are sustainable in a cost-efficient manner, a USV Life cycle Sustainment plan must be drafted to guide USVs' development and Fleet introduction. This report provides recommendations to be used in USV life cycle maintenance and sustainment planning to ensure that USVs can accommodate the tactical and operational needs of the Fleet. Life cycle "encompasses the entire system's life cycle: acquisition (design, develop, test, produce and deploy), sustainment (operations and support), and disposal." (Office of the Assistant Secretary of Defense for Sustainment 2014). As USVs are integrated into the Fleet, a maintenance analysis is required, as manned vessel's maintenance concepts rely on onboard sailors performing preventative and corrective maintenance actions that must be performed radically different on USVs.

A systems engineering approach based off the systems engineering Vee model was used to capture the sustainment activities, actors, and infrastructure involved in USV sustainment. As the Joint Capability Integrated Development System (JCIDS) process requires that capabilities documents include Sustainment key performance parameters (KPPs), (operational availability (A_O), materiel availability (A_M)) the sustainment KPPs and maintenance cost were selected as Measures of Effectiveness (MOEs) to judge the USV maintenance architectures against.

USV sustainment infrastructure required capabilities were derived from a variety of sources. A plan to implement these capabilities was captured in a USV logistics strategy, focusing on maintenance concepts. The strategy calls for an increased level of Condition Based Maintenance Plus (CBM+) as USVs will not have preventative maintenance performed while underway. This lack of preventative maintenance will blur the line between preventative maintenance availabilities (PMAVs) and corrective maintenance availabilities (CMAVs) that are traditionally separate availability periods scheduled according to each vessel's Optimized Fleet Response Plan (OFRP). It was determined that requiring additional preventative maintenance while not underway may increase USV maintenance facility utilization. Stakeholder needs were researched and brainstormed and use cases were developed to ensure all USV sustainment activities were captured. The as is sustainment infrastructure, use cases, and stakeholder needs were then traced to USV sustainment infrastructure requirements and these relationships were captured in Magic System of Systems Architecture (MSOSA), a Model-based Systems Engineering tool.

Requirements were categorized according to mission needs, personnel, cost mitigation, training, and programmatic sustainability. Each requirement was allocated to an activity to be performed to ensure the requirement could be met. These activities were then allocated to sustainment infrastructure actors and systems that must perform them. The Integrated Product Support (IPS) guidebook was used as a source for many of the activities that actors must perform pre-USV fielding.

MSOSA was also used to generate a back-of-the-envelope (BOE) model to output A_M and A_O to verify the outputs of a more detailed ExtendSim model. ExtendSim provided simulation capabilities for multiple USVs over time, allowing for USV processing and queuing to generate availability and cost data which was analyzed. Excel was used to generate input values for the ExtendSim model and to perform data analysis on the output data.

The ExtendSim model begins with USVs being created over time according to a USV fielding schedule. The USVs, upon returning from deployment, go to a depot/maintenance facility to receive preventative maintenance, corrective maintenance, or overhaul depending on the time since each of these activities occurred. These activities require an available maintenance bay, parts, and personnel.

A fractional factorial design of experiments (DOE) was used to generate alternative input configurations for the outside continental United States (OCONUS) maintenance facilities. Configurations tested were designed to cover a wide range of values, to determine where the sustainment system becomes stressed (meaning the system outputs a low A_m and A_O) as factors are varied.

Multiple ExtendSim simulations revealed that the primary factor affecting USV availability rates is the availability of corrective maintenance. Decreasing access to corrective maintenance facilities initiated a cascading effect, leading to backlogs throughout the USV sustainment and deployment cycle. The outcomes of multiple ExtendSim simulations highlight the pivotal role of corrective maintenance availability in influencing the USV sustainment life cycle and deployment. While the impact of decreased maintenance availability on USV availability rates was found to be minor, the overall finding highlights the importance of prioritizing corrective maintenance of USVs throughout their sustainment and deployment cycle.

To expand on this project, future work can include using real numbers for average time to perform corrective and preventative maintenance, as well as real cost data. The model could be validated against maintenance costs and facility needs for existing ship classes. Additionally, the model could be modified as necessary until it accurately predicts historical results when provided with historical input data. Furthermore, the model could be utilized to output expected USV A_M and A_O to see if it meets the parameters in the USV CDD. Additional maintenance concepts and more detailed models could be implemented to see their effects on A_M and A_O.

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Department of the Navy. *The Navy USV Master Plan.* Washington, DC: The Department of the Navy, 2007. https://apps.dtic.mil/sti/pdfs/ADA504867.pdf

Office of the Assistant Secretary of Defense for Sustainment. "Life Cycle Logisitics Workforce Development." Accessed April 23, 2023. https://www.acq.osd.mil/log/PS/Life_Cycle_LW_Development.html#:~:text=Life%20Cycle%20Logistics%20(LCL)%20is,(operations%20and%20support)%2C%20and

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I. INTRODUCTION AND TEAM OVERVIEW

The United States Navy is a major branch of the United States armed forces and is in charge of defending American interests and Allies through sea support. Moreover, the United States Navy's (USN or Navy) mission is to "defend American interests around the globe" (U.S. Navy Office of Information n.d.). To achieve this goal, the USN requires operational ships with military personnel manning various onboard systems for mission operations. There is a wide range of the resources required to accomplish the goal since "Navy ships combine a complex array of equipment and systems, ranging from propulsion to combat systems to electronics to food preparation" (Martin, et al. 2018, ix). The USN sends different types of warships strategically across the globe, broken up into various Fleets, which is a large formation of warships "under a single command" (Merriam-Webster Dictionary n.d.). The USN has seven numbered Fleets across the globe conducting daily mission operations. To facilitate this undertaking, various activities take place to maintain USN ships' operational capabilities and mission readiness. Providing ongoing maintenance is one of the strategies the USN undertakes to keep warships sustainable for years. To do this, the USN uses maintenance facilities in place on American soil but also Outside the Continental United States (OCONUS). Facilities are therefore set in place to provide services to USN assets without the need to return to home soil, especially in the case of critical repairs. In summary, the life cycle maintenance for USN systems and equipment is meant to strategically maximize the life of the equipment while minimizing cost and schedule delays.

To accomplish the USN mission, the Navy depends on military personnel to operate and maintain various warships while onboard. In 2007, the Department of the Navy initiated the integration of Unmanned Systems (UxS) to the Fleet (Department of the Navy 2007). The Navy plans to use UxS to accomplish tasks without endangering sailors' lives, increase efficiency, and expand defense capabilities in the maritime environment. UxS can be made to have minimal personnel onboard, be controlled remotely, or be developed to be fully autonomous. Additionally, UxS are versatile, as they can be implemented in the air, land, water surface, or underwater domains. As this new unmanned capability is integrated with a historically manned surface Navy, a maintenance analysis is required, as it alters how the USN conducts maintenance.

As part of the capstone project for the Master of Science in Systems Engineering, this report is intended to provide recommendations to be used in the Life Cycle Support Plan (LCSP) and maintenance concept of operations to accommodate tactical and operational needs of the Fleet. Parts of the systems life cycle include "the entire system's life cycle: acquisition (design, develop, test, produce and deploy), sustainment (operations and support), and disposal" (Office of the Assistant Secretary of Defense for Sustainment n.d.a.). By utilizing current USN processes to support ships with payloads, the unmanned surface vessel (USV) Sustainment Capstone team can analyze the existing processes to model and map a future USV life cycle. Further, the USV Sustainment Capstone team could analyze existing USN support processes to model and map notional required support processes as part of the USV life cycle. For example, by looking at the support provided by the Mission Package Support Facility (MPSF) and annex facilities, the USV Sustainment Capstone team can account for aspects of the life cycle to include processes for repair/replacement, OCONUS personnel support, warehousing, and training utilized worldwide to effectively conduct missions. Establishing the infrastructure based on existing Navy and Department of Defense (DOD) life cycle processes while leveraging existing structures, may allow for a systematic life cycle plan that both satisfies stakeholder requirements and completes the mission.

A. USV TEAM

To analyze and propose recommendations for life-cycle sustainment and maintenance of OCONUS USVs, the USV Sustainment Capstone team took a systematic approach of defining the team, responsibilities, stakeholders, and the needs and requirements that had to be met. The USV Sustainment Capstone team members are listed in Table 1, along with their current work organization.

Table 1. USV Sustainment Capstone Team Members and Work Organization

Team Member	Work Organization
Michael Berger	NIWC Pacific, 53433 Afloat Enterprise Engineering Branch
Aaron Chan	NSWC PHD, E56 Evolved SeaSparrow Missile All Up Round Branch
Patricia Gomez	NSWC PHD, E73 Cooperative Engagement Capability Branch
Jonathan Kutsunai	NSWC PHD, E56 Evolved SeaSparrow Missile All Up Round Branch
Nathaly Navarrete	NSWC PHD, D53 Total Ship Computing Systems Branch

The USV Sustainment Capstone team assigned roles and responsibilities. Each team member was assigned a primary and secondary role. Each team member will additionally assist in completing tasks outside their primary and secondary roles as needed. Assigned roles can be seen in Table 2 and Figure 1.

Table 2. USV Sustainment Capstone Team Role Assignments

Role	Primary Role	Secondary Role
Chairperson/Project Manager	Nathaly Navarrete	Michael Berger
Scheduler	Jonathan Kutsunai	Aaron Chan
Configuration Manager/ Editor	Patricia Gomez	Jonathan Kutsunai
Architect/Model Based System Engineering (MBSE)	Michael Berger	Patricia Gomez
Data Analysis	Aaron Chan	Nathaly Navarrete

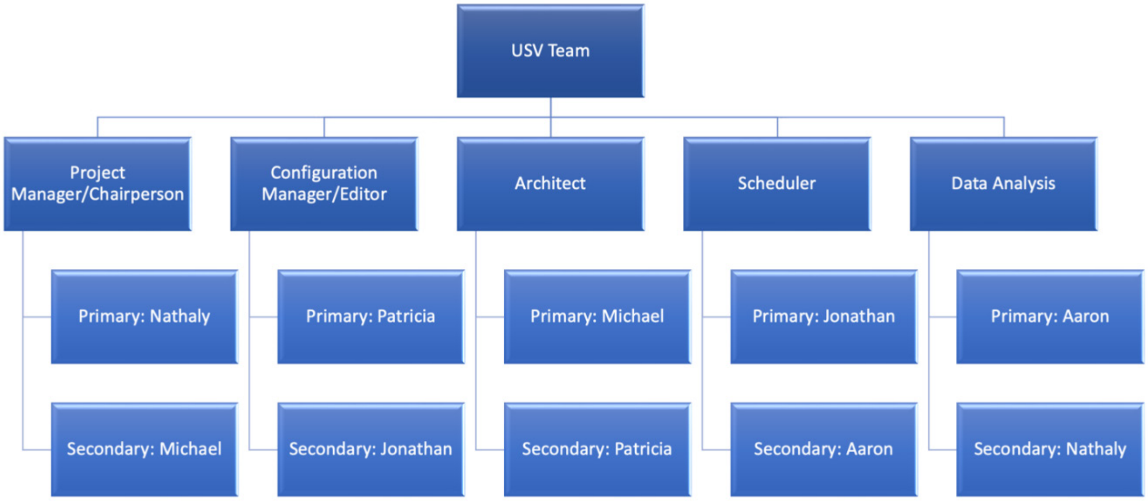

Figure 1. USV Sustainment Capstone Team Organization Structure

Table 3 provides the responsibility descriptions for each identified role in the USV Sustainment Capstone team.

Table 3. USV Sustainment Capstone Team Roles and Responsibilities

Roles	Responsibilities
Chairperson/Project Manager	The Chairperson / Project manager has responsibilities such as: • Communicating with the project sponsors • Setting up internal and external meetings • Managing risks
Scheduler	The Scheduler has responsibilities such as: • Creating and managing the Integrated Master Schedule (IMS) • Verifying that events are occurring on schedule and providing status to the project manager
Configuration Manager/ Editor	The Configuration Manager/Editor has responsibilities such as: • Keeping version control of deliverables and reports • Storing sources and ensuring information is properly referenced • Editing of deliverables which include reviewing, rewriting, and editing the work of team members.
Architect/MBSE	The Architect/MBSE has responsibilities such as: • Developing and maintaining an MBSE model to include context diagrams, black box diagrams, white box diagrams, functional architecture, and physical architecture • Lead development of the concept of operations (CONOPS)

Roles	Responsibilities
Data Analyst	The Data Analyst has responsibilities such as: • Performing simulation studies • Developing back of the envelope models • Developing detailed simulation models • Analyzing results of simulation studies

B. PROJECT STATEMENT/ STATEMENT OF NEED

The 2022 Chief of Naval Operations (CNO) Navigation Plan states, "In the 2040s and beyond, [the Navy] envision [s] [a] hybrid Fleet to require about 150 large unmanned surface and subsurface platforms" (United States Navy Chief of Navy Operations 2022, 10). The Department of the Navy (DON) anticipates adding over 150 USVs by 2045 to the Navy Surface Fleet (United States Navy Chief of Navy Operations 2022, 10). The DON requires the USVs to be forward deployed to accommodate tactical and operational needs.

According to the DON, the challenge to define the end operations environment will:

- Advance a culture of learning to broaden and deepen knowledge.
- Advance a culture of adaptation for continuous improvement.
- Maximize teamwork to align investments, reuse and development of capabilities, and interoperability of all analytic data.
- Utilize analysis, experimentation, and feedback loops to drive lethality.
- Focus on providing total solutions to include enablers and not only platforms.
- Scale subsystems, prototypes, and technologies that have been tested and proven.
- Strengthen relationships with stakeholders and build solutions for emerging needs. (Department of the Navy 2021, 23)

C. STAKEHOLDERS

The big picture stakeholders identified for the USV sustainment capstone project are listed in Table 4 and grouped together by respective category. An overview of how the stakeholders were initially identified is discussed further in Chapter II Section B.

Table 4. USV Big Picture Stakeholders

Category	Stakeholders
Fleet	
	Operational Commanders
	TYCOM
	Non-USV Warfighters
	Surface Development Squadron One (SURFDEVRON-1)
	Unmanned Surface Vessel Division One (USVDIV-1)
Government Maintainers	
	Sailor Maintainers
	Regional Maintenance Centers (RMCs)
	Warfare Center (WFC) In-Service Engineering Agents (ISEAs)
	Forward Deployed Maintenance Facilities
	Navy Supply Systems Command (NAVSUP)
Industry Partners	
	Vessel Shipbuilders
	Payload Vendors
	Depot Maintainers
Program Office	
	USV / Payload Program Offices
	Resource Sponsors

As determined by reviewing references and documentations, the specific objectives for this project are to:

- Develop recommendations for USV specific needs to supplement the USV program office efforts to create a LCSP for vessels, to include their embarked payload using current Navy processes.

- Determine how the Unmanned Program can leverage existing DOD infrastructure.
- Determine the process for repair/replace OCONUS sustainment to include maintenance such as repair and replacement, personnel support, warehousing, training, and cost.

D. PROJECT ASSUMPTIONS AND CONSTRAINTS

1. Assumptions

The following initial assumptions were made by the USV Sustainment Capstone team:

- Approximately 100 USVs will enter service within the next 10 years. This will affect the required number and size of support facilities and sustainers and gives a reasonable data point for an accurate output.
- USVs will need to be forward deployed to accommodate tactical and operational needs and will be required to maintain a similar operation tempo to the rest of the surface fleet (O'Rourke 2023.b). Reasonable to assume that to maintain a similar tempo, similar operations must be conducted.

2. Constraints

To minimize rework and sustainment costs, current USN processes were utilized for the USV sustainment infrastructure design. Constraints include OCONUS travel for humans and cargo since OCONUS travel is on existing and coordinated schedules to maximize returns and deliveries. Additionally, OCONUS travel can be limited if air travel is not deemed safe for transport as alternative methods such as ship riding affects the schedule and cost due to delays. This impacted inventory shipments, spares, ISEAs, and refurbished systems/subsystems, etc., that are coming into these facilities, as well as constraints in shipping back defective units, parts, spares, etc., that either need refurbishment or specified destruction. The USVs in this project will be forward deployed so facilities are identified that can support/maintain them in terms of dockside power, storage for classified materials, port/base security, the machinery and capabilities to transport the USV to be worked on, and the tools to perform maintenance and repair summarized in Figure 2.

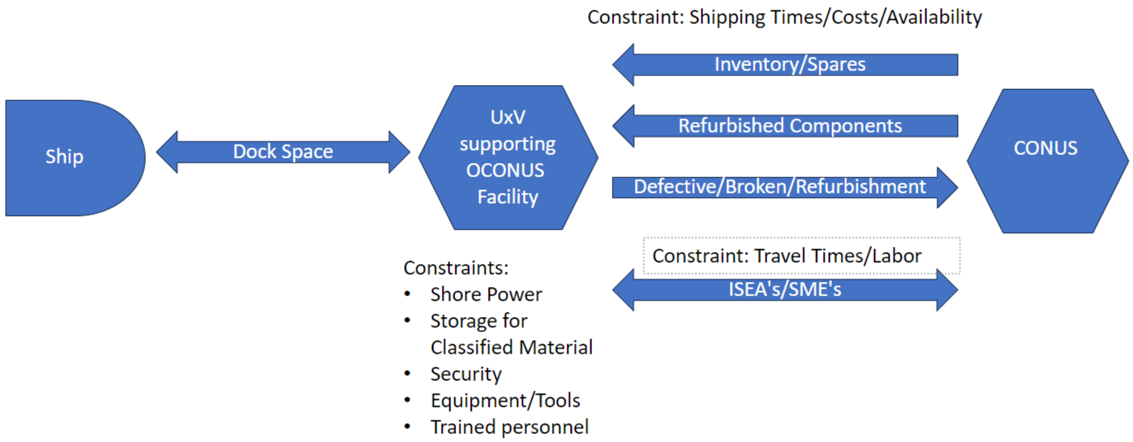

Figure 2. USV Sustainment Summarized

E. SYSTEMS ENGINEERING APPROACH

The Systems Engineering Vee model (Fabrycky 2014, 37), was followed in this engineering investigation. Detailed background information on the Vee model along with other project background information and literature review is discussed in Chapter II. First, stakeholders provided the capstone team with documentation and references regarding the USV envisioned system operation and employment. This information was used to develop a maintenance CONOPS. Needs were then developed from the resources provided. Top-level requirements were developed and traced to the stakeholder needs to ensure full coverage (refer to Chapter IV Section E for the completed requirements traceability matrix). These top-level requirements were further refined into a full set of system requirements. The CONOPS and the system requirements were then used to develop a top-level functional architecture, consisting of required use cases and functions. Each functional requirement was traced to at least one function. A physical architecture was then developed, showing a breakdown of subsystems and how energy, matter, and information

(EMI) (Gunn 2022) was exchanged within the system. Additionally, each function was allocated to a piece of the physical architecture to create an allocated architecture. This process of drilling down by developing lower-level requirements, allocating these requirements to functions, and allocating these functions to physical components was repeated as was necessary to meet the goals of this engineering investigation. Finally, traceability was also employed to identify shortfalls, redundancies, parent-child relationships, and orphan requirements.

Due to the impracticality of testing the system, elements of the functional architecture were used as inputs for detailed simulations. The results of these simulations were used to verify a subset of the top-level requirements.

F. CHAPTER SUMMARY

The USN is expecting to see a huge growth in the number of USVs in service. These USVs will not have embarked operators and thus will require a new maintenance CONOPS. The USV Sustainment Capstone team determined positions and assigned roles and responsibilities to create team member accountability and increase the chance of project success. In the final analysis, the overall goal of the USV Sustainment Capstone team is to provide recommendations for the USV's life cycle sustainment support plan. With the CNO's navigation plan requiring the integration of USVs into the fleet, there is a need for the USVs to be forward deployed for tactical and operational needs of the USN. As USVs are developed, providing maintenance and sustainment to them is a priority to keep them operational in the fleet. Once the project need was established, the USV sustainment big picture stakeholders were identified by the USV Sustainment Capstone team which helped determine the specific project objectives. This led to the review of references and documentation to determine the project assumptions and constraints. Finally, the chapter concluded by describing the USV Sustainment Capstone team's approach to following the systems engineering Vee model for the engineering investigation. In the following Chapter USV background information will be discussed as well as review of prior work that has been completed in this area.

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II. PROJECT BACKGROUND AND LITERATURE REVIEW

This chapter provides background on the project, on specific topics that are used throughout the rest of the report, and a literature review.

A. BACKGROUND

UxS technology is a quickly evolving capability that the USN and other "U.S. military services are pursuing to meet emerging military challenges" (O'Rourke 2023.b, 1). Starting in fiscal year (FY) 2024, the USN wants to develop and procure both USVs and unmanned underwater vessels (UUVs). The three classes of vessels the Navy are focused on acquiring include the large unmanned surface vessel (LUSV), medium unmanned surface vehicle (MUSV), and extra-large unmanned undersea vessel (XLUUV) (O'Rourke 2023.b, 1). USVs "can be equipped with sensors, weapons, or other payloads, and be operated remotely, semi-autonomously, or with [current in-development] technological advancements, autonomously" (O'Rourke 2023.b, 1). In fact, the Navy significantly ramped up its investment in MUSVs and LUSVs over the past several years. These vessels are predicted to be individually less expensive to acquire than manned ships (O'Rourke 2023.b, 1). Additionally, after further technological maturation, the USV design will not need to account for onboard human operators. Furthermore, cost-benefit analysis research was done at the Massachusetts Institute of Technology (MIT) and used current naval operations versus a projected replacement of UxS for a similar mission. A CONOPS comparison of "Mine detection, classification, identification, and neutralization" (Larson 2012, 57) found that "each mine requires 0.2 UUV-hours for detection for a total cost of $529 per mine, which is 92% cost savings over manned systems." (Larson 2012, 58). The MIT study reflects the potential for large cost savings over numerous manned missions. Due to the range in size of the USVs and UUVs, there is the potential impact for minimally manned missions that either require specialized skills or onboard support/maintenance, with the assumption that these would not be a large factor in terms of the overall cost analysis when compared to a fully manned ship. USVs are suitable for "missions that pose a high risk of injury, death, or capture of" (O'Rourke 2023.b, 2) embarked personnel, as the USVs can be unmanned as needed. For several years, the Navy has tested and developed different UxVs and "transitioned some of these efforts, particularly those for Unmanned Aerial Vehicles (UAVs), into procurement programs" (O'Rourke 2023.b, 2).

The three previously mentioned vessels vary in size and operational capability. LUSVs are set to be "low-cost, high-endurance, reconfigurable ships" (O'Rourke 2023.b, 5) that can carry various payloads and can be anywhere from 200 feet to 300 feet long with a displacement of 1,000 to 2,000 tons (O'Rourke 2023.b, 5). LUSVs can have a "Vertical Launch System (VLS) with 16–32 missile-launch tubes for anti-surface warfare (ASuW)" (O'Rourke 2023.b, 5). The LUSV prototypes are currently "lightly manned" (O'Rourke 2023.b, 5) and have some onboard crew members, as the Navy continues working through operational concepts. Like LUSVs, MUSVs are also "low-cost, high-endurance, and reconfigurable to accommodate various payloads" (O'Rourke 2023.b, 12); however, these payloads are set to be "intelligence, surveillance, and reconnaissance (ISR) and electronic warfare (EW) systems" (O'Rourke 2023.b, 12). MUSVs also vary in size, as they are set to be anywhere from 45–90 feet in length with a displacement of approximately 500 tons (O'Rourke 2023.b, 12). One XLUUV in use by the Navy, the Orca, has a diameter of more than 84 inches (Vavasseur 2019). Due to the large diameter, the XLUUV cannot deploy from a manned submarine; it must be deployed from a pier (O'Rourke 2023.b, 16). The Navy is set to utilize XLUUVs to deploy Hammerhead mines, which are "planned mine [s] that would be tethered to the seabed and armed with an antisubmarine torpedo" (O'Rourke 2023.b, 16). All the information for the UxVs is compiled in Table 5.

Table 5. UxV Vessels Summary

UxV Type	Length (ft)	Displacement (tons)	Mission/Capability
Harbor Class	35	9	Mine Countermeasures, Guns
Snorkeler Class	~35	~9	Mine Countermeasures, Shield, Torpedo
X-Class (Small)	Non-standard <45	2.5	Battle Space Awareness (BSA), Special Operation Support, Reconnaissance

UxV Type	Length (ft)	Displacement (tons)	Mission/Capability
Fleet Class	~49	2.5	Search/Delivery, ISR, Guns
Medium (MUSV)	45-90	Up to 500	EW, ISR
Large (LUSV)	200-300	1,000-2,000	VLS
Extra Large (XLUUV)	78	50	Mines, Anti-Submarine Torpedoes

The Navy's vision is to make UxS a "trusted and sustainable part of the Naval force structure, integrated at speed to provide lethal, survivable, and scalable effects in support of future maritime mission" (Department of the Navy 2021, 8) . In addition to large USVs, the Navy wants to develop and procure smaller USVs, UUVs, and UAVs, due to the capabilites and advantages they can provide the Navy warfighter on the battlefield (O'Rourke 2023.b, 1). It is important that the Navy employs new strategies to combat upcoming threats. Figure 2 illustrates the Navy's vision for UxS (Department of the Navy 2021, 10).

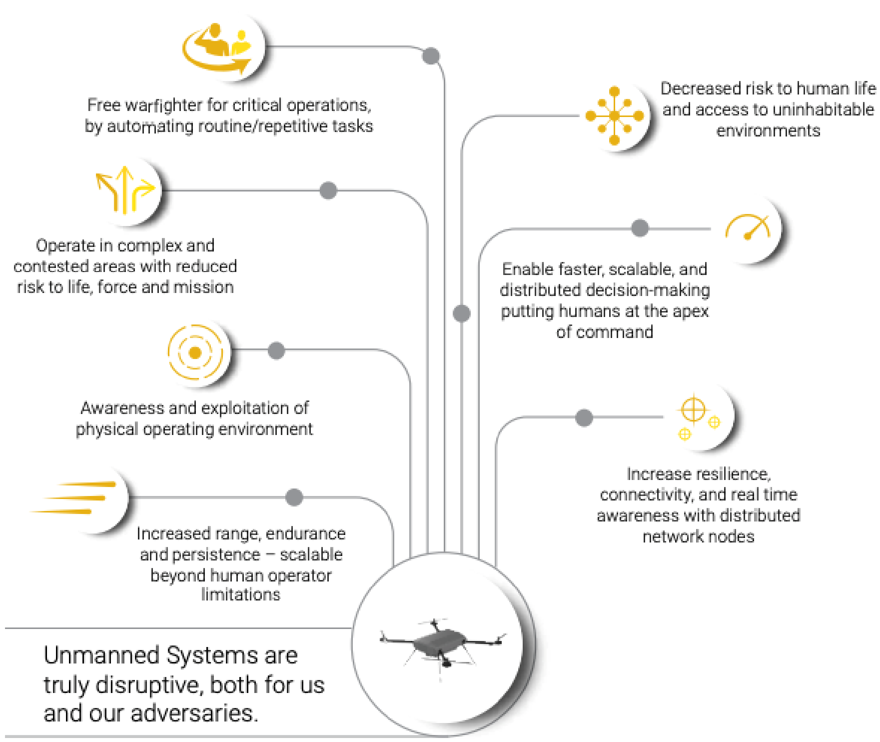

Figure 3. UxS End-State Source: (Department of the Navy 2021, 10)

As mentioned in the 2021 *Department of the Navy Unmanned Campaign Framework*, the Navy's USV programs will partner with "different stakeholders to integrate" all USV-related systems (Department of the Navy 2021, 3). It is also understood that DON leadership is set to "focus on resourcing and building an environment that can partner with industry, apply resources, and develop in a synchronized and deliberate way" (Department of the Navy 2021, 8) as networks and foundations are developed. As further explained in the 2021 *Department of the Navy Unmanned Campaign Framework* part of the USV program's growth and development, detailed life-cycle sustainment plans for their ships and payloads must be developed along with determining how existing DOD infrastructure can be leveraged to minimize cost and disruption. The Navy how unmanned system designs have to balance one another as "a physical platform alone cannot carry out missions without the appropriate key enablers, core technologies, and interoperability standards" (Department of the Navy 2021, 18).

B. STAKEHOLDERS

Stakeholders are any person, group, organization, etc., that reflect those impacted by the system in some way or need the system to solve or provide an opportunity to be realized within defined constraints (SEBoK Editorial Board 2023). Identifying the stakeholders for USV sustainment was necessary to understand the needs of the project. These needs communicate the stakeholder expectations for the end-state, once the system is delivered. Multiple stakeholders were initially considered for maintaining and supporting USVs OCONUS.

C. POWER INTEREST GRID

The power interest grid is a methodology used to examine, categorize, and properly manage the different stakeholders during the life of the project. The stakeholders are plotted on a grid "in relation to the power and interest they have in respect of the project" (Improvement Service n.d.). To illustrate, the power interest grid is separated into four quadrants: high power/high interest, high power/low interest, low power/high interest, low power/low interest (Improvement Service n.d.). The "power" is on the y-axis, the higher power stakeholder is on the y-axis. Power is defined as the ability to make decisions affecting the project. Equally important, the "interest" is on the x-axis. The farther right the stakeholder is placed, the greater the interest in the project. Figure 4 displays a general figure of a power interest grid.

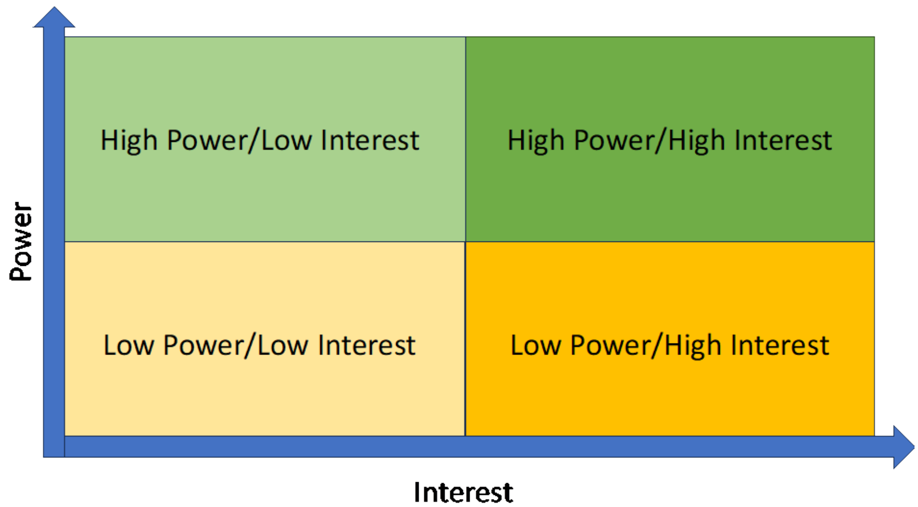

Figure 4. Generic Power Interest Grid

D. SYSTEMS ENGINEERING DEFINITIONS

1. Vee Model

For this project, various systems engineering life cycle process models were analyzed to decide as a team the model that would best fit the project and engineering investigation. The systems engineering Vee Model, shown in Figure 5, was decided to be the best fit as its core "involves a sequential progression of plans, specifications, and products that are baselined and put under configuration management" (Fairley, et al. 2023). Ultimately this means that the Vee model has an evolving baseline "from user requirements agreement to identification of a system concept to definition of system components that will comprise the final product," (INCOSE 2007, 3.5) which is what this project needed to do to be able to provide recommendations to be used in the life cycle sustainment support plan. In terms of the Vee Model, as time goes on the system progresses to the right side of the Vee, the system matures as it moves vertically, the left side of the Vee is defined by the evolving baseline, and the right side is developed as the entities are constructed, verified, and integrated (INCOSE 2007, 3.5).

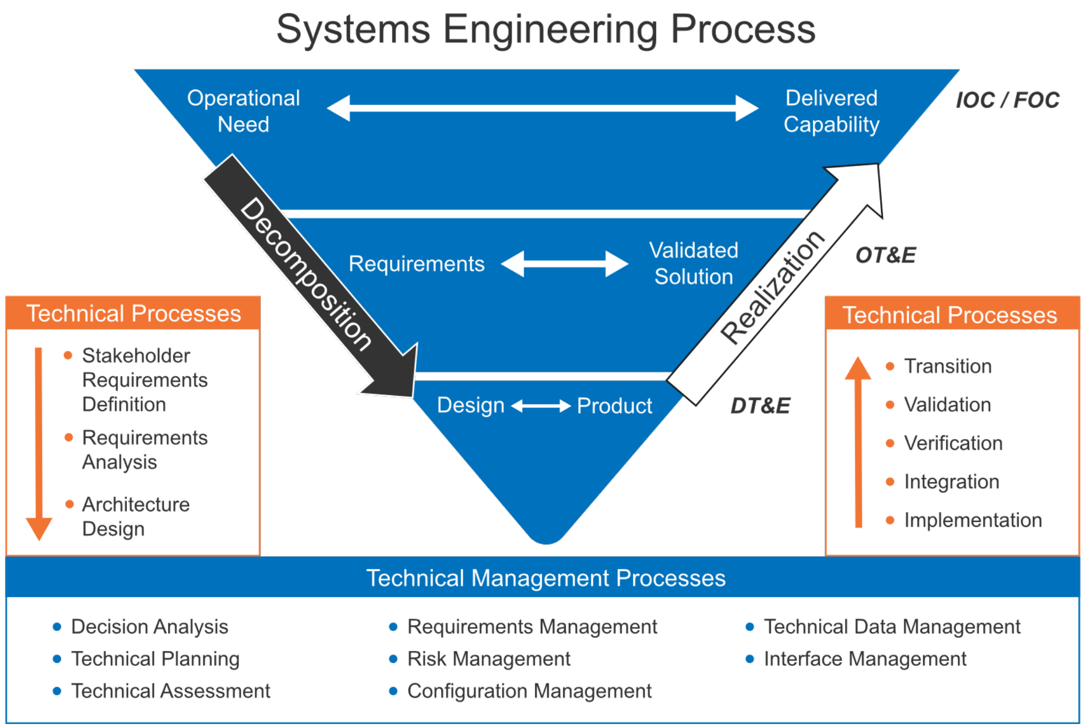

Figure 5. Systems Engineering Vee Model.
Source: Defense Acquisition University (2022).

2. Physical Architecture

The USV Sustainment Capstone team developed a physical architecture. A physical architecture is important as it is "an arrangement of physical elements, (system elements and physical interfaces) that provides the solution for a product, service, or enterprise" (Faisandier Adcock 2023). The intent of it is to satisfy the "logical architecture elements and system requirements … The resulting system architecture is assessed with system analysis and when completed becomes the basis for system realization" (Faisandier Adcock 2023). In systems engineering, system realization means "the activities required to build a system, integrate disparate system elements, and ensure that a system both meets the need of stakeholders and aligns with the requirements identified in the system definition stage" (Faisandier Adcock 2023). Thus, the physical architecture developed by the USV

Sustainment Capstone team supports requirement analysis and allocation of functionality, which was used to develop the life cycle recommendations.

3. Concept of Operations

The concept of Operations (CONOPS) is “the key artifact (knowledge base) for conveying the problematic situation model and intended effects along with evidence of model quality” (Ring 2014, 14). Its purpose is to communicate the vision of the system’s operations and assumptions utilizing both verbal and graphic statements (SEBoK Editoral Board 2023).

4. Verification and Validation

Verification and validation is an iterative approach of the system engineering process. Explained further by Blanchard and Fabrycky, verifying a system starts with “system-level requirements [which] are identified through the definition of system operational requirements and the maintenance and support concept” (Fabrycky 2014, 150). They continue that for “each new requirement that is established, the question is” (Fabrycky 2014, 151) how to validate those results. This leads to an iterative thought and testing process where the requirements are developed, the system is laid out to satisfy those requirements, then those systems break down to subsystems or pieces of the system which get tested and evaluated, and if those produced values/processes are satisfactory and accurate, then the next piece is validated until the entire system is complete, otherwise alternatives must be identified, and the cycle continued until the system was produced.

E. PLANNED MAINTENANCE AND CONDITION-BASED MAINTENANCE PLUS

The USN warships have various systems ranging from Hull, Mechanical and Electrical (HM&E), weapons, sensors, combat systems, network backbone, and many more. Various subject matter experts (SMEs) from different commands design and develop maintenance procedures for the numerous systems that make up the specific class of warship. The approved procedures developed by the SMEs result in Maintenance Requirement Cards (MRCs) and Maintenance Index Pages (MIPs). The MRC contains step-by step procedures on how to conduct maintenance on a piece of equipment (Naval Education and Training Professional Development and Technology Center 2001, 7-1). Additionally, the MRC will detail "who is to perform the maintenance … and when, how, and with what resources a specific requirement is to be accomplished" (Naval Education and Training Professional Development and Technology Center 2001, 7-5). MIPs are used as reference guides when performing maintenance on equipment, but each index contains information of all the MRCs needed to conduct maintenance on one system. MIPs are different in that they "are prepared and issued for each installed system or piece of equipment for which PMS [planned maintenance system] support has been established" (Naval Education and Training Professional Development and Technology Center 2001, 7-3). These procedures and index pages are implemented into the overall PMS.

a. Routine Maintenance

As warships go in-service, it is the USN Type Commander's (TYCOM) responsibility to maintain, train, and ensure the readiness of the ships assigned to each fleet (Maurer 2022, 8). Such routine preventative maintenance on the warship's equipment and systems avoids downtime and keeps warships ready for mission operations. Corrective maintenance on warships is to restore ships' equipment or systems after unforeseen failures, and, most likely, requires re-certifications of ship's systems before conducting mission operations. Preventative maintenance checks can turn into corrective maintenance if failures are discovered. In regards to the maintenance periods designated for accomplishing preventative and corrective maintenance activities, the GAO states, "these maintenance periods can include major repair, overhaul, or the complete rebuilding of systems needed for ships to reach their expected service lives, and involve complex structural, mechanical, and electrical repairs" (Maurer 2022, 8).

Multiple groups are involved in preventative and corrective maintenance due to the number of checks and the level of effort in which Ships Force cannot conduct on their own. Regional Maintenance Centers (RMCs) are responsible for coordinating maintenance periods, a difficult task due to demanding schedules of ship maintenance that must be completed during the ship's availability to be operational and ready to support the mission

(Naval Sea Systems Command n.d.). Preventative Maintenance Availability (PMAV) and Corrective Maintenance Availability (CMAV) are availabilities set for warships to conduct a specific type of maintenance. During the PMAV and CMAV, ships are located pier side, as some of the maintenance requires removing equipment off the ships. Various levels of support are provided during the availabilities such as utilizing facilities for equipment repair, acquiring parts that are on-the-shelf, and having expert personnel on-site to go onboard and troubleshoot. The periodicity of the PMAV and CMAV depends on the specific class of ship. For example, for the Littoral Combat Ship (LCS) program each ships has a PMAV scheduled for five days every month and CMAV scheduled for 14 days every quarter (Chief of Information of the United States Navy 2023). The PMAV and CMAV are an integral part of the life cycle maintenance for the in-service life of warships.

b. Condition-Based Maintenance Plus

Condition-Based Maintenance Plus (CBM+) was founded by the RCM and is the DOD's initiative for "sustaining materiel readiness at optimum cost" (Department of Defense 2020, 1). CBM+ in the DOD is defined as the "application and integration of processes, technologies, and knowledge-based capabilities to improve the reliability and maintenance effectiveness of DOD systems and components" (Office of the Assistant Secretary of Defense for Sustainment n.d.b., 1). CBM+ requires hardware and software products that collect, transmit, and analyze data. The way CBM+ works is by "analyzing equipment and system maintenance requirements, diagnosing equipment and system conditions, reporting condition status and maintenance data, performing maintenance according to established guidelines for preventative maintenance (PM) and predictive maintenance (PdM), and total life cycle management (TLCM)" (National Center for Manufacturing Sciences n.d.). The sensors that are embedded in equipment are monitored in near-real time and the data is reported to a computer system that interprets the data to detect performance deterioration or a possible failure and if detected maintenance is scheduled. Using the data from the sensors, the CBM+ technologies calculate the remaining life of the system or piece of equipment. CBM+ improves the "availability and reduces life cycle cost by minimizing unscheduled maintenance and enabling predictive maintenance" (Department of Defense 2020, 1).

c. Reliability, Availability, Maintainability

For the USN to successfully execute mission operations, the USN needs its ships and its ship's systems to continue to operate successfully. Realistically, a system or piece of equipment cannot run all the time and is bound to go down at some point. Obtaining systems with quality equipment functions that meet requirements in restricted environments are some of the factors that affect Reliability, Availability, and Maintainability (RAM). DOD acquisition's primary objective "is to acquire quality products that satisfy user needs with measurable improvements to mission capability and operation support in a timely manner" (Jackson 2005, 1). The DOD objective is partially achieved through system attributes of RAM. Each of these attributes is defined under the Guide for Achieving Reliability, Availability, and Maintainability where Reliability is defined as "the probability that the system will perform without failure over a specific interval, under specified conditions" (Defense Acquisition University n.d.c.). Availability is a measure probability the system "is in an operable state and can be committed at the start of a mission" (Defense Acquistion University n.d.a.). Maintainability "is the ability of an item to be retained in or restored to" its specific configuration/condition (Wang 2016, 115). Furthermore, each of the attributes is specified by a measure. Measure examples include mean time between maintenance (MTBM), mean time between corrective maintenance (MTBCM), mean time between preventative maintenance (MTBPM) or mean time to maintenance (MTTM), and maintenance downtime (MDT). MTBM is a measure of reliability and factors in the maintenance policy (Reliability HotWire 2013). MTBCM can also be described as mean time to repair, is the time it takes to bring a system to operational state (Atlassian 2023). MTBPM or MTTM is "the time needed to perform planned maintenance task on the component" (Cadwallader 2012, 4). MDT "is the average total downtime required to restore an asset to its full operational capabilities" (Defense Acquisition University n.d.b.) . Using the averages or measures, decisions can be made to change or improve onboard systems to allow the vessel to have the required mission capabilities to execute mission operations.

F. MEASURES OF EFFECTIVENESS, MEASURES OF PERFORMANCE, AND KEY PERFORMANCE PARAMETERS

In the early stages of the capstone, the USV Sustainment Capstone team met with key stakeholders to gather documents and relevant references to understand the overall project goals. The information received from the documents and references provided by the stakeholders assisted in guiding the USV Sustainment Capstone team in creating relevant requirements. The team developed measures of effectiveness (MOEs) and measures of performance (MOPs) for the project, and the MOEs were used to evaluate the team's sustainment design. A MOE is "a criterion used to assess changes in system behavior, capability, or operational environment that is tied to measuring the attainment of an end state, achievement of an objective, or creation of an effect" (Gueffey and Westphal 2014). Additionally, a MOP is "a criterion used to assess actions that are tied to measuring task accomplishment" (Curtis E. Lemay Center 2016).

Key Performance Parameters (KPPs) is another metric the USV Sustainment Capstone team used to quantify performance attributes of a system that are critical to the development of the USV sustainment capability. Changes to KPPs later in the life cycle can significantly impact the performance of the system as well as its schedule and cost (AcqNotes LLC n.d.a.). KPPs are identified in the Capabilities Development Document (CDD) and expressed in terms of MOPs (Defense Acquisition University 2023). These performance attributes will be realized through the USV's design, logistics strategy, and sustainment infrastructure.

G. MODELING AND SIMULATION

Modeling and simulation (M&S) are powerful tools for evaluating complex systems and processes. As stated in DOD Directive 5000.59, "modeling and simulation is a key enabler of DOD activities" (Department of Defense 2018, 2) to effectively achieve the goals of the DOD. Additionally, the directive states that models and simulations should play a leading, guiding, and supportive role in facilitating analysis, training, and acquisition efforts across the DON (The Secretary of the Navy 2002). A model, as defined in the DOD Modeling and Simulation Body of Knowledge "is a physical, mathematical or otherwise logical representation of a system, entity, phenomenon or process" (Department of Defense 2008, 6) Additionally, simulation is defined as "a method for implementing a model over time" (Department of Defense 2008, 9).

Modeling and simulation allow for the emergent properties of multiple candidate system architectures to be estimated without requiring the use of a real-world system or prototype. Not requiring the use of real-world systems or prototypes has many benefits when selecting a system architecture. Using real-world systems or developing prototypes can be both expensive and time consuming, which severely limits the number of system architectures that can be experimented on. Modeling and simulation allow a much greater number of candidate architectures to be experimented on, and since these systems are synthetic, they can be given a range of input parameters and quickly output results based off numerical calculations (Department of Defense 2008, 13). Additionally, numerical simulation can output data much quicker and cheaper than real world experiments allowing many more input parameters to be varied. Finally, input parameters can be selected to stress the systems in simulation which could damage or destroy real-world systems or prototypes and not allow for further testing. From the input parameters, design of experiments (DOE) factors are selected to run simulations that maximize the information gained for the project. A DOE is a "statistical methodology for planning, conducting, and analyzing a test" (The Office of the Director, Operational Test and Evaluation n.d., 1).

H. USV JOINT CAPABILITIES INTEGRATION AND DEVELOPMENT SYSTEM

According to the *Manual for the Operation of the Joint Capabilities Integration and Development System* (JCIDS), "the purpose of JCIDS is to enable the Joint Requirements Oversight Council (JROC) to execute its statutory duties to assess joint military capabilities, and identify, approve, and prioritize gaps in these capabilities, to meet applicable requirements in the [National Defense Strategy]" (J-8 Joint Capabilities Division 2018, A-1). As part of the JCIDS deliberate staffing process, capability documents such as Initial Capability Documents (ICDs) and their successors, Capability Development Documents (CDDs) are developed. These documents contain the required capabilities a program must meet to pass its major milestone reviews as part of the Defense Acquisition System (DAS) and eventually reach Full Operating Capability (FOC).

I. LITERATURE REVIEW

The USN has a life cycle requirement to establish a maintenance and sustainment plan across various systems and platforms. For the purposes of this project, the USV Sustainment Capstone team reviewed the latest DON Life Cycle Logistics Workforce Strategic Implementation Plan (Assistant Secretary of the Navy 2017). Understanding the DON strategic plan will assist the USV Sustainment Capstone team in developing and aligning the sustainment plan focus. Additionally, the proposed capstone report will follow the existing processes the USN uses today to support its assets, such as DOD Instruction 5000.91 that supports "product support management for the adaptive acquisition framework" (Department of Defense 2021, 1). The project vision owners at NSWC PHD have asked the USV Sustainment Capstone team to look into existing infrastructure and previous planning for the use of USVs, documented in *The Navy Unmanned Surface Vehicle (USV) Master Plan*, with the focus area being the use of the LCS MPSF infrastructure (Department of the Navy 2007). Notably, the LCS MPSF has established multiple facilities at the LCS's homeports and at OCONUS facilities. At these facilities, LCS personnel can repair parts assigned for an Organizational (O) level and Intermediate (I) level maintenance known as O-Level and I-Level Maintenance in its life cycle. The capability is to have sailors and or local groups provide the maintenance to the equipment in operation. The O-Level is represented at the Organizational level of repair, meaning it is mostly the sailor conducting the repair. The I-Level is represented at the Intermediate level, meaning it is mostly the local RMC and its employees conducting the repair. An understanding of this infrastructure will help the USV Sustainment Capstone team during the development and research of this project and provide recommendations for USV sustainment.

USVs are not a novel endeavor and represent part of the future focus of the DON, and the expected use and capability towards mission requirements is described in a statement put out by DON for UUV and USV Systems (Mortimore 2020). The DON issued a statement outlining the importance of USVs in the Fleet and what size(s) USVs will help achieve the mission after Middle East testing (Lagrone 2022). The Congressional Research Service (CRS) reported that the "Navy wants to develop and acquire LUSVs, MUSVs, and XLUUVs as part of an effort to shift the Navy to a more distributed fleet architecture," demonstrating a concerted effort to diversify the Fleet and the capability through a variety of UxS as early as FY 2024 (O'Rourke 2023.b, 2).

Prior work and research have been conducted regarding how USVs are defined and how they could be implemented as a part of maritime warfare as detailed in a report from a Naval Postgraduate School (NPS) thesis defining the potential physical architecture and "integration of unmanned surface vehicles into the order of battle for Distributed Maritime Operations (DMO)" (Winstead 2018, xxiii). The DOD also published an Unmanned Systems Roadmap 2007–2032, detailing their plans for UxS throughout the DOD, and specifies the classes defined above, and even plans to have subclasses of USVs including "Fleet Class USVs…Snorkeler Class USVs…Harbor Class USVs,… X Class USVs" and how each prototype and class of USVs would be implemented due to their size, capability, and mission requirements (Office of the Secretary of Defense 2007, 153-167). Currently, there is ongoing research on the *SeaHunter* USV that is operating under the "The Navy's SURFDEVRON-1 in San Diego which … has been exercising with guided-missile destroyers and the AEGIS Combat System" (Burgess 2020). One thesis published by the NPS looked at developing "concept of operations and system design decisions related to the usage of UxS … capability-level analysis of an Unmanned Vehicle Carrier (UVC) through system design characteristics and operational activities in a simulation model, and operational availability (A_O) and time-on-station (TOS) for maintenance, refueling, and rearming facilities without the need for long transit times to shore-based facilities or distributed support vessels" (Arnold 2021, v). This thesis provides a baseline for a CONOPS that operates throughout the life cycle, while also allowing for a deeper dive and wider berth to OCONUS and more specific maintenance, repair, and training costs.

J. CHAPTER SUMMARY

The USN has seen cost growth for sustaining its recently introduced ships that cannot be afforded for USVs, given the constrained budgetary environment and the growing capabilities of U.S. adversaries. To ensure that USVs are sustainable in a cost-efficient manner, recommendations made for the LCSP must be developed to guide USVs' development and fleet introduction. A thorough systems engineering approach based off the systems engineering Vee model was used to capture the sustainment activities, actors, and infrastructure involved. Several topics were introduced which will be elaborated on in later chapters as they help develop the recommendations for the USV life cycle sustainment support plan which include the power interest grid, project stakeholders, physical architecture, CONOPS, maintenance descriptions, MOEs, MOPs, KPPs, and modeling and simulation.

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III. SYSTEM OVERVIEW

This chapter discusses the USV sustainment system overview, including an analysis of the stakeholders to obtain a better understanding of capability identification, mission scenarios, and to help define the constraints of USV sustainment. Additionally, the project's logistic strategy is discussed along with the identified capabilities including the KPPs, MOEs, MOPs, and inputs and outputs related to the overall system.

A. USV SUSTAINMENT STAKEHOLDERS AND POWER INTEREST GRID

The USV Sustainment Capstone team analyzed the overall groups that make up the USV program and identified key stakeholders. For the USV LCSP, stakeholders range from fleet to government maintainers, industry partners, and program offices. Each stakeholder brings a different perspective to the project scope. Additionally, different stakeholders have various powers and influence during the life of the project. Many stakeholders have a vested interest in the USV program and would impact or feel the impact of any changes or developments. A power interest grid shown in Figure 6 was developed by the USV Sustainment Capstone team to identify the key stakeholders, categorized by their level of interest (how involved they are in the development and actual processes) and their implied power (chain of command and program office oversight).

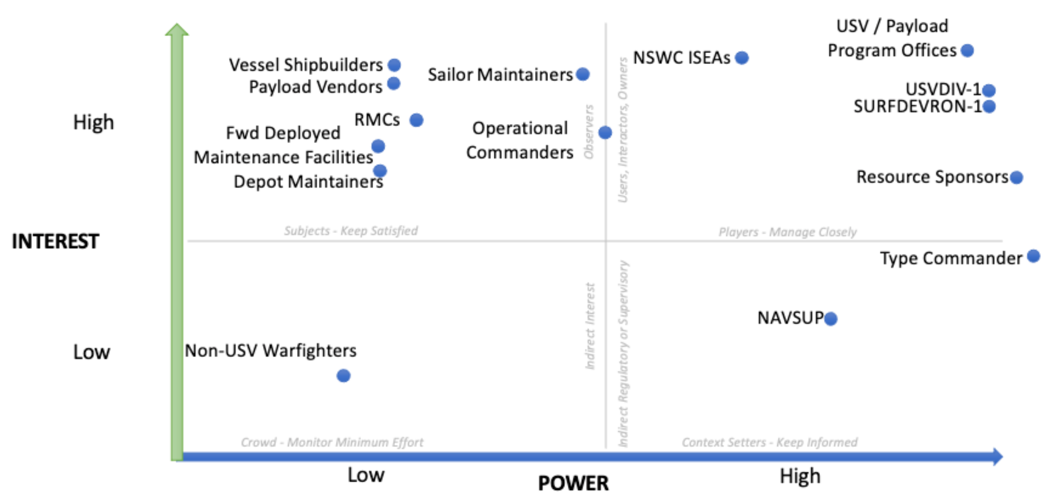

Figure 6. USV Sustainment Stakeholders Power Interest Grid

Utilizing the power interest grid in Figure 6, the USV Sustainment Capstone team was able to identify key stakeholders listed in Table 6 who provided input in the form of documents and references that were used to narrow the project's scope and needs. It is important to note that the stakeholders are listed as the overall job class and not specific individuals.

Table 6. USV Sustainment Key Stakeholders' Goals/Needs

Key Stakeholders	Goal/Need
WFC ISEAs	Have vessels and payloads be sustainable by using existing Navy processes and resources available to the WFCs
USV / Payload Program Offices (PMS 406, Program Executive Office (PEO) Integrated Warfare Systems (IWS), PEO C4I)	Design, build, and sustain vessels and payloads that meet the required capabilities laid out in Joint Capabilities Integration and Development System (JCIDS) products within budget constraints provided by the National Defense Authorization Act (NDAA) and resource sponsors
USVDIV-1 / SURFDEVRON-1	Receive vessels and payloads that support the CONOPS and assigned missions with the required level of availability
Resource Sponsors (N2N6, N96)	Fund vessels and payloads that fill capability gaps for the least amount of resources

B. STAKEHOLDER ANALYSIS

At project initiation, stakeholders who will benefit from or utilize the LCSP were identified. Utilizing the power interest grid shown in Figure 6, the team was able to further narrow the project's scope by identifying the key stakeholders along with their overall goal/ need as listed in Table 6. Through the review of prior work and technical documentation of USVs and LCSPs, the USV Sustainment Capstone team gained insight into the current environment and forward deployed ship maintenance facilities. Additional information was obtained by researching and referencing documentation provided by stakeholders on USV standard operations. Based on the documentation review and information provided by key stakeholders, their respective activities and concerns related to this USV sustainment project are listed in Table 7.

Table 7. USV Sustainment Key Stakeholders Activities and Concerns

Key Stakeholders	Activities	Concerns
WFC ISEAs	• Engineers develop and logisticians process MRCs & MIPs • Provide distance/on-site support during repairs	• The level of supportability required • Resource availability in OCONUS locations • Timeframe availability during preventative or corrective maintenance
USV/Payload Program Offices (PMS 406, PEO IWS, PEO C4I)	• Govern program structure • Fund tasks/activities • Coordinate program plan • Delivers new USVs to the Fleet	• Risks to the program and delay work execution • Program success • Mission readiness timeframe
USVDIV-1/ SURFDEVRON-1	• Ensure USV is mission ready • Accelerate delivery of reliable system • Provide personnel required for repair activities and availabilities • In charge during maintenance availabilities of USV (Seapower Staff 2022)	• The level of foundational knowledge sailors are trained to operate and maintain USVs • Maintenance required and support needed to maintain USVs • Timeframe availability during preventative or corrective maintenance
Resource Sponsors (N2N6, N96)	• Provide "end-to-end accountability for Navy information requirements, investments, capabilities, and forces" (Stiner 2023) • Navy's primary office that resources capabilities such as "intelligence, cyber warfare, command and control, electronic warfare, battle management, oceanography, and meteorology" (Stiner 2023)	• Mission Readiness • Strategic Planning • Budget and Resources • International Relations • Safety Risks and Threats

As seen in Table 7, each key stakeholder has a unique perspective that influences their concerns and assists in determining the project requirements with the common goal of ensuring the USVs are readily available to support the mission.

As mentioned in the background information, MOEs and MOPs are the measures to assess if the design is meeting the objectives and how effectively the objectives are being met. Based on inputs and previous works, Table 8 and 9 summarize the MOEs and MOPs identified for the respective stakeholder. Accordingly, the USV Capstone Sustainment team focused on materiel availability, operational availability, and maintenance cost reduction to assess the USV sustainment design.

Table 8. USV Sustainment MOEs

MOE	Interested Stakeholder
Maintenance Cost Reduction	• USV/Payload Program Offices (PMS 406, PEO IWS, PEO C4I) • USVDIV-1 / SURFDEVRON-1 • Resource Sponsors (N2N6, N96) • WFC ISEAs
Operational Availability Percentage	• Resource Sponsors (N2N6, N96) • USVDIV-1 / SURFDEVRON-1
Operational Capability Improvement	• Resource Sponsors (N2N6, N96) • USVDIV-1/ SURFDEVRON-1
Equipment Reliability	• WFC ISEAs • USVDIV-1 / SURFDEVRON-1
Materiel Availability	• Resource Sponsors (N2N6, N96) • USVDIV-1 / SURFDEVRON-1

Table 9. USV Sustainment MOPs

MOP	Interested Stakeholder
Mean Time to Repair	• USVDIV-1 / SURFDEVRON-1 • WFC ISEAs • Resource Sponsors (N2N6, N96)
Maintenance Cost	• WFC ISEAs • USV / Payload Program Offices (PMS 406, PEO IWS, PEO C4I) • Resource Sponsors (N2N6, N96)

The MOEs and MOPs were drafted during the planning phase and refined or amended as the project understanding improved. In general, the capstone team has prioritized their efforts to best support the USV's sustainment objectives.

C. LOGISTICS STRATEGY AND CONCEPT OF OPERATIONS

The USV Sustainment Capstone team developed a notional logistics strategy as there is no currently approved logistics strategy for USVs. Inputs to this logistics strategy included referencing documentation provided by the project vision owners and stakeholders on how USVs will be operated, as well as Navy strategy and policy documents. The urgent need to introduce USVs to the fleet and the Navy's constrained budgetary environment drives the USV logistics strategy to utilize standard Navy practices whenever possible to minimize disruption and cost. These standard practices include the development of sustainment products and performing sustainment analysis, training practices, and maintenance and equipment swap-out practices.

The standard sustainment products developed at the USV platform level are governed by DOD 5000.2, the Adaptive Acquisition Framework. These products will be the same as those for manned vessels. This includes standard documents at the platform level such as the LCSP. Sustainment products will also be developed at the system level and are included in Appendix A.

Training practices include performing a job duty task analysis to determine the tasks that the USV maintainers and operators are required to perform. Analyses will then be performed on the best way to implement this training. Additionally, new USV Military Occupational Specialties will be implemented and added into the Navy training pipeline. Existing courses will need to be modified and new courses added to cover training for systems the Navy has not needed to operate and maintain in the past, such as autonomy systems. None of the sustainment products and training practices will be a paradigm shift for the Navy, and thus will not be the focus of the analysis performed for this capstone.

Like the development of sustainment products, training, maintenance, and equipment change out for USVs will utilize standard Navy practices when possible. However, maintenance and equipment change out will require modeling and simulation to ensure the suggested configuration for maintenance and equipment change out is in the solution space due to the USV's lack of embarked personnel, the USV's payloads, and an increase in the number of Navy vessels to be forward deployed compared to the number of vessels forward deployed today. The design of the maintenance and equipment change out configuration will be the focus of the simulation performed in this capstone report. Several assumptions must be made to develop an accurate model. In addition to the initial assumptions listed in Chapter III Section C.1, additional assumptions were developed by the capstone team based on the provided references from the project vision owners and additional research.

- USVs' embarked personnel will not perform preventative maintenance and will not have specialized training to perform corrective maintenance
- USV maintenance and equipment change out will occur using present day technology. E.g., robots will not move around the ship performing maintenance on the vessel
- USVs will operate as part of a Carrier Strike Group (CSG), Expeditionary Strike Group (ESG), Amphibious Ready Group (ARG), Surface Action Group (SAG), or another Navy deploying group and will not be independently deployed
- USVs will be forward deployed to the Indo-Pacific
- USVs will have the ability to change payloads in theater
- USVs will follow a modified version of the Navy Optimized Fleet Response Plan (OFRP) for Forward Deployed Naval Forces (FDNF)

While manned vessels are underway, sailors constantly perform preventative maintenance, governed by the PMS. Each PoR system will have had a reliability centered maintenance (RCM) analysis performed to determine this schedule which determines what maintenance tasks need to be performed at what periodicity. A maintenance task analysis (MTA) is then performed to "[identify] … the steps, spares and materials, tools, support equipment, personnel skill levels as well as any facility issues that must be considered for a given repair task" (Defense Acquisition University 2021, 152). The maintenance concept for USVs does not include preventative maintenance being performed on them while underway. Some preventative maintenance performed today on manned vessels will be automated or eliminated. USV adapted systems designed to operate while unmanned will be fielded, but some portion of the maintenance that would traditionally be performed by manned operators will be deferred until after the USV has returned to port. With less preventative maintenance and eyes and ears onboard to see and hear minor problems before they become major issues, and without further changes, system failures would increase. CBM+ capabilities will be implemented to minimize the number of system failures. It is assumed that CBM+ will drive an increase in preventative maintenance in the near-term, as the Navy will be unlikely to eliminate maintenance checks until CBM+ technology has matured and the Navy has seen its effects on reliability. Due to deferring maintenance and CBM+, to allow for this maintenance to be performed, the windows for PMAVs and CMAVs will be increased in comparison to similarly sized vessels to allow time for this maintenance to be performed.

Due to these vessels being forward deployed, maintenance must occur without the vessels returning to the continental United States (CONUS). O-level and I-level maintenance will be performed at existing Navy facilities such as RMCs and MPSF annexes. Simulations will determine whether existing facilities can handle a workload increase that the USVs will bring. If it is determined that additional facilities will be needed, options such as utilizing contractor facilities and creating additional facilities through military construction (MILCON) projects will be analyzed to determine their required number, possible locations, and cost effectiveness. Depot level maintenance will be performed at various facilities OCONUS and CONUS to be determined by a depot source of repair analysis. Payloads will be swapped out as required to support the USV's next mission at these maintenance facilities. Payloads may be swapped out in any phase of the OFRP. The OFRP is the "force readiness generation construct [that is used to] maximize employability through a disciplined, repeatable, predictable approach that balances mid- and long-term readiness production stability for the fleet with the agility to support dynamic employment" (Department of the Navy 2020, 7). Figure 7 shows the three phases of OFRP which are Force Development (FD), Force Generation (FG), and Force Employment (FE), where FD involves "integrating and synchronizing existing processes" that will be used to enter the FG phase (Department of the Navy 2020, 38). The FG phase includes the "maintenance, modernization, training, and certification process" (Department of the Navy 2020, 38) and lastly the FE phase includes the sustainment and deployment periods and begins once there is a group or unit certification. To minimize time at the maintenance facilities, spare payloads will be maintained at these maintenance facilities and swapped with the embarked payloads. Major USV system modernization and overhaul will occur at CONUS facilities during the Maintenance Phase as called out in the OFRP to minimize the workload for maintenance facilities, close to the forward deployed region.

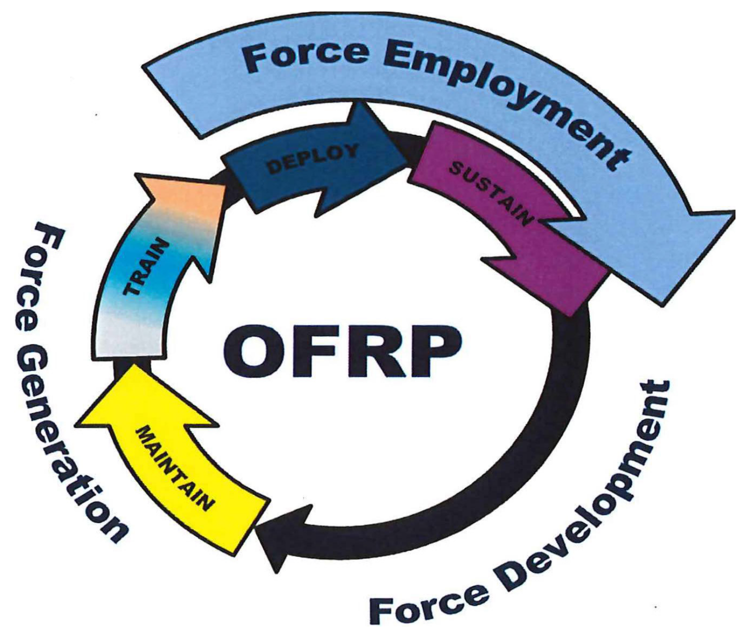

Figure 7. OFRP Diagram. Source: Department of the Navy (2020, 38).

D. USV CAPABILITIES

Both the MUSV and LUSV are likely to be designated as Acquisition Category (ACAT) 1 programs based off their procurement costs. The JCIDS Manual of Operations mandates required capabilities for ACAT 1 programs, including two sustainment KPPs relevant to this capstone: Materiel Availability (A_M) and Operational Availability (A_O) (AcqNotes LLC n.d.b.).

From the JCIDS manual, materiel availability is defined by "… the measure of the percentage of the total inventory of a system operationally capable, based on materiel condition, of performing an assigned mission" (J-8 Joint Capabilities Division 2018, B-G-D-2). The general formula for calculating materiel availability is shown in Equation 1.

$$A_M = \frac{Number\ of\ operational\ end\ items}{Total\ Population} \tag{1}$$

Materiel availability considers USVs used for training, USVs that are in a maintenance phase and are not mission capable, as well as USVs expected to perform a mission that are not currently mission capable. The equation to calculate A_M for USVs is shown in Equation 2.

$$A_M = \frac{Number\ of\ Operationally\ Available\ USVs}{Total\ USV\ Population} \tag{2}$$

Furthermore, the JCIDS manual defines operational availability as "… the measure of the percentage of time that a system or group of systems within a unit are operationally capable of performing an assigned mission" (J-8 Joint Capabilities Division 2018, B-G-D-3). The general formula for calculating operational availability is shown in Equation 3.

$$A_O = \frac{Uptime}{Uptime + Downtime} \tag{3}$$

Operational availability considers only USVs expected to perform a mission that are not currently mission capable. The equation to calculate A_O for USVs is shown in Equation 4.

$$A_O = \frac{Uptime\ of\ USV}{Uptime\ of\ USV + Downtime\ USV} \tag{4}$$

To sustain USVs that are forward deployed, there are required capabilities for the USV sustainment infrastructure to meet the stakeholder's needs and ensure a successful system. From analysis of the stakeholder needs, top-level requirements were developed that must be met to ensure the USV can be sustained. These requirements will be described in detail in Chapter V Requirements. The required sustainment capabilities from the CDD will be the metrics used as outputs of simulation to determine whether the facility configurations identified by this capstone are adequate to perform OCONUS maintenance and sustain USVs while forward deployed. The top-level requirements will also be met for the designated facilities, but this is not expected to alter the results of the simulations. To determine if the outputs were satisfied, a data set that could be a reasonable standard needed to be used. Based on data provided in the 2023 *Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress* by Ronald O'Rourke who projected the currently contracted development of USVs and the potential for growth, the team assumed that 100 UxVs being produced in the next decade was a reasonable assumption, Table 10 depicts the predicted rollout of UxVs.

Table 10. Prediction of UxVs Rollout in 10 years

FY/UxV	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**
LUSV		P2	P2		1	2	3	3	*9*	*9*	*9*	*8*
MUSV	P2				1-8				*9*	*9*	*9*	*7*
XXULV	P2					1	1	1	*1*	*1*	*1*	*1*
Total					**16**	**19**	**23**	**27**	***46***	***65***	***84***	***100***

*P stands for prototypes

**Highlighted cells are assumptions based off provided and currently planned/contracted UxVs per the Congressional Research Services Report "Navy Large Unmanned Surface and Undersea Vehicles: Background and Issues for Congress" (O'Rourke 2023.b).

E. CAPABILITIES: USV SUSTAINMENT INFRASTRUCTURE

Though JCIDS capabilities documents are traditionally generated for a system as part of an ACAT program, this capstone report treats the USV sustainment infrastructure as a system. Capabilities for the sustainment infrastructure required to accommodate tactical and operational needs for the Fleet were identified by the capstone team below. The capabilities came as a result of the KPPs, MOEs, and MOPs previously listed which explain the performance attributes that are essential for the USV sustainment to be successful. The team referenced the Manual for the Operations of the JCIDS by J-8 Joint Capabilities Division 2018 document to develop the capabilities.

- Infrastructure: The facilities and location should be established, have space readily available for USVs, and have utilities.
- Reliability: After departing the maintenance facility, the USVs' should demonstrate a high level of reliability, ensuring the USV can consistently perform its required functions without failures.
- Availability: The number of USVs that the facility can support at an instance. Additional metrics may include maximum availability on equipment, spare parts, or consumables.
- Workforce: The facility should have a qualified workforce with necessary skills to perform maintenance tasks on USVs.
- Safety: The facility should have protocols and procedures in place to ensure a safe working environment for personnel.
- Equipment: The facility should be equipped with necessary equipment required to perform maintenance or analysis on the USV.
- Cost: The program office should consider the total cost of the USV life cycle.

- Supply Chain: The facility should have a process to ensure the availability of equipment, spare parts, or consumables.
- Configuration Management: The configuration management system should document all changes done to all systems or equipment. This is to ensure that the system or equipment is aligned with the intended configuration or operational requirement.
- Information Management: The information management system should be able to track maintenance activities, including work orders, inventory, history, and documentation.
- Collaboration: Define collaboration goals and establish communication with stakeholders and vendors. Coordinate with ISEAs about problems that are discovered in the maintenance facilities, collaboration accelerates continuous improvement.

F. CHAPTER SUMMARY

In summary, there are many stakeholders in USV sustainment. Stakeholders were initially categorized using a power interest grid to allow for the stakeholder needs analysis and requirement development technical processes. Stakeholder needs were considered from those stakeholders who had both a high-level of interest and power. These stakeholders were WFC ISEAs, USV/Payload Program Offices (PMS 406, PEO IWS, PEO C4I), USVDIV-1/SURFDEVRON-1, and the resource sponsors (N2N6, N96). A logistics strategy was developed to meet the stakeholder needs. The logistics strategy then focused on areas of logistics specific to USVs. Then, the JCIDS process was introduced and the sustainment KPPs that will apply to the USVs, A_M and A_O were laid out. What these metrics are and how they are calculated were also delineated. Finally, the chapter concluded by describing capabilities the USV sustainment infrastructure must have to meet the stakeholder needs and satisfy the USV sustainment KPPs.

IV. REQUIREMENTS

This chapter discusses the development of requirements for the USV sustainment infrastructure. Traceability flows downwards from the CONOPS, JCIDS documents, suggested logistics strategy, and stakeholder needs to the top-level requirements and activities.

A. SYSTEM DEFINITION

This capstone report analyzed the USV sustainment infrastructure as the system of interest. Figure 8 shows the high-level required functions of the USV sustainment infrastructure which includes resupply, maintenance, training, and system evolution to the fully loaded USV. These functions are implemented by different types of sustainment personnel.

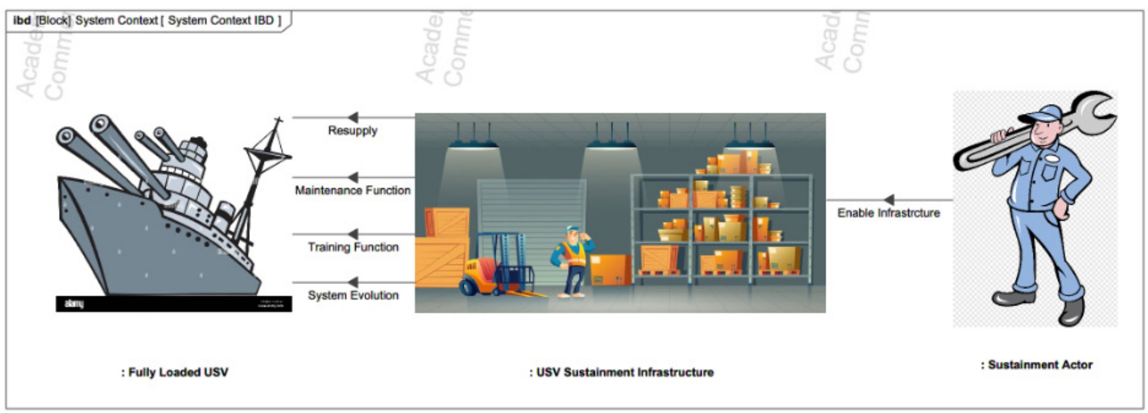

Figure 8. USV Sustainment High-Level Required Functions

The USV sustainment infrastructure resides in the system context, which also includes a fully loaded USV and sustainment actors. Figure 9 shows the composition of these elements. As seen in the figure, a fully loaded USV consists of the USV and its embarked payload. The USV sustainment infrastructure is composed of training facilities, maintenance facilities, and supply infrastructure. Also shown are the USV sustainment actors, which are composed of trainers, maintainers, and logisticians who interact with training facilities, maintenance facilities, and supply infrastructure, respectively. Some blocks in the figure include a reference section displaying their reference properties, which are properties that "specif [y] a reference of its containing Block to another Block" (Dassault Systems 2022).

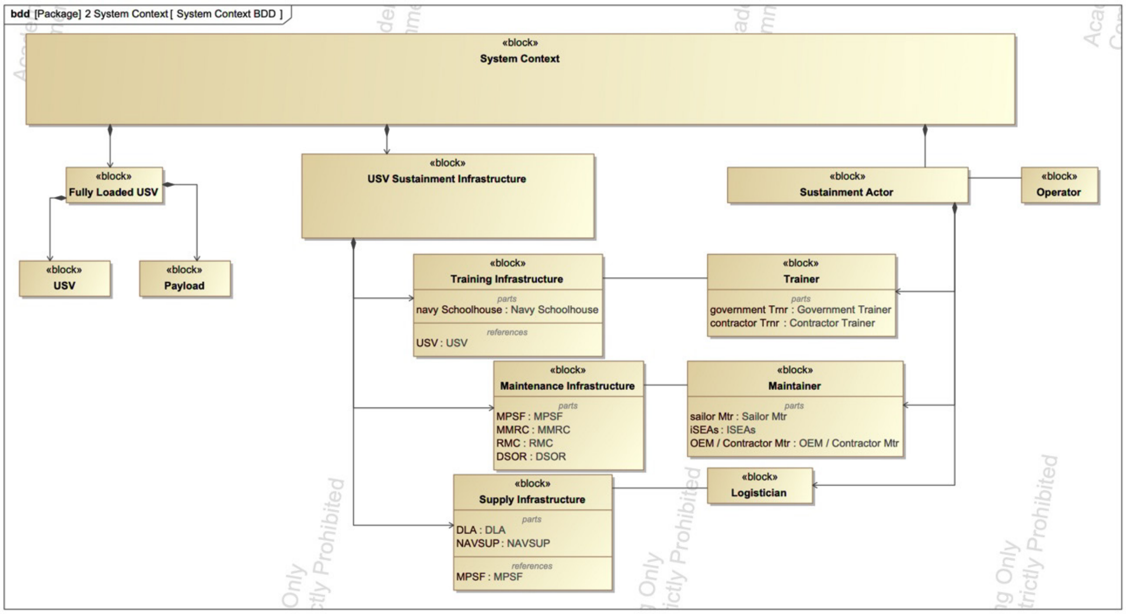

Figure 9. USV Sustainment System Context

Going from system context view to hierarchy of components, training facility, maintenance facility, and supply infrastructure are, themselves, decomposed into lower-level elements. First, the training facility is composed of Navy Schoolhouses and have reference properties to the USVs for on-the-job training and to trainers who will perform the training shown in Figure 10.

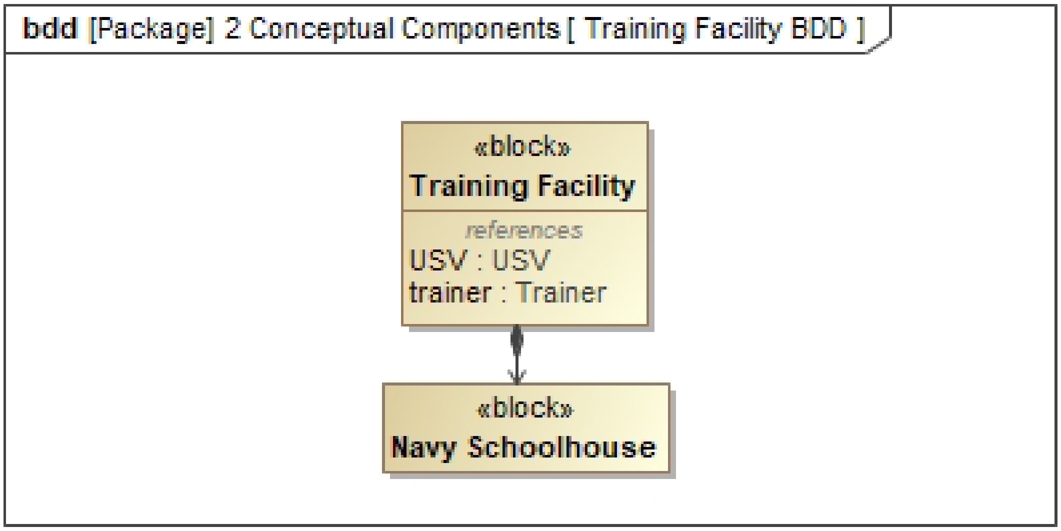

Figure 10. USV Training Facility Elements

Second, the maintenance facility is composed of the MPSF, depot sources of repair (DSOR), RMCs, and Mission Module Readiness Centers MMRCs and has reference properties to the maintainers who perform the maintenance, shown in Figure 11.

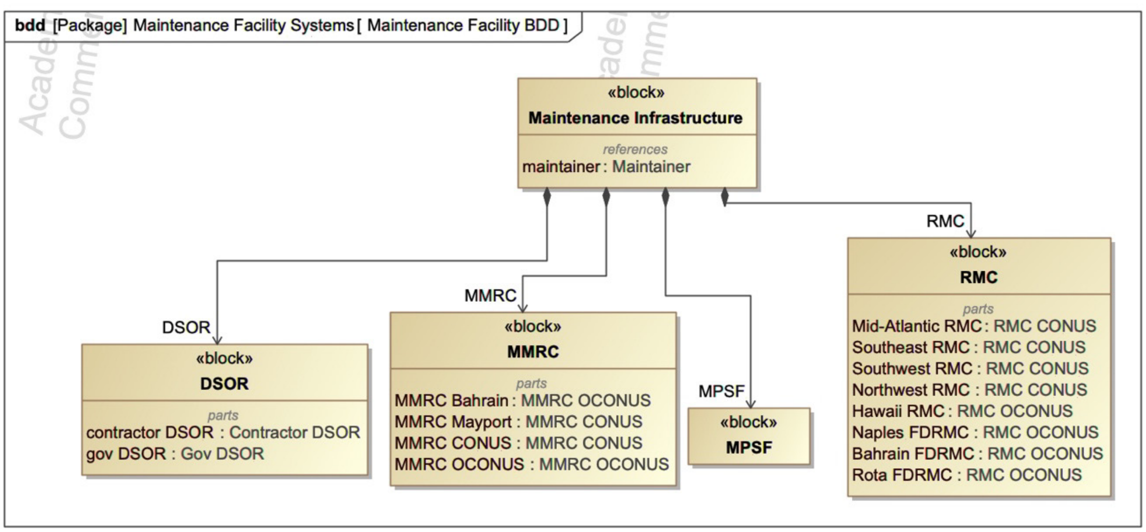

Figure 11. USV Maintenance Facility System Elements

Lastly, the supply infrastructure shown in Figure 12 is composed of the Defense Logistics Agency (DLA) and Naval Supply Systems Command (NAVSUP) and has reference to logisticians who control shipment and storage of parts and equipment, as well as the MPSF, which may also be used for parts and equipment storage, as well as a maintenance facility.

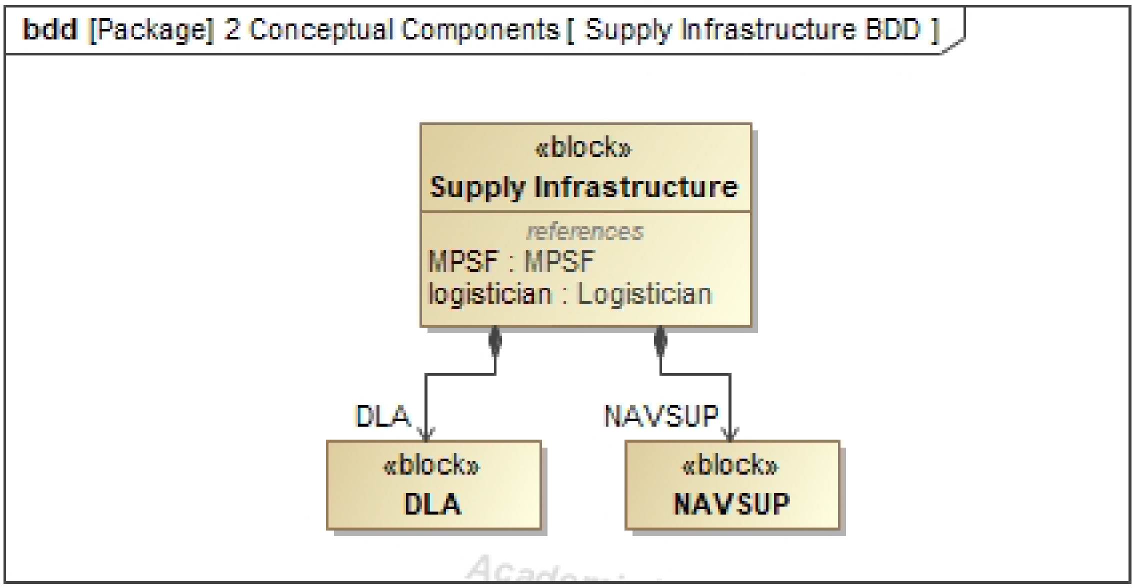

Figure 12. USV Supply Infrastructure Elements

B. USV SUSTAINMENT INFRASTRUCTURE USE CASES

The use case diagram "describes the relationship between the structural elements of the system and the external domain; and a set of object diagrams that are more definitive than the class diagram about the structural elements of the system and their relationships over time" (Buede 2009, 24-25). A use case diagram was created for the USV sustainment infrastructure, shown in Figure 13. Importantly, the use case diagram provides a high-level view of the "individual use cases or usage scenarios combine within operational concepts to describe how stakeholders think the system will be operated" (Buede 2009, 82). As seen in Figure 13, use cases on the left side are generalizations of the use case on the right side.

For instance, train operators, train maintainers, and train trainers are all generalizations of the use case perform training, meaning they inherit the same characteristics.

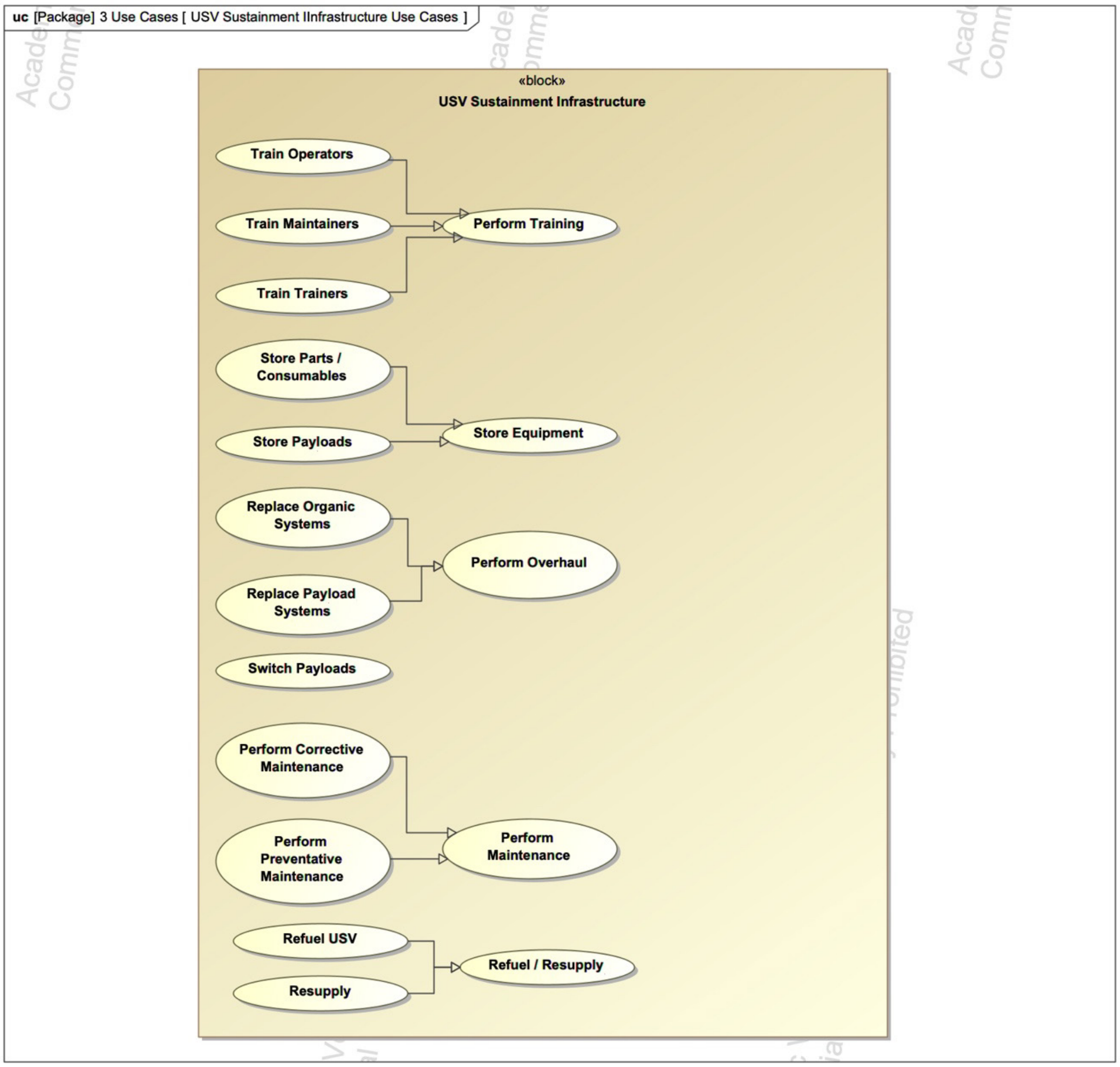

Figure 13. USV Sustainment Infrastructure Use Case

C. TOP-LEVEL REQUIREMENTS

Requirements for USV sustainment include functional requirements that "specify what the system should be able to do when fielded and operated in its intended operating environment" (INCOSE 2007, 4.6) and non-functional requirements which "are not directly related to the primary capability [of the system]" (INCOSE 2007, 7.12). The requirements were separated into top-level requirements and then decomposed to lower-level requirements which are required to accomplish the top-level functions (INCOSE 2004, 123). Lastly, the top-level functions were established based on analyzing and evaluating the system's baseline requirements to confirm it "provide [s] the required capabilities of each component in the system-level design" (INCOSE 2007, Appendix J-5). In summary, the selected top-level requirements and descriptions are listed in Table 11.

Table 11. USV Sustainment Top-Level Requirements

#	Top-Level Requirement Name	Requirement Text
1	Mission Needs	The USV and payloads shall support the USV CONOPS.
2	Personnel Requirements	USV and embarked payload shall minimize additional required personnel.
3	Cost Mitigation	USV and embarked payload sustainment costs shall be minimized.
4	Training	USV and embarked payload operators and sustainers shall undergo training to the level needed to support USV operations and sustainment.
5	Programmatic Sustainability	USV and embarked payloads shall be sustainable at scale.

D. LOWER-LEVEL REQUIREMENTS

Furthermore, the top-level requirements are decomposed into lower-level requirements, which are utilized to satisfy the top-level requirements. Some lower-level requirements were further decomposed to allow for proper synthesis efforts to fully support the USV sustainment functions. Thus, the lower-level requirements from the model are shown in Figure 14 through Figure 22, where the mission needs are shown over five figures (Figure 14 through Figure 18) due to the length of requirements.

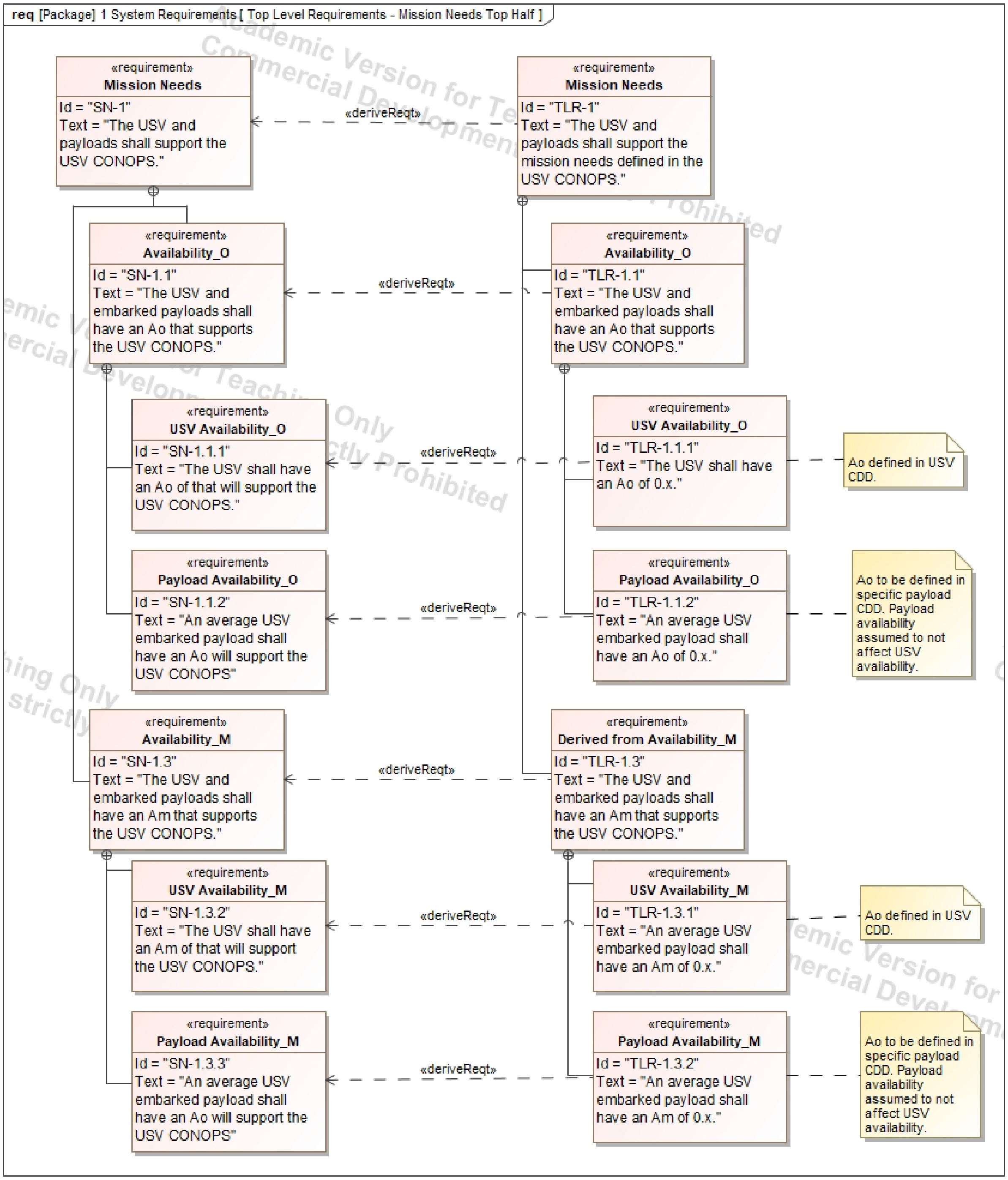

Figure 14. USV Sustainment Top-Level Requirements: Mission Needs Part I

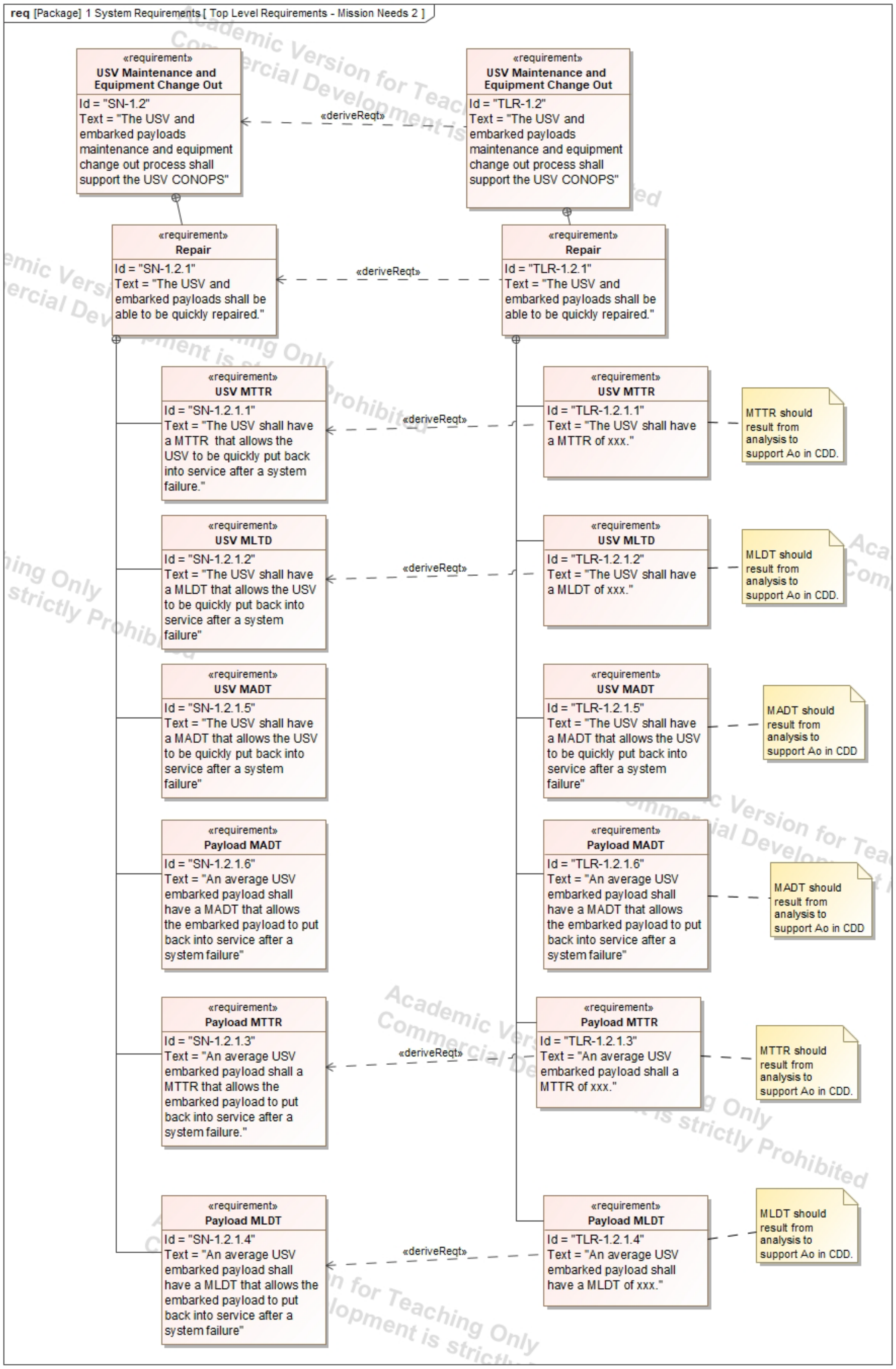

Figure 15. USV Sustainment Top-Level Requirements: Mission Needs Part II

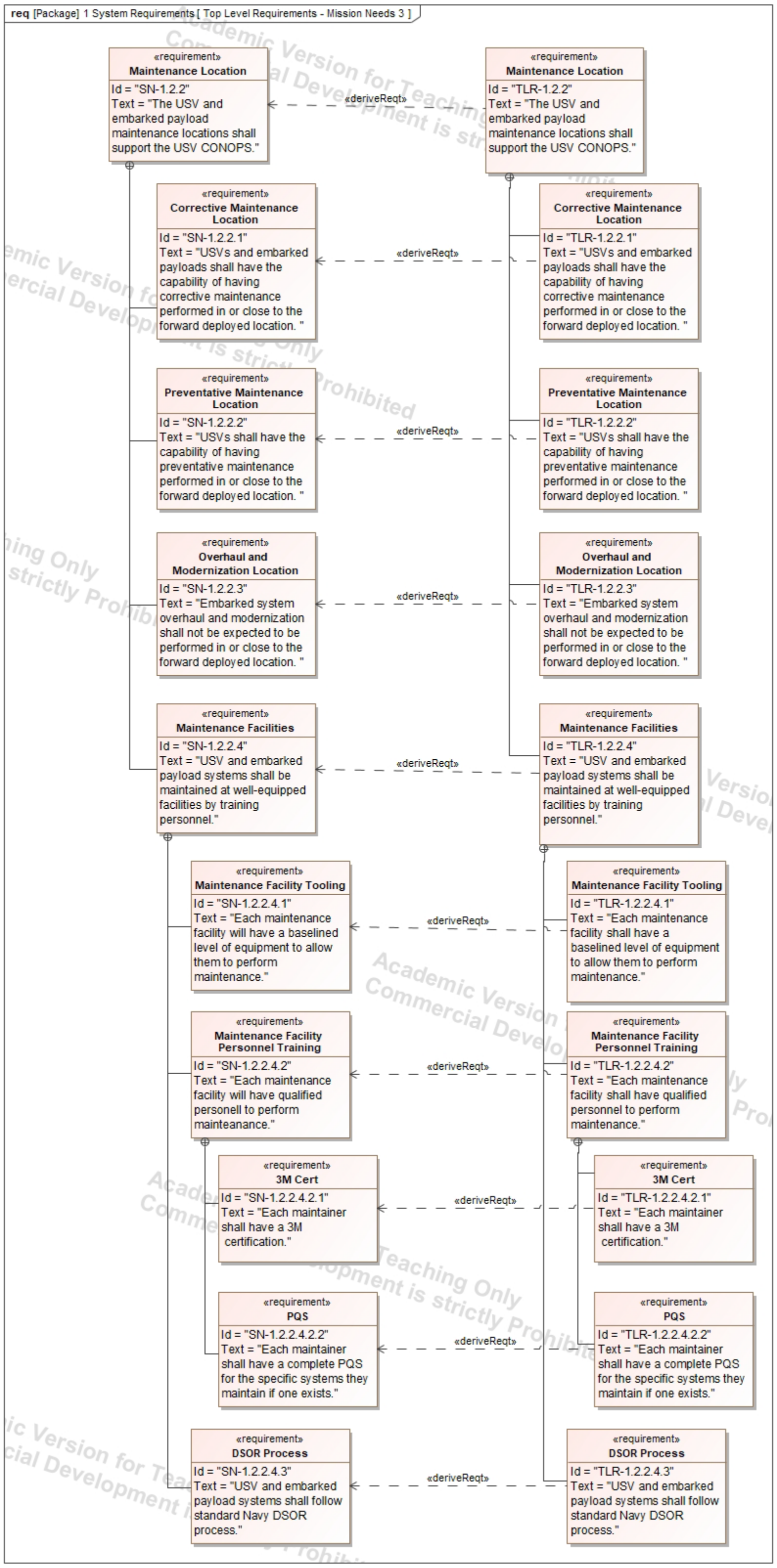

Figure 16. USV Sustainment Top-Level Requirements: Mission Needs Part III

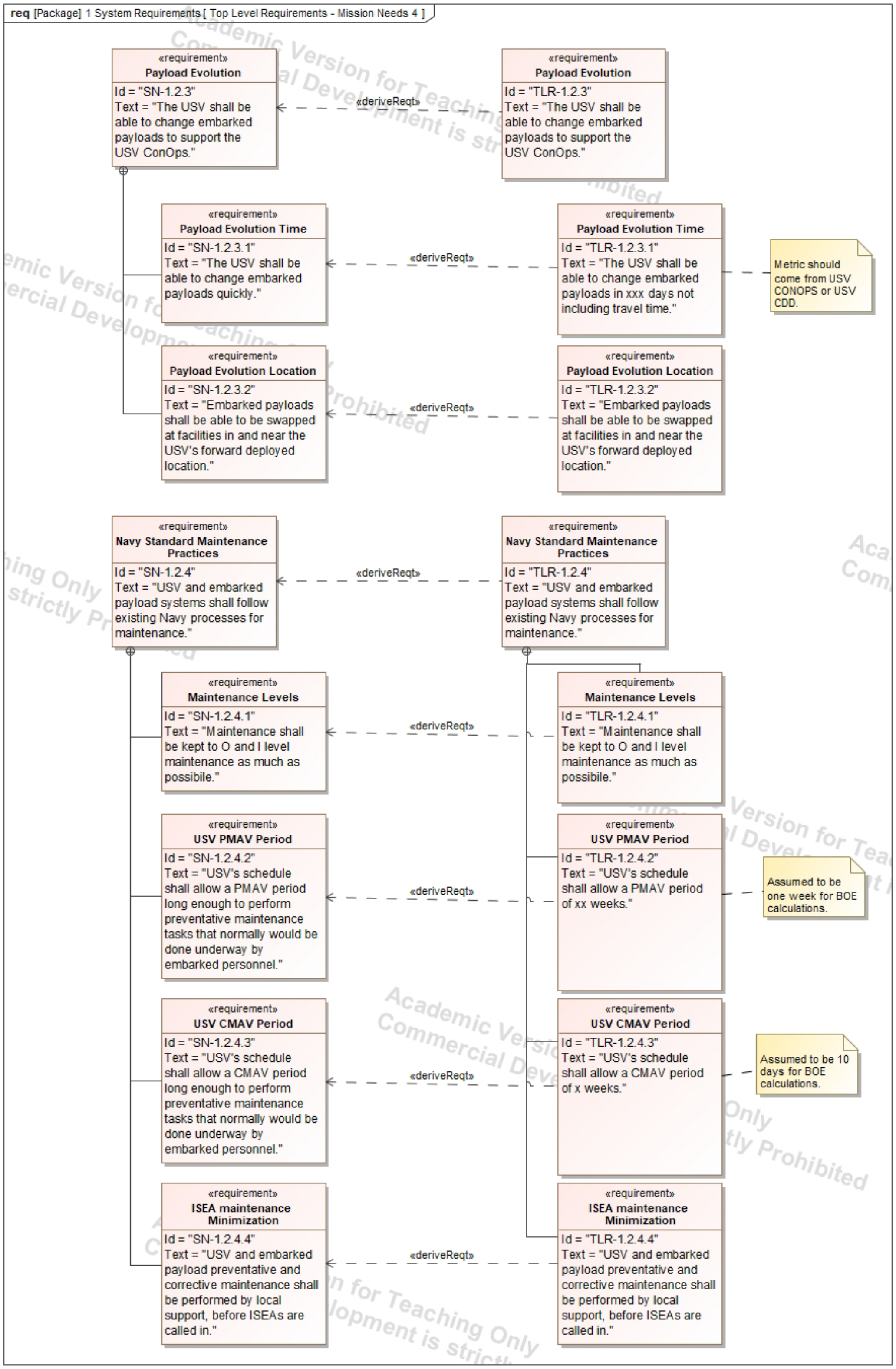

Figure 17. USV Sustainment Top-Level Requirements: Mission Needs Part IV

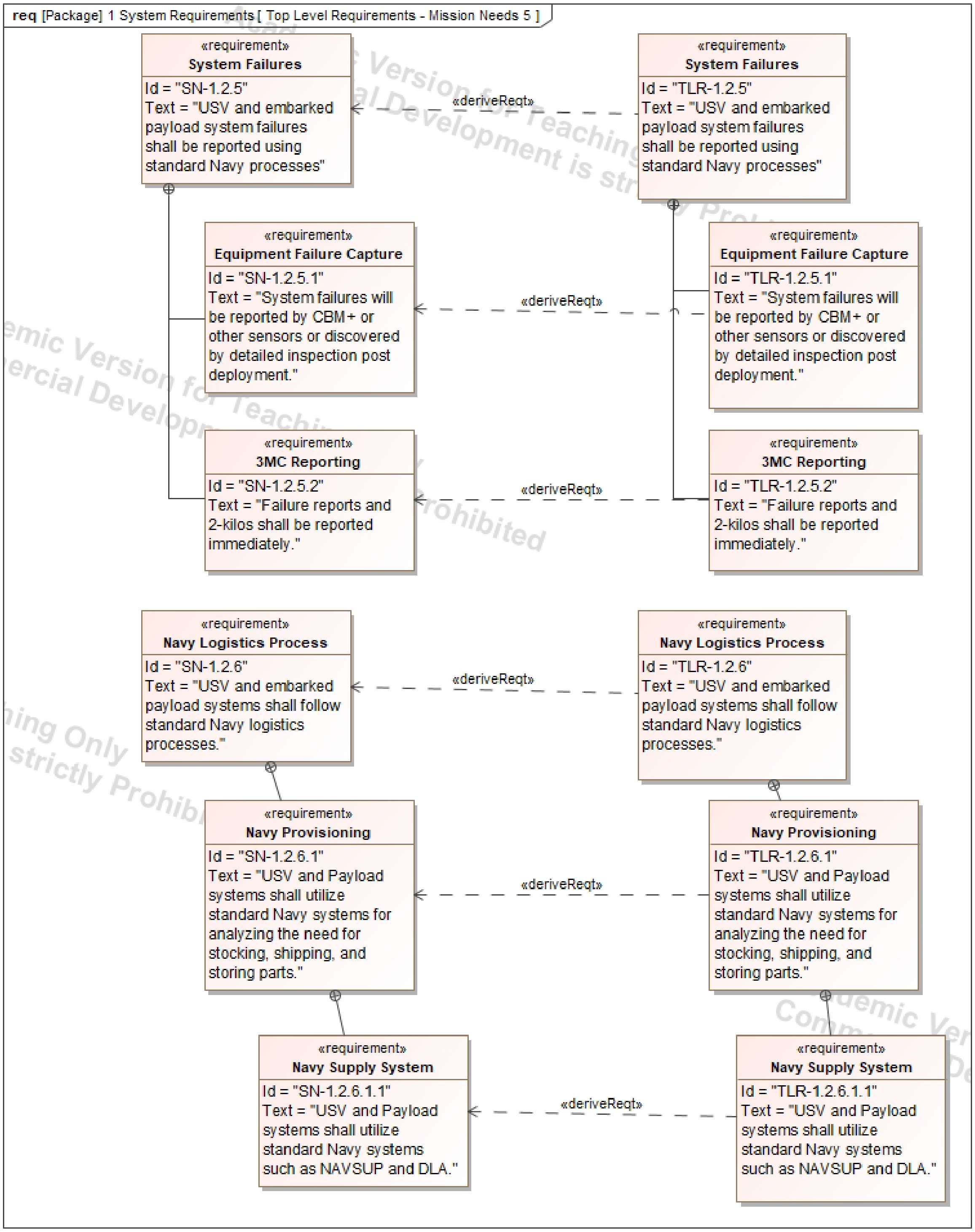

Figure 18. USV Sustainment Top-Level Requirements: Mission Needs Part V

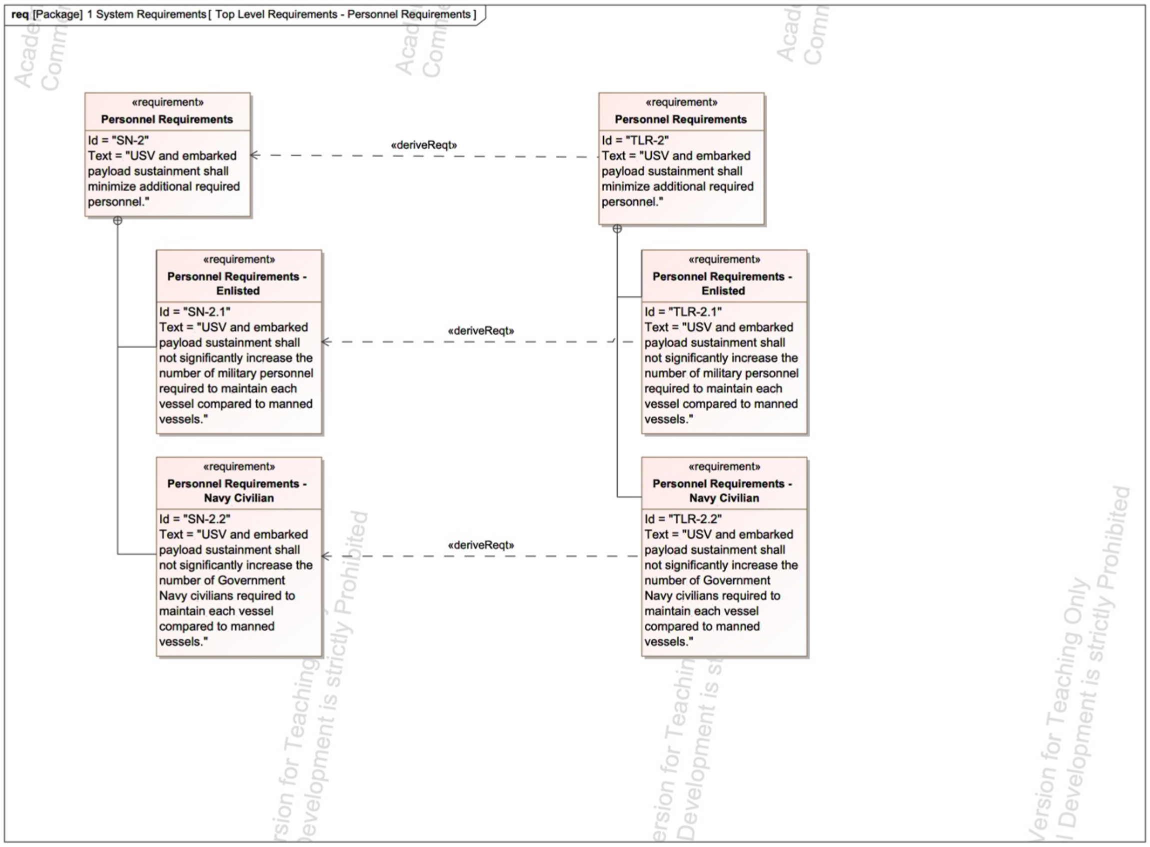

Figure 19. USV Sustainment Top-Level Requirements: Personnel Requirements

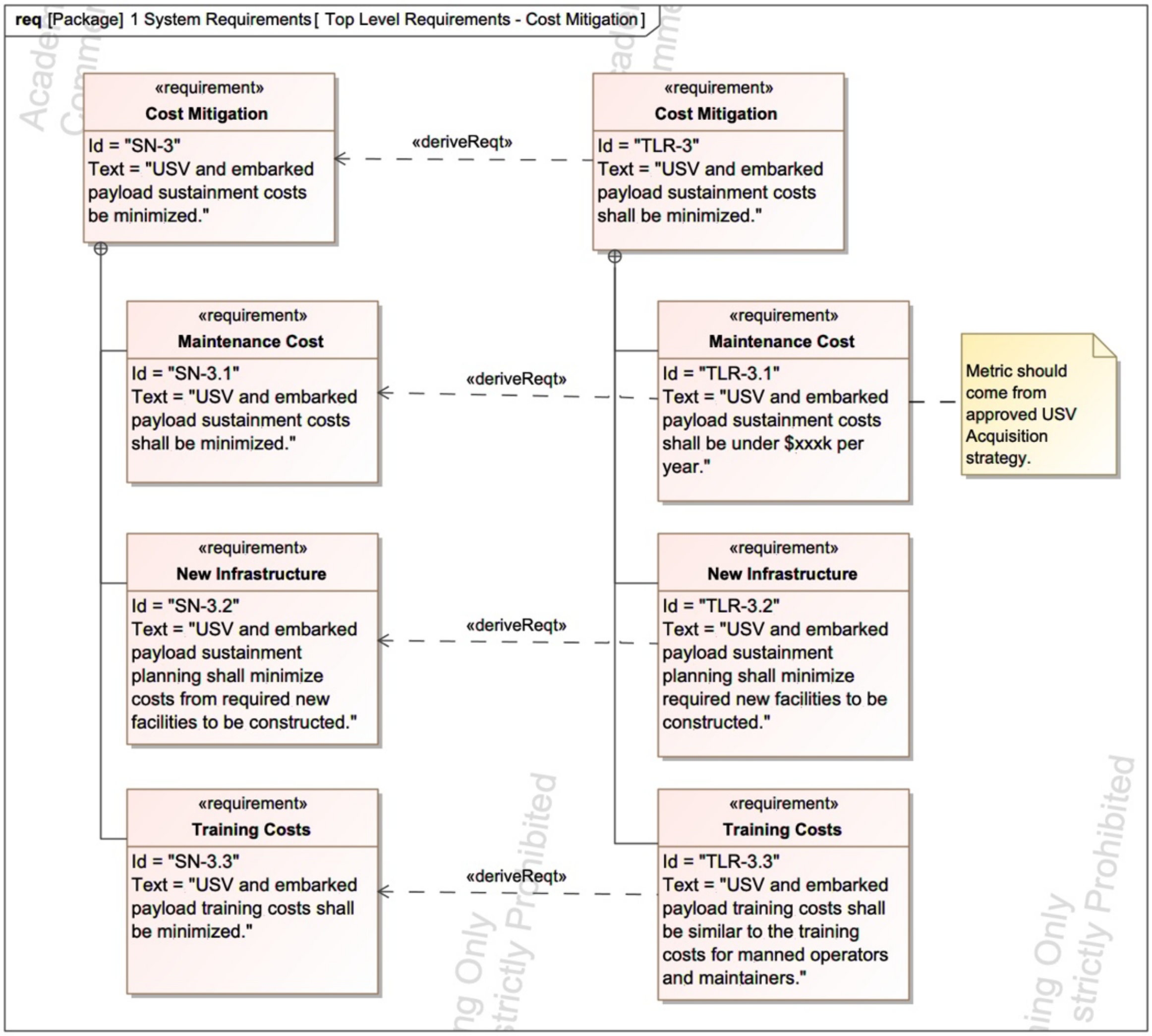

Figure 20. USV Sustainment Top-Level Requirements: Cost Mitigation

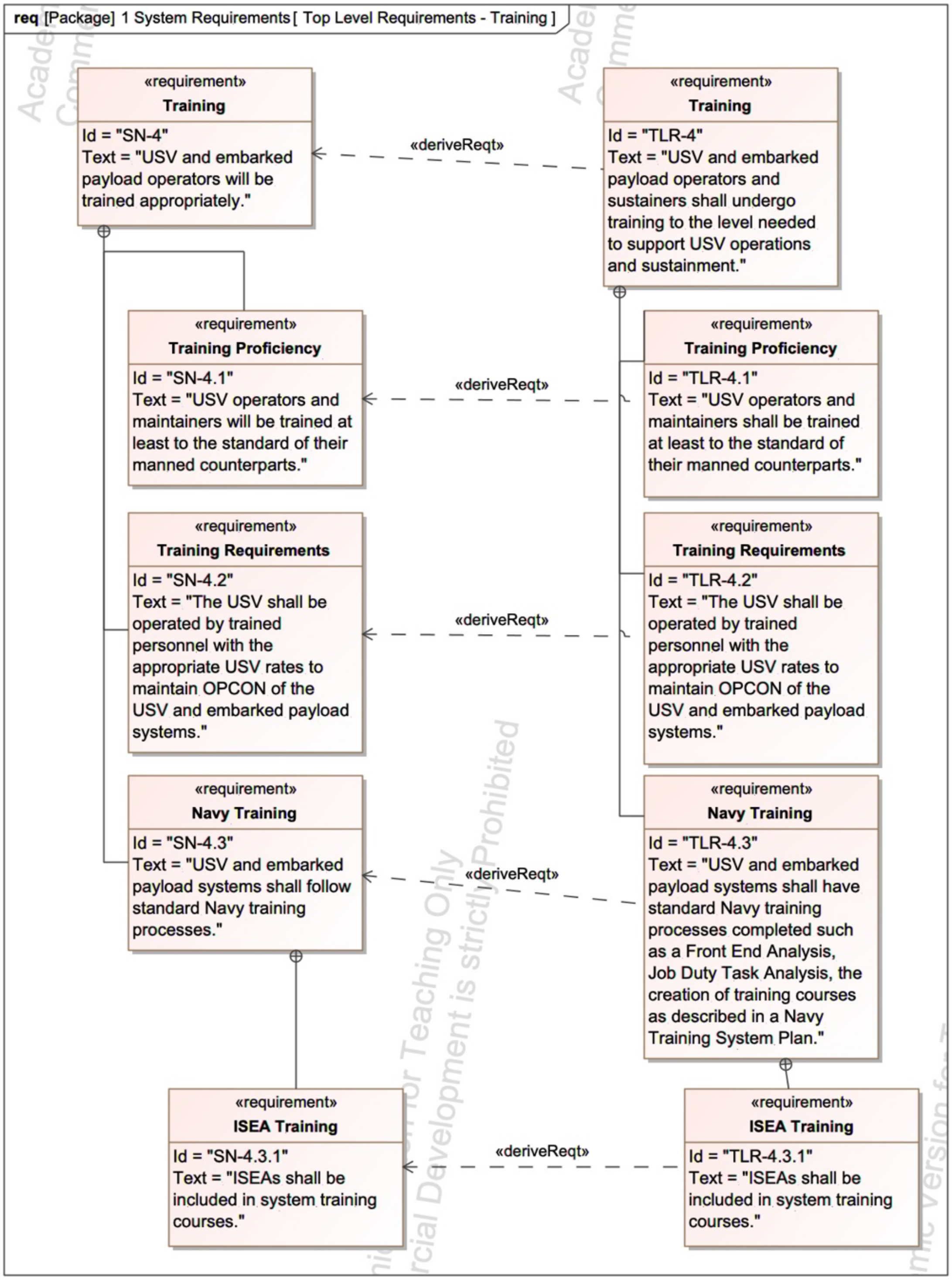

Figure 21. USV Sustainment Top-Level Requirements: Training

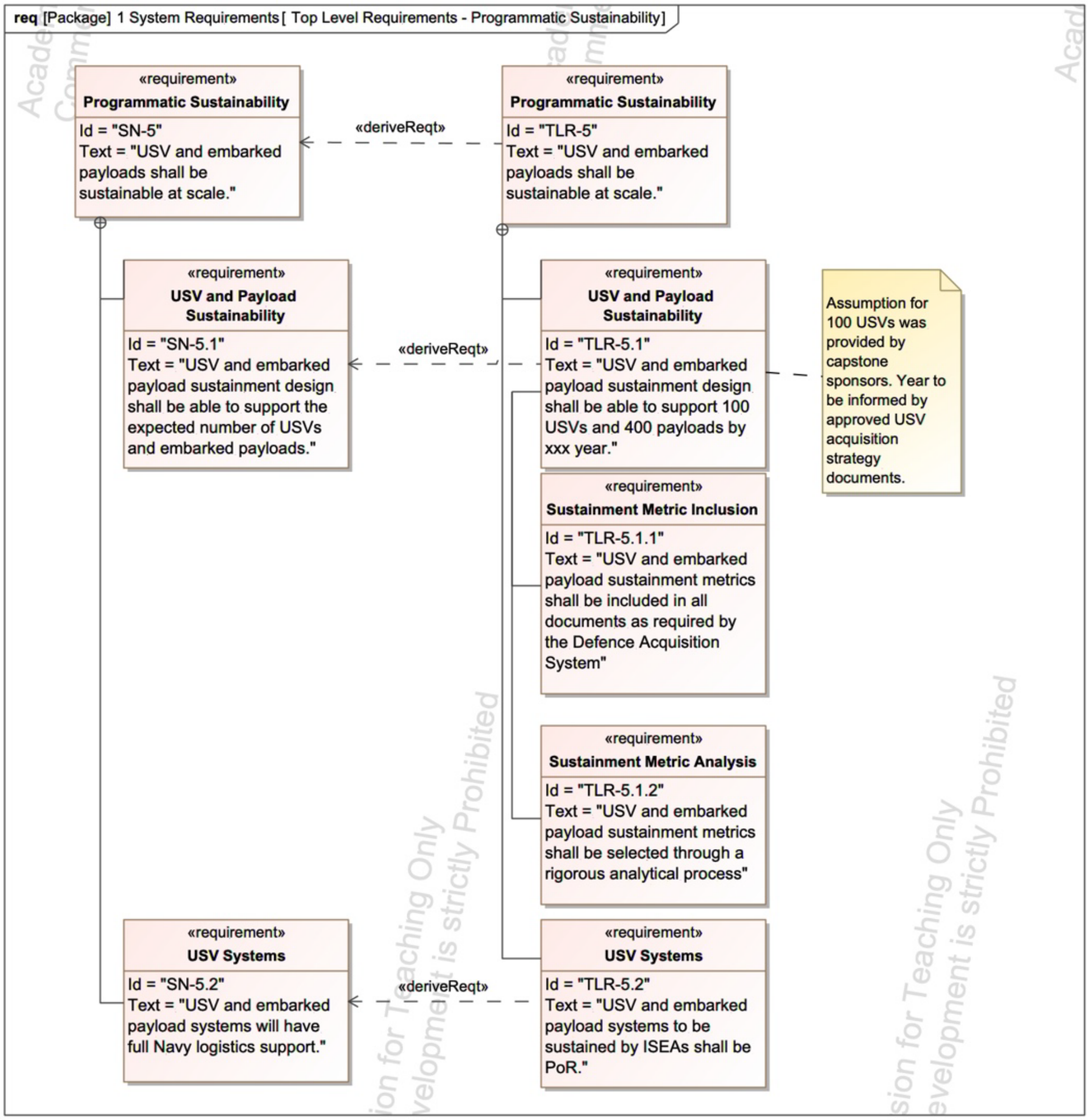

Figure 22. USV Sustainment Top-Level Requirements: Programmatic Sustainability

E. REQUIREMENTS TRACEABILITY

With the top-level requirements identified and decomposed, they now need to be traced to an activity. Hence, the traceability between requirements and activities can be seen in the traceability matrix, Figure 23. From the matrix, the requirements listed on the left are all traced to the activities which run horizontally from the top.

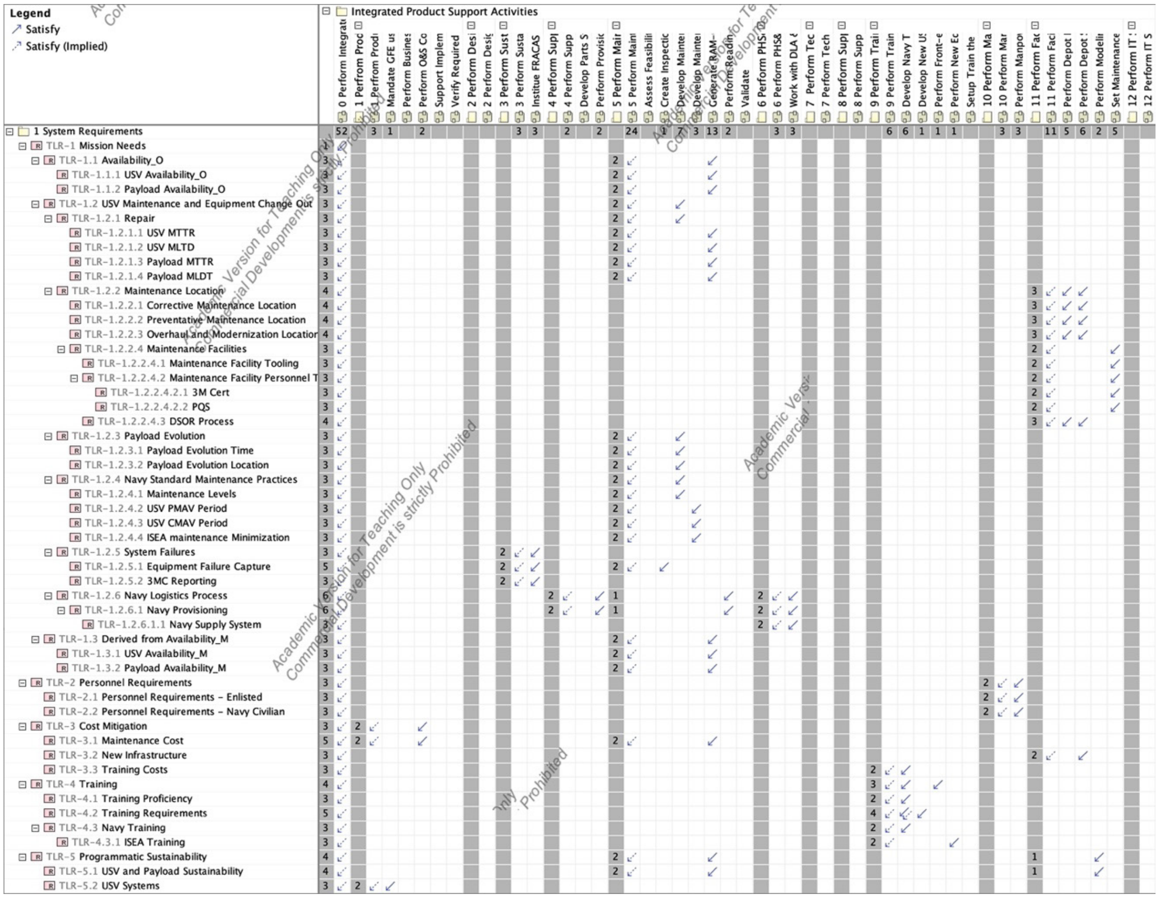

Figure 23. USV Requirements and Activities Traceability Matrix

The list of activities for USV sustainment can be seen in Table 12 which is a reproduction of the activities table from the MSOSA model and includes details of citations for the activity descriptions.

Table 12. USV Sustainment Activities Reproduced from MSOSA Model

Activity	Activity Description
Alignment and Adjustment	Alignment and Adjustment (Fabrycky 2014, 479).
Assess Feasibility	"Develop a composite model using legacy or analogous data to show the sustainment parameters are feasible and consistent with the current state of the art and technical maturity" (Office of the Deputy Assistant Secretary of Defense 2018, 11).
Calibration	"Calibration is a set of graduations to indicate values or positions" (Defense Acquisition University 2021, 238).
Change Fielded System	Change an installed system on the USV.
Checkout	One of the steps in the preventative maintenance cycle. To verify completion of the preventative maintenance activity (Fabrycky 2014, 488).
Condition Verification (Checkout)	Condition Verification (Checkout) (Fabrycky 2014, 479).
Create Inspection Process	Developing inspection standards / process for equipment that will not have preventative maintenance performed while underway.
Detect	Detect that failure has occurred (Fabrycky 2014, 479).
Develop Maintenance CONOPS	"The Maintenance Concept is a "statement of general guidelines to be used in developing the detailed maintenance plan for a system" (Defense Acquisition University 2021, 151).
Develop Maintenance Plan	"A system's Maintenance Plan evolves from the maintenance concept. It prescribes maintenance actions, including intervals; repair levels and locations; personnel numbers and skills; technical data; tools; equipment; facilities; and spares and repair parts for each significant item of a system or equipment" (Defense Acquisition University 2021, 152).
Develop Navy Training System Plan	Development of the high-level strategy for USV system training and a plan to have a detailed system (NTSP) created for new systems.
Develop New USV Rates	Determine the need for and if necessary create new Navy MOS for USV unique functionality.
Develop Parts Storage Concept for USVs	Determine the concept for part storage between the USV, on the controlling vessel, on fly-away teams, or at pre-positioned locations.
Develop Training Curriculum	Develop training curriculum.

Activity	Activity Description
Disassembly (Access)	Identify faulty item and disassemble (Fabrycky 2014, 479).
Explain	Explanation performed during training.
Generate RAM-C Rationale Report	“The Reliability, Availability, Maintainability and Cost (RAM-C) Rationale Report will document the supporting rationale for the JCIDS sustainment parameters. The focus of the trade studies in the RAM-C report will be the sensitivity analysis made between the sustainment parameters (reliability, availability, maintainability, and O&S cost)” (Defense Acquisition University 2021, 99).
Inspection	One of the steps in the preventative maintenance cycle. The portion prior to the active repair activity (Fabrycky 2014, 488).
Installation of Spare/ Repair Part	Installation of Spare/Repair Part
Institute FRACAS System	PSM to mandate Failure Reporting and Corrective Action System be used.
Localization and Isolation	Begin performing maintenance. Localize and isolate failure (Fabrycky 2014, 479).
Mandate GFE use PoR or PoR Transition Agreements	Mandate in product support strategy documentation that all GFE be PoR or have PoR transition agreements.
Metrics Holder Activity	The top-level activity the system context simulates within.
Modify Payload	Modify payload equipment.
Other Resupply	Resupply of non-parts, consumables, or equipment.
Overhaul	“The restoration of an item to a completely serviceable condition as prescribed by serviceability standards” (Military Factory n.d.).
Perform Business Case Analyses & Trade Studies	“The Product Support Business Case Analysis (BCA) is a structured methodology and document that aids decision making by identifying and comparing alternatives by examining the mission and business impacts (both financial and non-financial), risks, and sensitivities” (Defense Acquisition University 2021, 27).
Perform Corrective Maintenance	“Unscheduled maintenance accomplished, as a result of failure, to restore a system or product to a specified level of performance. This includes the initial detection of failure(s), localization and fault isolation (diagnostics), disassembly (access), removal and replacement (or repair) of faulty component, reassembly, adjustment and/or alignment (as required), and final checkout and verification of proper system

Activity	Activity Description
	performance; that is, the corrective maintenance cycle" (Fabrycky 2014, 478).
Perform Depot Maintenance Study	Identify the needs and capabilities for depot maintenance.
Perform Depot Source of Repair Determination Process	Assign workloads to depots or identify the need for the creation of a new DSOR (Defense Acquisition University 2021, 161).
Perform Design Interface Activities	"Design interface is the integration of the quantitative design characteristics of systems engineering (reliability, maintainability, etc.) with the functional Integrated Product Support Elements (i.e., Integrated Product Support Elements)" (Defense Acquisition University 2021, 65).
Perform Facilities and Infrastructure Activities	"Identify, plan, resource, and acquire facilities to enable training, maintenance, and storage to maximize effectiveness of system operation and the logistic support system at the lowest TOC. Identify and prepare plans for the acquisition of facilities to enable responsive support for the Warfighter" (Defense Acquisition University 2021, 285).
Perform Front-end Analysis	"Front-end analysis, also referred to as Training Systems Requirements Analysis (TRSA), is the structured process used to examine training requirements and identify alternative approaches to training job tasks" (Defense Acquisition University 2021, 259).
Perform Integrated Product Support Activities	To perform an activity related to Integrated Product Support (IPS). Top-level activity in IPS activity taxonomy.
Perform IT Support Activities	"Identify, plan, resource, and acquire facilities, hardware, software, documentation, manpower and personnel necessary for planning and management of mission critical computer hardware and software systems" (Defense Acquisition University 2021, 313).
Perform Maintenance	The general activity of performing maintenance. "Maintenance constitutes a series of actions to be taken to restore or retain a system in an effective operational state" (Fabrycky 2014, 477).
Perform Maintenance Planning and Management Activities	"Identify, plan, resource, and implement maintenance concepts and requirements to ensure the best possible equipment/ capability is available when the Warfighter needs it at the lowest possible TOC" (Defense Acquisition University 2021, 150).

Activity	Activity Description
Perform Manpower and Personnel Activities	"Identification and acquisition of required numbers of active and reserve military officers and enlisted personnel as well as civilian personnel with the skills and grades required for system operation" (Defense Acquisition University 2021, 271).
Perform Manpower and Personnel Analysis	Analysis to support the required number and mixture of required personnel.
Perform Modeling and Simulation	Perform modeling and simulation to verify the needs and capabilities for depot maintenance.
Perform New Equipment Training	"New equipment training transfers knowledge gained during materiel development to trainers, users, and support personnel during development and fielding of new equipment. NET provides for the initial training from the program office or contractor to the tester and user" (Defense Acquisition University 2021, 252).
Perform O&S Cost Estimation	Analyzing available data and identifying cost driving elements across the life cycle (Defense Acquisition University 2021, 30).
Perform PHS&T Planning and Management Activities	"Identify, plan, resource, and acquire packaging/preservation, handling, storage, and transportation (PHS&T) requirements to maximize availability and usability of the materiel to include support items whenever they are needed for training or mission success" (Defense Acquisition University 2021, 172).
Perform Preventative Maintenance	"Preventive maintenance. Scheduled maintenance accomplished to retain a system at a specified level of performance by providing systematic inspection, detection, servicing, or the prevention of impending failures through periodic item replacements" (Fabrycky 2014, 478).
Perform Product Support Manager Activities	"Plan, manage, and fund product support across all IPS Elements" (Defense Acquisition University 2021, 8).
Perform Provisioning Tasks	"Provisioning is the process of determining the range and quantity of specific items of supply necessary to operate and maintain an end item for an initial period of operation" (Defense Acquisition University 2021, 125).
Perform Readiness Based Sparing	"Readiness-Based Sparing (RBS) is the practice of using advanced analytics to set spares levels and locations to maximize system readiness. Readiness-Based Sparing determines the inventory requirements for achievement of readiness goals" (Defense Acquisition University 2021, 126).
Perform Supply Support Activities	"Supply support consists of all management actions, procedures, and techniques necessary to determine requirements to acquire, catalog, receive, store, transfer, issue and dispose of

Activity	Activity Description
	spares, repair parts, and supplies" (Defense Acquisition University 2021, 121).
Perform Support Equipment Activities	"Identify, plan, resource and implement management actions to acquire and support the equipment (mobile or fixed) required to sustain the operation and maintenance of the system to ensure that the system is available to the Warfighter when it is needed at the lowest Total Ownership Cost (TOC)" (Defense Acquisition University 2021, 232).
Perform Sustaining Engineering Activities	"Sustaining engineering returns a system to its baseline configuration and capability and identifies opportunities for performance and capability enhancement. It includes the measurement, identification, and verification of system technical and supportability deficiencies, associated root cause analyses, evaluation of the potential for deficiency correction and the development of a range of corrective action options" (Defense Acquisition University 2021, 95).
Perform Technical Data Activities	"Identify, plan, validate, resource, and implement management actions to develop and acquire information" (Defense Acquisition University 2021, 193).
Perform Training	Provide training.
Perform Training and Training Support Activities	"Plan, resource, and implement a cohesive integrated strategy early in the development process to train military and civilian personnel to maximize the effectiveness of the doctrine, manpower and personnel, to fight, operate, and maintain the equipment throughout the life cycle. As part of the strategy, plan, resource, and implement management actions to identify, develop, and acquire Training Aids, Devices, Simulators, and Simulations (TADSS) to maximize the effectiveness of the manpower and personnel to fight, operate, and sustain equipment at the lowest TOC" (Defense Acquisition University 2021, 248).
Prepare for Maintenance	Confirm that failure has occurred and prepare for maintenance (Fabrycky 2014, 479).
Provide Shipping	Ship parts, consumables, or equipment.
Provide Storage	Store parts, consumables, or equipment.
Reassembly	Reassembly (Fabrycky 2014, 479).
Refuel	Refuel the USV.
Refuel/Resupply	Refuel or resupply the USV.
Removal of Faulty Item	Removal of Faulty Item (Fabrycky 2014, 479).

Activity	Activity Description
Repair of Equipment	Repair of Equipment (Fabrycky 2014, 479).
Servicing	One of the steps in the preventative maintenance cycle. The active repair portion (Fabrycky 2014, 488).
Set Maintenance Facility & Personnel Standards	Set standards for required facility equipment and personnel standards those in organic and contractor DSORs are to meet.
Setup Train the Trainer Program	"Ensuring that those individuals who will conduct the training are not only subject matter experts but also knowledgeable in actual teaching/training practices is important" (Defense Acquisition University 2021, 256).
Support Implementation of JCIDS Sustainment Measures	PSM to perform engineering analysis to recommend and or validate appropriate measure values for suitability metrics included in JCIDS capability documents.
Swap Organic USV System	Remove and replace installed organic equipment on USV.
Swap Payload	Remove and replace installed payload on USV.
Train by Classroom	Provide training in a classroom environment.
Train by Doing	On-the-job training.
Update Training Materials	Updating training materials to correct errors or due to system change.
USV Sustainment Infrastructure Loop	The top-level activity related to USV sustainment.
Validate	"Analyze the sustainment parameters to show they are consistent with the CONOPS, the OMS/MP and maintenance/ sustainment concept and that they support each other (the math works)" (Office of the Deputy Assistant Secretary of Defense 2018, 11).
Verify Required Metrics are Included	PSM to verify required suitability metrics are included in JCIDS capability documents per the JCIDS manual.
Work with DLA & NAVSUP to Verify PHS&T Requirements	Work with DLA & NAVSUP to verify the correct PHS&T requirements are included in GFE.

Each use case is allocated to at least one activity, the allocation between activities and use cases is seen in the allocation matrix, Figure 24.

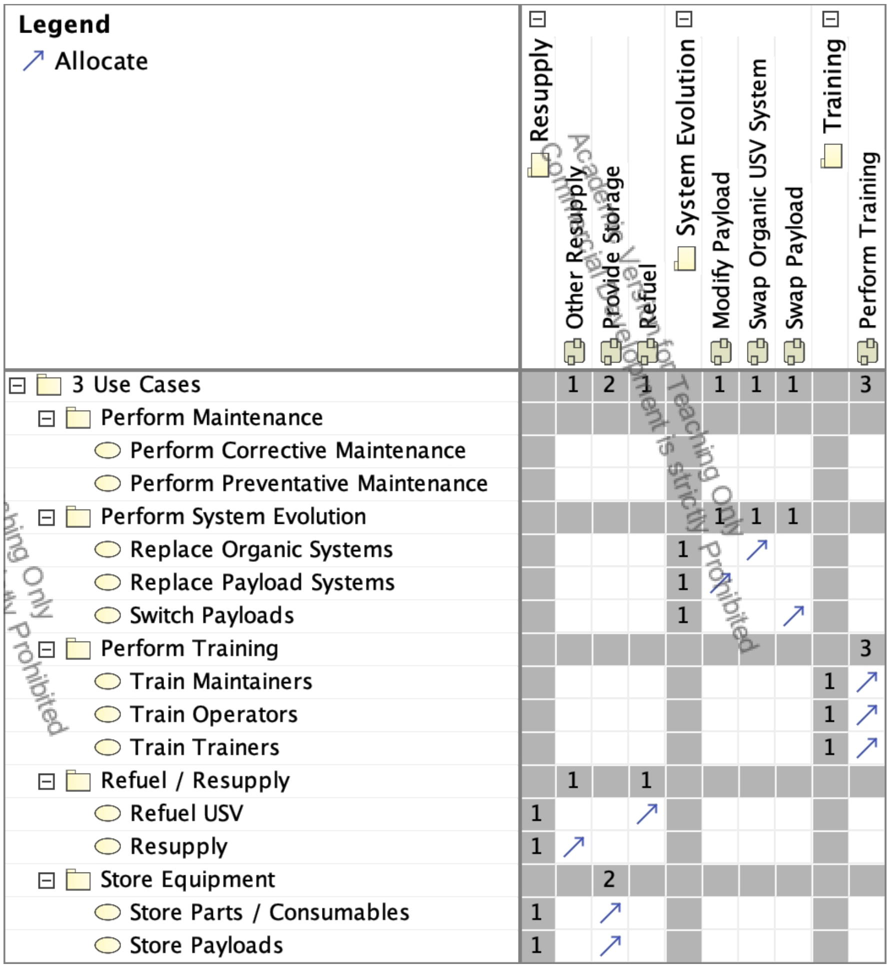

Figure 24. USV Sustainment Allocation of Activities and Structure

F. USV SUSTAINMENT INTEGRATED PRODUCT SUPPORT

Guidance is to be provided by the USV Sustainment Capstone team to the USV IPS team so they can perform trade studies to ensure that the USV will meet Fleet needs while being able to be sustained in a cost-effective manner. The USV Sustainment Capstone team will analyze preventative and corrective maintenance activities to occur OCONUS on up to 100 USVs as part of a DSOR analysis. Then, the findings will be documented and reported to the USV PMS team, so it can be reviewed as a part of the decision-making process for other integrated product support (IPS) decisions, such as the development of a Maintenance CONOPS or DSOR assignment that will be handled by the appointed USV IPS team.

The USV Sustainment Capstone team provided a process to follow for USV product support teams to use for their specific USV. Part of the simulation analysis took place which included the RAM-C Analysis step 4 which is to "Analyze the sustainment parameters to show they are consistent with the CONOPS, the Operational Mode Summary/ Mission Profile (OMS/MP) and maintenance/sustainment concept and that they support each other (the math works)" (Office of the Deputy Assistant Secretary of Defense 2018). Due to the USV maintenance CONOPS, it does not have the capability to perform preventative or corrective maintenance while underway, thus increasing the difficulty of meeting the sustainment KPP at the platform level. It is critical that the USV CONOPS, OMS/MP, sustainment KPP, and maintenance CONOPS are to be validated as early as possible by the USV Program Office to minimize the risk of USV system development. As part of the modeling and simulation and data analysis, simulations will be run to recommend the depot configuration that provides the greatest capability at the lowest cost. Step 5 of the RAM-C Analysis is to "[d]evelop a composite model using legacy or analogous data to show the sustainment parameters are feasible and consistent with the current state of the art and technical maturity" (Office of the Deputy Assistant Secretary of Defense 2018). Of course, the Navy will need to develop bespoke USV systems which will receive reliability and availability allocations from the platform. Additionally, it must allow the USV to perform its intended missions according to the documents discussed earlier. It is critical these systems receive their allocations while in the requirement development phase.

G. CHAPTER SUMMARY

To conclude, the USV sustainment infrastructure, which includes resupply, maintenance, training, and system evolution has requirements that were derived from multiple areas. These areas included CONOPSs, JCIDS documents, notional logistics strategy and maintenance CONOPS, and stakeholders. Understanding the composition of the Navy as-is sustainment infrastructures that includes training facilities, maintenance facilities, and the supply infrastructure allowed for a hierarchy of components to be developed. Requirements were then developed, decomposed, and traced to activities. Use cases were also developed and traced to activities to ensure there were no missing activities.

The use cases help illustrate the operations and intended behavior of the system. The activities generated include recommended activities for the USV IPS team to perform and verify that their specific USV can be effectively sustained. The USV Sustainment Capstone team will analyze the USV preventative and corrective maintenance activities to provide guidance to the USV PMS team to assist in meeting the fleet's sustainment needs.

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V. MODELING, SIMULATION, AND ANALYSIS

This chapter discusses the modeling and simulation tools selected for this project, focusing on the back-of-the-envelope and ExtendSim models that were created. Additionally, the verification and validation of the models, data analysis, and cost analysis are discussed in detail.

A. MODELING AND SIMULATION TOOLS BACKGROUND

Two of the goals of the DOD Digital Engineering Strategy include "[formalizing] the development, integration, and use of models to inform enterprise and program decision making" and "[providing] an enduring, authoritative source of truth" (Office of the Deputy Assistant Secretary of Defense for Systems Engineering 2018, 4). To achieve these goals, many different M&S tools were considered by the USV Sustainment Capstone team. To develop a single source of truth and traceability throughout the system life cycle tying together requirements, system behavior, and realizing system elements, it was determined that MBSE was required. Examples of some popular MBSE tools include Magic Systems of Systems Architect (MSOSA)/Cameo System Modeler, Innoslate, IBM Rhapsody, Sparx Enterprise Architect, and Vitech Genesys. MSOSA was selected as the MBSE tool as it fully implements the System Modeling Language (SysML) specification and is widely used in Navy acquisition. For more detailed modeling and simulation, some available tools include ExtendSim, MATLAB, and Simio. ExtendSim was selected as the USV Sustainment Capstone team had experience with the tool and it was able to output the required data. Lastly, for data analysis, some available tools include: MiniTab, MS Excel, R, and Python statistical libraries. MS Excel was chosen due to the team's familiarity with the tool as well as MS Excel's versatility for developing random input data, performing analysis, and displaying customizable graphs and tables all without leaving the tool.

B. MODELING TOOL DOWNSELECT

As mentioned earlier, MSOSA, MS Excel, and ExtendSim were the tools selected for modeling, simulation, and analysis, to cater to the needs of the USV's sustainment infrastructure stakeholders. MSOSA, as discussed earlier, was first used to capture the USV sustainment infrastructure, including its requirements, use cases, activities, and realizing elements. MSOSA was then used to generate a back-of-the-envelope (BOE) model to output A_M and A_O to verify the outputs of the more detailed ExtendSim model. ExtendSim provided simulation capabilities for multiple USVs over time, allowing for USV processing and queuing to generate more accurate availability and cost data for later analysis. MS Excel was used to generate input values for the ExtendSim model and to perform data analysis on the output data.

C. BOE MODEL

The team developed a BOE model in MSOSA to provide a source of data to verify the results from the yet-to-be-developed ExtendSim model. The BOE model was designed to output A_M and A_O for a fleet of USVs given a set of input conditions. The formulas for calculating A_M and A_O were previously listed in Chapter IV Section D, Equation 2 and 4 respectively.

Several assumptions were made for the BOE model which are listed in Table 13 and are expanded upon in the following section.

Table 13. BOE Model Assumptions

Name	Description
USV Population	USV population assumed to be at a constant value of 100
USV Operational Availability (A_O)	USV population expected to perfectly follow the FDNF-Japan deployment profile in terms of the USV being available to perform a mission
USV Materiel Availability (A_M)	USV population not expected to include any assets used for training or spares which would lower A_M
Mean-time between preventative maintenance (MTBPM)	MTBPM assumed to be constant value of 40 days
Mean-time between failure (MTBF)	MTBF assumed to be 40 days

The total USV population is assumed to be 100 as a middle ground of publicly discussed figures between 59 and 166 MUSVs and LUSVs (O'Rourke 2023.a, 9). This analysis can be repeated with the correct number of USVs using figures from the USV's acquisition strategy. The average number of available USVs was calculated based on the number of USVs expected to be in a deployable phase and the percentage of USVs in a deployable phase expected to be operational at a given moment, also known as A_O.

To calculate A_M, the average number of operationally availably USVs and the total USV population are needed. Utilizing the model, A_M was calculated using a parametric diagram shown in Figure 25.

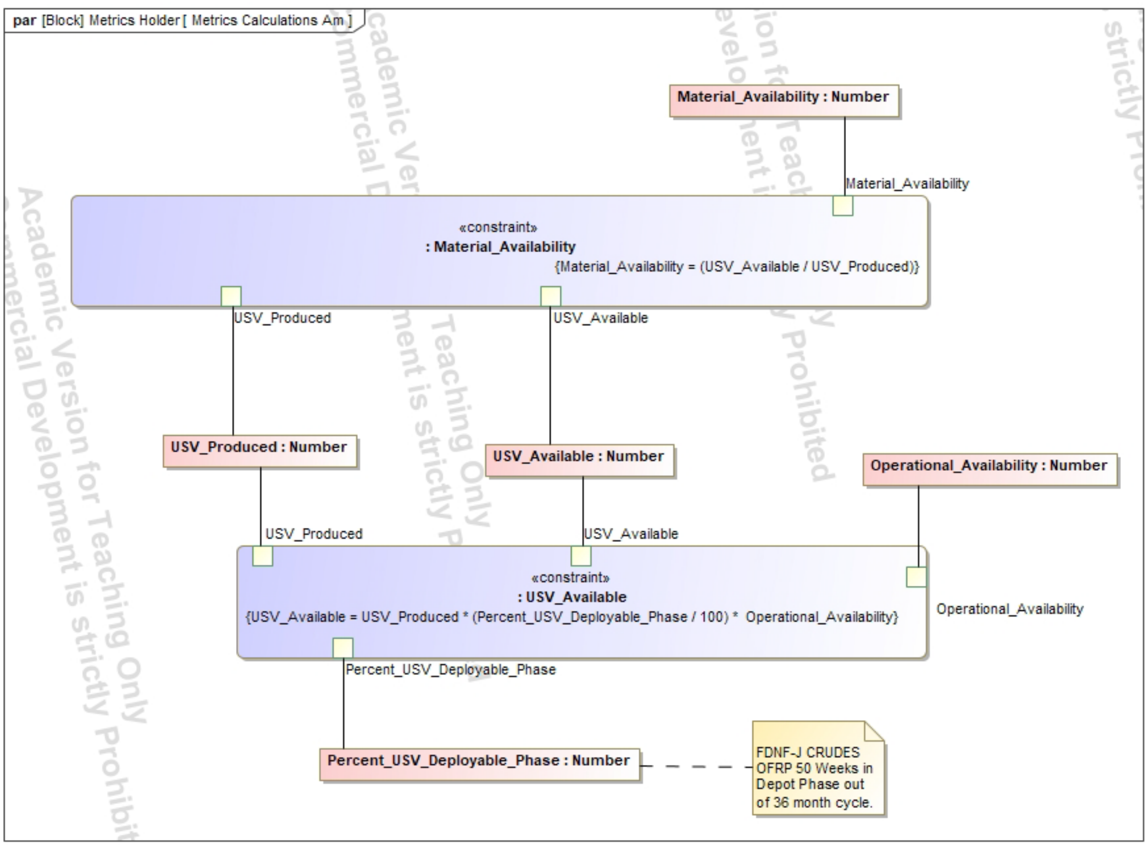

Figure 25. A_M BOE Calculation

To calculate A_O, the mean time between maintenance (MTBM) and the mean maintenance downtime (MDT) are needed as MTBM represents the uptime for the USV and MDT represents the downtime of the USV from Equation 4 and is shown in Figure 26.

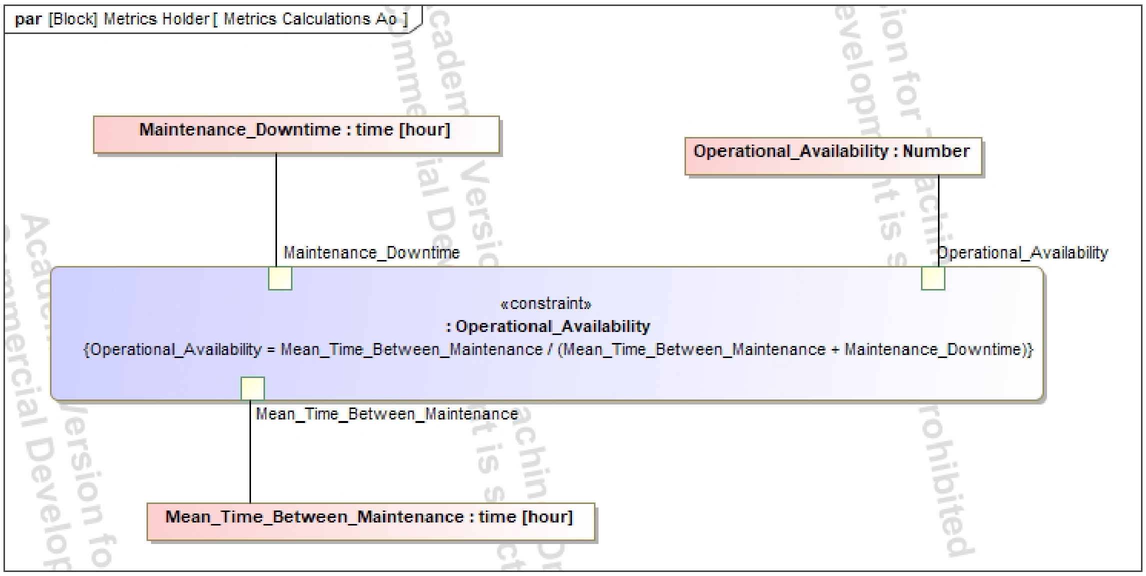

Figure 26. A_O BOE Calculation

The mean time between maintenance was assumed as an input and was assumed to be 40 days given the maintenance concept of not performing maintenance while underway. The mean maintenance downtime was calculated based off the mean active maintenance time, mean logistics delay time, and mean administrative delay time as seen in Figure 27 and in Equation 5 and 6.

$$Active\ Maintenance_{Time} = Corrective\ Maintenance_{Time} + Preventative\ Maintenance_{Time} \quad (5)$$

$$MDT = Active_{Maintenanc_{Time}} + Logistics_{Delay_{Time}} + Administrative\ Delay_{Time} \quad (6)$$

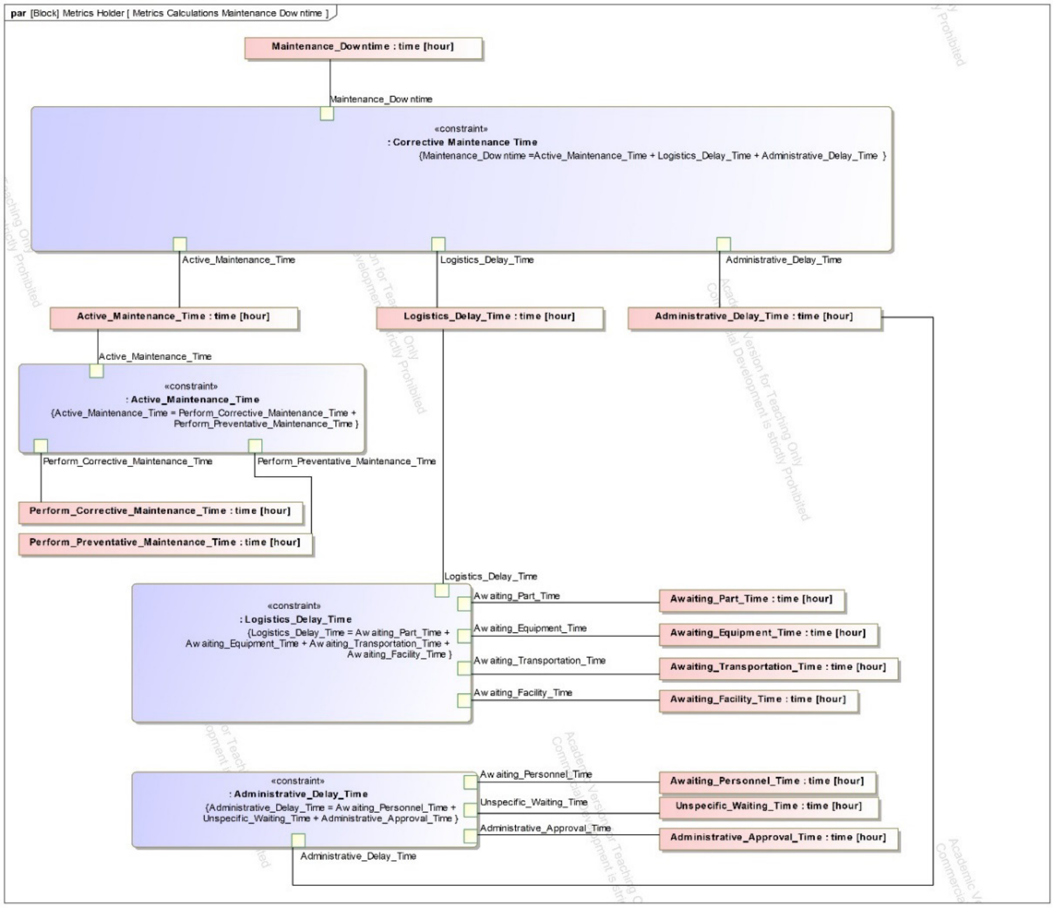

Figure 27. Mean Maintenance Downtime BOE Calculation

The active maintenance time is composed of the actual work of performing maintenance. The processes for corrective and preventative maintenance were taken from (Fabrycky 2014, 37). As seen in Figure 28, the activities for corrective maintenance are to:

- Detect
- Prepare for maintenance
- Localization and isolation
- Disassembly
- Repair equipment or remove and replace equipment
- Reassembly

- Alignment and adjustment
- Equipment checkout.

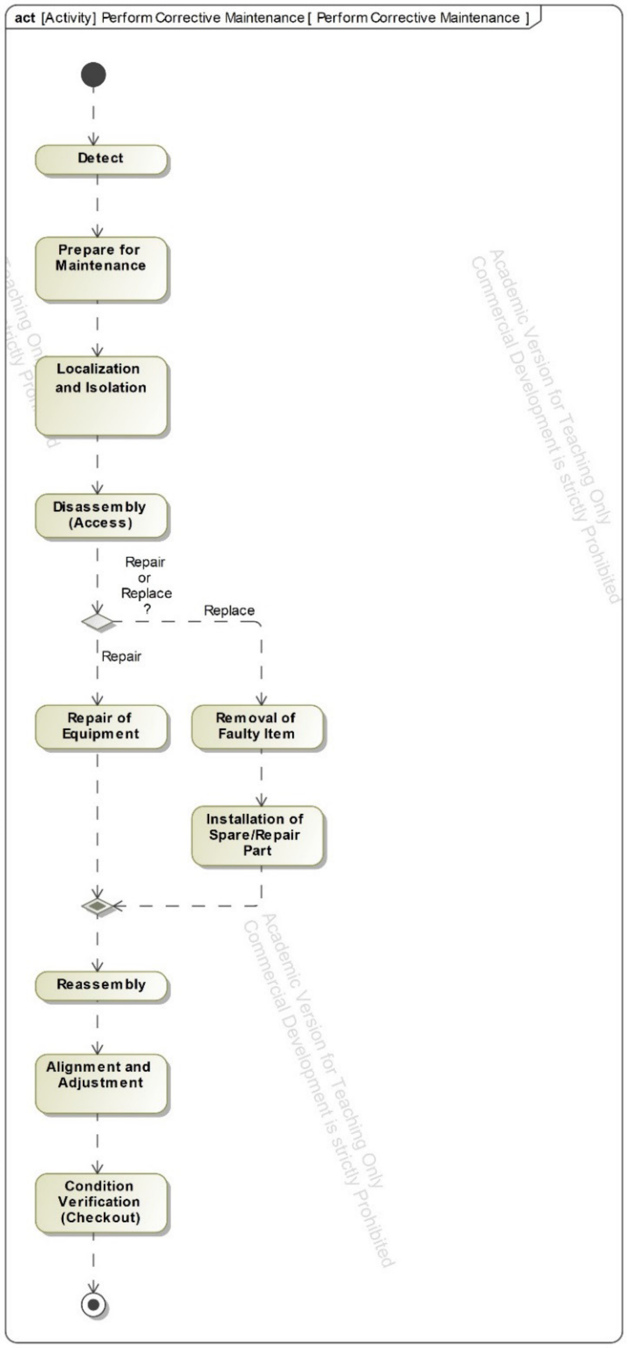

Figure 28. Corrective Maintenance Steps

As seen in Figure 29 the steps for performing preventative maintenance are:

- Preparing for maintenance
- Inspection
- Servicing
- Equipment checkout.

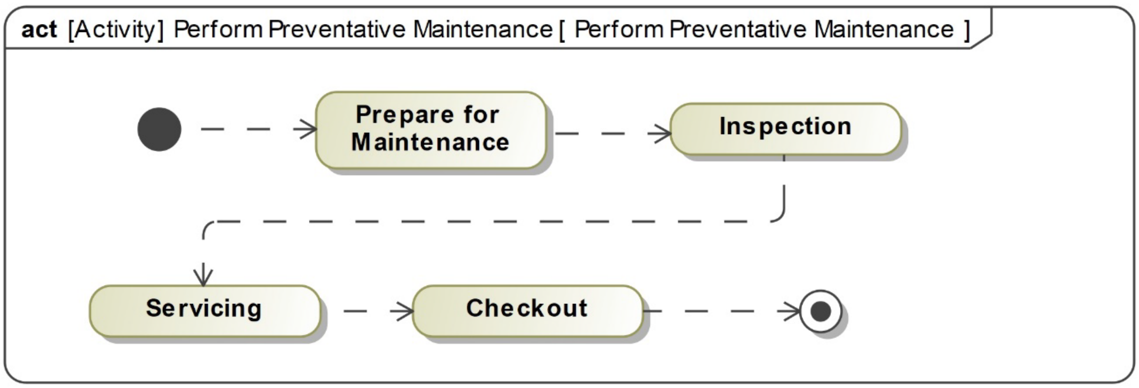

Figure 29. Preventative Maintenance Steps

The time required to perform active corrective and preventative maintenance was selected from historical open-source data from the LCS program for length and time required to complete PMAVs and CMAVs. The mean logistics delay time was composed of time waiting for parts, equipment, transportation, and facilities, while the mean administrative delay time was composed of time waiting for personnel availability, time waiting for approvals, and a general unspecific waiting time. Times for mean delays were selected based off intuition and experience, since there was not open-source data available to allow the report to remain Distribution A. Figure 30 shows in a single diagram how all these calculations work together to produce an A_M and A_O.

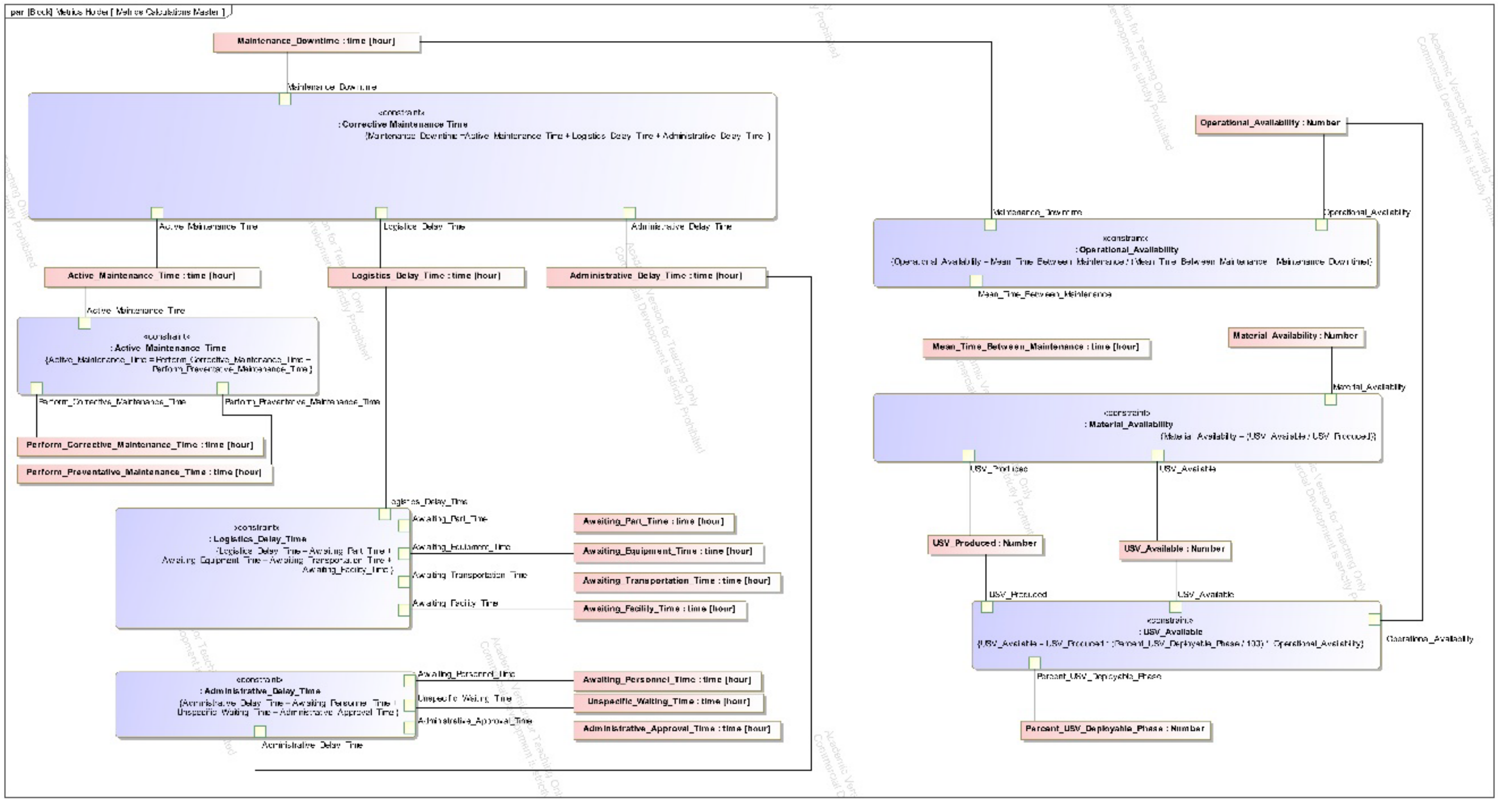

Figure 30. Overall BOE Model

Table 14 and Table 15 show the assumed input parameters and the output metrics respectively from the BOE model.

Table 14. BOE Input Parameters

Input Parameter	Time (days) per ship
Mean time to perform corrective maintenance	14
Mean time to perform preventative maintenance	5
Mean time waiting for parts	1
Mean time waiting for equipment	1
Mean time waiting for transportation	1
Mean time waiting for personnel availability	1
Mean time waiting for approvals	3

Table 15. BOE Output Metrics

Output Parameter	Metric Result
A_M	0.42
A_O	0.61

The ExtendSim model was later verified in this report using the above input and output parameters during its development to check that the model was created correctly.

D. MODELING METHODOLOGY

An ExtendSim model, shown in Figure 31, depicts functional elements utilized for generating statistics, data outputs, and addressing model issues. Figure 32 offers a closer look at the model, specifically focusing on the creation of the USV and its initiation of the maintenance processes. Each USV is assigned a maintenance history identifier initialized with the value zero (0). Value zero (0) indicates that the USV has been recently fielded and has not had its first maintenance cycle. Value one (1) indicates that the USV has received preventative maintenance, value two (2) the USV has received corrective maintenance, and value (3) the USV has received overhaul maintenance. It is assumed that the USV begins its first deployment before the start of the simulation and that the creator block represents the return of the deployed USV. Once the USV returns, it will integrate into the maintenance queue with other USVs and begin their respective maintenance.

The USV moves through various queues and activities until maintenance is completed. If any one of the required resources (maintenance bay, parts, or personnel) are unavailable, the USV will remain in queue until the required resources become available. Bay unavailability, delayed shipment of parts, and shortage of personnel all contribute to extended USV downtime and reduce USV availability.

At the start of each respective maintenance decision block, the MTBPM, MTBCM, and MTTO determines if the USV requires a specific maintenance type. Preventative and corrective maintenance are performed at OCONUS maintenance bays, while overhaul is performed at CONUS maintenance bays. After completing the required maintenance, the respective criteria timer resets and the USV proceeds to the next maintenance cycle or deployment. After deployment, the USV repeats the maintenance cycle phase again, starting with preventative maintenance.

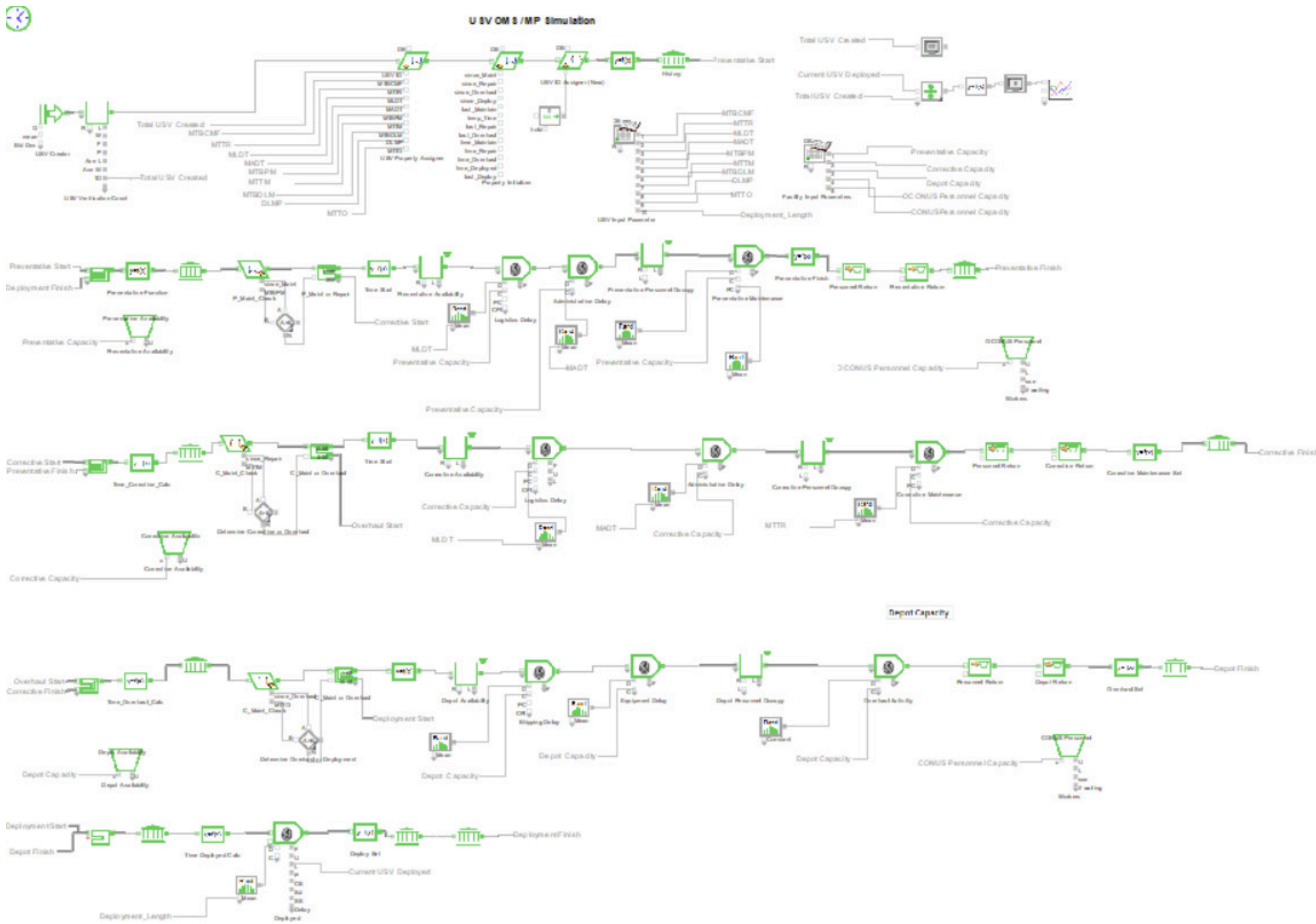

Figure 31. Complete ExtendSim Model

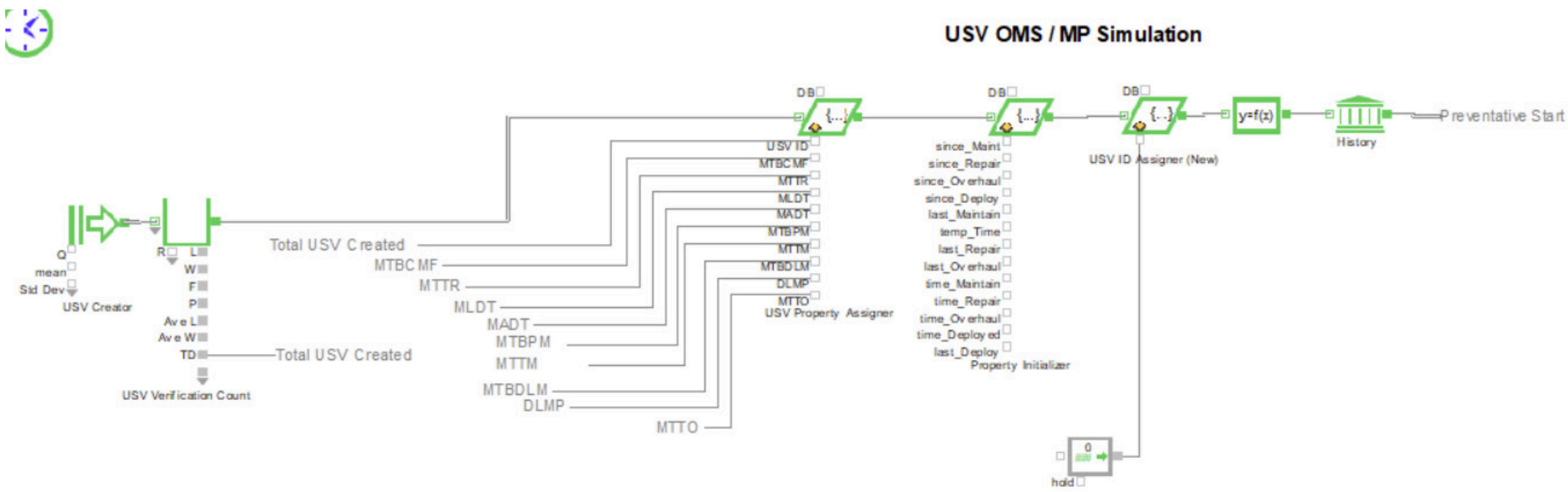

Figure 32. ExtendSim Model Highlight

An ExtendSim model was developed to capture expected maintenance activities on USVs over a 10-year period. The model's assumptions are shown in Table 16, which include the additional assumptions from the BOE model assumptions from Table 13, while Table 17 lists the model's input parameters.

Table 16. ExtendSim Model Assumptions

Name	Description
USV Population	USV population initiates with the count of 1 and expands to 100, consistently throughout the 10-year period
USV Operational Availability (A_O)	USV population follows a custom maintenance schedule influenced by LCS's PMAV, CMAV, and deployment profile. This framework determines the USV's availability to perform a mission.
USV Materiel Availability (A_M)	USV population not expected to include any assets used for training or spares which would lower A_M
Mean-Time Between Preventative Maintenance (MTBPM)	MTBPM assumed to be 40 days
Mean-Time Between Corrective Maintenance (MTBCM)	MTBCM assumed to be 40 days
Mean-Time to Overhaul (MTTO)	MTTO assumed to be 153 days

Table 17. ExtendSim Model Parameters

Input Parameters	Time (days) per ship
Mean time to perform corrective maintenance	14 days
Mean time to perform preventative maintenance	5 days
Mean time to perform overhaul	47 days
Mean time for deployment	40 days
Mean time delay for administration	3 days
Mean time delay for logistics	4 days

E. MODEL VERIFICATION AND VALIDATION

To verify and validate the outcomes, a model was constructed with both the system and its subsystems. The model required iterative and parallel actions to effectively capture metrics. In "system design, various analytical techniques may be used to predict and evaluate the anticipated characteristics of a proposed system" (Fabrycky 2014, 151). The analytical technique to predict the anticipated characteristics involved utilizing available stand-in LCS data in the BOE model referenced above to provide a comparative data set since real-world USVs data was unavailable. Once those outputs of the BOE model were validated, the ExtendSim model began verification by entering the same input parameters and comparing the outputs to the BOE model. Characterized by a lognormal distribution, preventative, corrective, and overhaul maintenance cycle, incorporate logistics delay time (LDT) and administrative delay time (ADT). Validation for the ExtendSim model was set to create a USV population that initiates with the count of 1 and expands to 100, consistently throughout the 10-year period with deterministic parameters. Given that actualized current data would create a CUI document, similar values were chosen to illustrate that the system produces realistic numbers and outputs. Those results shown in Table 18 helped determine which areas of the systems were efficient and where changes and suggestions can be made.

When the ExtendSim Model was simulated using the factors from the BOE model, it was found that both results were within five percent. The closeness of these two results, calculated in very different ways verifies that the ExtendSim model is most likely operating properly.

Table 18. ExtendSim Model Verification Results

Output Parameter	Metric Result (40 Days)
A_M	Time Deployed: 1561 Maintenance Downtime: 1869 **Result: 46%**
A_O	Time Deployed: 1561 Maintenance Downtime: 1228 **Result: 56%**

F. DESIGN OF EXPERIMENTS AND SIMULATION METHODOLOGY

To minimize the number of required simulations while maximizing the amount of information gained, DOE was utilized to select the model input parameters, or DOE factors, seen in the below table. A fractional factorial DOE was used to generate alternative input configurations for the OCONUS maintenance facilities. To make the initial analysis possible, only the number of available OCONUS maintenance bays was varied. The number of overhaul maintenance bays, personnel required, and delay times for each activity block were kept constant. These configurations tested were designed to cover a wide range of values, to determine where the sustainment system becomes stressed (meaning the system outputs a low A_M and A_O) as factors are varied. The factors are listed in Table 19 and the different model configurations that were run are shown in Table 20.

Table 19. DOE Factors

Factor	Value(s)
Number of maintenance bays capable of being utilized for preventative maintenance	[10, 25, 40]
Number of maintenance bays capable of being utilized for corrective maintenance	[15, 35, 55]
Number of maintenance bays capable of being utilized for overhaul maintenance	30
Capacity of personnel required for CONUS	90
Capacity of personnel required for OCONUS	180

Table 20. ExtendSim Model Configuration Builds

Configuration Number	Build
1 (Baseline)	Preventative Capacity: 25 Corrective Capacity: 25 Depot Capacity: 30 CONUS Personnel Capacity: 90 OCONUS Personnel Capacity: 180

Configuration Number	Build
2	Preventative Capacity: 10 Corrective Capacity: 55 Depot Capacity: 30 CONUS Personnel Capacity: 90 OCONUS Personnel Capacity: 180
3	Preventative Capacity: 40 Corrective Capacity: 15 Depot Capacity: 30 CONUS Personnel Capacity: 90 OCONUS Personnel Capacity: 180
4	Preventative Capacity: 10 Corrective Capacity: 15 Depot Capacity: 30 CONUS Personnel Capacity: 60 OCONUS Personnel Capacity: 180
5	Preventative Capacity: 40 Corrective Capacity: 55 Depot Capacity: 30 CONUS Personnel Capacity: 60 OCONUS Personnel Capacity: 180

G. MODEL ANALYSIS

ExtendSim was used to generate cost data for each configuration from the DOE. The cost data was then exported to MS Excel for cost benefit analysis. Costs are incurred when USVs pass through the following activity blocks: administrative delay, logistics delay, preventative maintenance, corrective maintenance, and overhaul. The cost of performing overhaul is dependent on the CONUS personnel's hourly rate and the number of days required to conduct overhaul while the cost of performing preventative and corrective maintenance is dependent on the OCONUS personnel's hourly rate and the number of days required to conduct preventative and corrective maintenance.

The following rates were used in the ExtendSim simulation:

- OCONUS Personnel Rate (per hour): $135 (McAndrew 2023)
    - This value came from summing the average rates identified in the *Fiscal Year 2023 Department of Defense Reimbursable Rates*, the cost came to $132.38. The USV Sustainment Capstone team decided to use round up to the next multiple of 5, so $135.00 was used.
- Preventative Maintenance: $6,000,000
    - Open-source data was not available, therefore the value selected was from an estimate of the total maintenance cost for UUVs, which amounted to $15,000,000, 40% of the cost was allocated for preventative maintenance.
- Corrective Maintenance: $9,000,000
    - Open-source data was not available, therefore the value selected was from an estimate of the total maintenance cost for UUVs, which amounted to $15,000,000, 60% of the cost was allocated for corrective maintenance.
- Overhaul Maintenance: Not accounted for as that would be related to CONUS maintenance cost
- Logistics Delay: Cost is factored into corrective, maintenance, and overhaul maintenance
- Administrative Delay: Cost is factored into corrective, maintenance, and overhaul maintenance

The recommended configuration for the USV sustainment infrastructure must meet the USV's required A_O and A_M. A_O and A_M were charted below versus cost. The least expensive configurations, those that have bay or personnel availability limitations, will incur backlogs on multiple maintenance facilities.

With an assumed 180-day deployment length (Military OneSource 2021), the current traditional U.S. Navy ship deployment data indicates that approximately 28% of the total battle force is currently deploying an average of 82 out of a total of 291 (Lagrone 2023). However, it is important to note that due to the suggested USV Maintenance CONOPS, which does not have maintenance performed underway, it was assumed for the simulation that the average deployment length for USVs is 40 days, to allow for preventative and corrective maintenance to be performed while in port. This maintenance construct leads to a significantly lower average underway percentage for USVs when compared to traditional U.S. Navy ship deployments.

In the data analysis, the simulations were conducted using both 180-day and 40-day deployment scenarios to compare the average underway percentages relative to the total battle force. The results are shown in Tables 21 and 22. It was concluded when 100 USVs were deployed for 180 days, the average underway percentage was approximately 35% meanwhile the average percentage for a 40-day deployment was approximately 23%. The reason for the difference in the total percentage deployed is due to the short deployments for USVs and the maintenance cycles of preventative, corrective, and overhaul at times overlapping causing the USV to come back from deployment and needing to undergo a combination of maintenances. Configuration 1 serves as a baseline as it showcases the USV sustainment and deployment cycle without any queues in maintenance action block. Configuration 2 excels in corrective maintenance performance by increasing maintenance action block utilizations with minimal backlog. Configuration 3 excels in preventative maintenance performance by increasing maintenance action block utilizations with minimal backlog. Configuration 4 emphasizes on cost saving approaches while operating with minimal backlog, however reduced maintenance bays and personnel slightly impact materiel and operational availability. Configuration 5 operates like configuration 1, but with spare maintenance bays.

Table 21. USV Simulation Results for 40 and 180-Day Deployments

Configuration	Total % Deployed for 40 Day Deployment	Total % Deployed for 180 Day Deployment
1 (Baseline)	23%	35%
2	22%	35%
3	20%	35%
4	20%	35%
5	23%	35%

Table 22. 40-Day A_O and A_M Configuration Analysis Results

Configuration	A_O	A_M
1 (Baseline)	56%	46%
2	55%	44%
3	52%	41%
4	52%	41%
5	56%	45%

In a simulation with one USV, the USV passed through the PMAV and CMAV activity block 80 times during a 10-year period. Equation 7 is used to calculate the cost rate per USV processed in CMAV or PMAV.

$$USV\ Cost\ Rate = \frac{Cost\ Rate\ for\ PMAV\ or\ CMAV}{Number\ of\ Processed\ Actions} \tag{7}$$

Utilizing Equation 7 with the rate of $12,479,747 for PMAV and CMAV, 90 total processed actions, gives the rate of $277,327 per USV processed in a CMAV or PMAV activity block.

Equation 8 shows the general equation of the different costs that are needed to calculate the total cost of a system undergoing maintenance. This general equation is modified to calculate the total OCONUS USV maintenance cost shown in Equation 9.

$$Total\ Maintenance\ Cost = Preventative\ Maintenance\ Cost + Corrective\ Maintenance \quad (8)$$

$$Total\ USV\ Maintenance\ Cost = \begin{bmatrix} (\#\ of\ OCONUS\ Personnel) * \\ (Cost\ per\ OCONUS\ Personnel) \end{bmatrix} + [(\#\ of\ PMAVs) * (Cost\ per\ PMAV)] + [(\#\ of\ CMAVs) * (Cost\ per\ CMAV)] \quad (9)$$

The configurations that meet the threshold availability are presented in Table 23. A baseline was drawn to show which configurations are the best candidate. From the selected configurations the expected total USV maintenance costs are calculated utilizing Equation 9 over a 10-year period, the results are shown in Table 23.

Table 23. Maintenance Facility Configuration vs. Life cycle Cost

Configuration	Total Cost (Millions $)
1 (Baseline)	OCONUS Personnel: $102,090,240 No. of PMAVs: 2030 PMAV Cost per PMAV: $150,000 No. of CMAVs: 2009 CMAV Cost per CMAV: $225,000 **TOTAL COST: $858,615,240**
2	OCONUS Personnel: $94,927,680 No. of PMAVs: 1888 PMAV Cost per PMAV: $150,000 No. of CMAVs: 1868 CMAV Cost per CMAV: $225,000 **TOTAL COST: $798,427,680**

Configuration	Total Cost (Millions $)
3	OCONUS Personnel: $88,469,280 No. of PMAVs: 1784 PMAV Cost per PMAV: $150,000 No. of CMAVs: 1738 CMAV Cost per CMAV: $250,000 **TOTAL COST: $760,740,240**
4	OCONUS Personnel: $88,244,640 No. of PMAVs: 1776 PMAV Cost per PMAV: $150,000 No. of CMAVs: 1734 CMAV Cost per CMAV: $250,000 **TOTAL COST: $758,640,240**
5	OCONUS Personnel: $102,135,600 No. of PMAVs: 2030PMAV Cost per PMAV: $150,000 No. of CMAVs: 2010 CMAV Cost per CMAV: $250,000 **TOTAL COST: $858,840,240**

Based on the results of each configuration, the data was then used to calculate the respective cost based on the operational availability and the materiel availability. The data was then plotted in Figures 33 and 34 to show each configuration's cost for based on their respective operational availability and materiel availability. Following the evaluation of 5 distinct setups, configuration 4 emerges as the most economically efficient solution without significantly disrupting the deployment requirements and maintenance schedule of the USV. Configuration 4 requires the least amount of cost to maintain OCONUS facilities while satisfying A_O, A_M, and deployment requirements.

Figure 33. Operational Availability vs. Cost for USV Sustainment Configurations

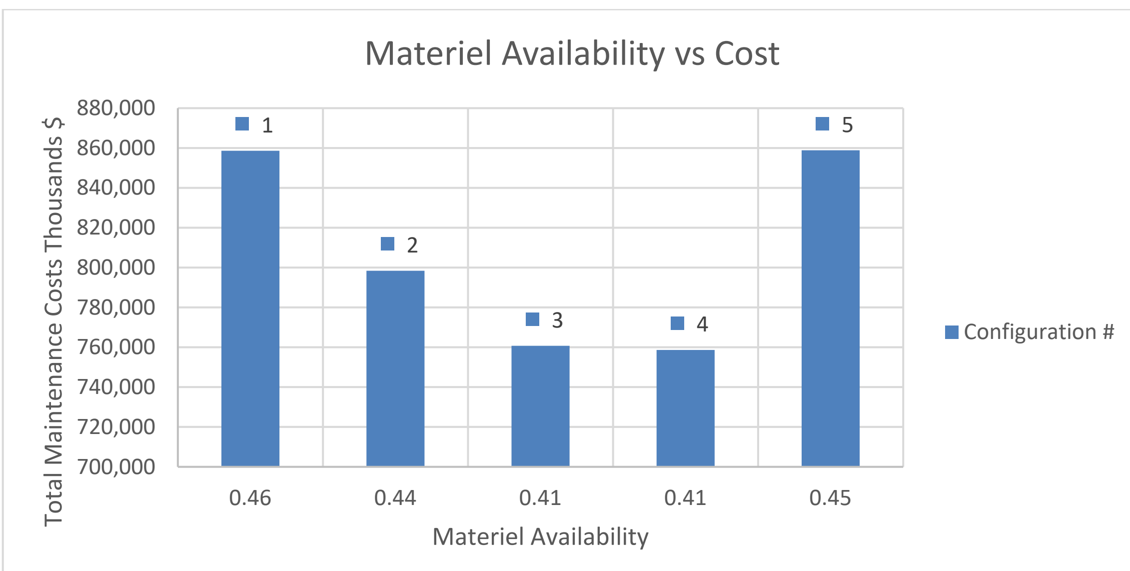

Figure 34. Materiel Availability vs. Cost for USV Sustainment Configurations

H. CHAPTER SUMMARY

In this chapter, the selection and use of modeling tools was discussed. First, the development of the BOE model was described to illustrate how the metrics to make up A_O and A_M are calculated. Results from the BOE model were then used to verify the higher fidelity ExtendSim model. Next, the ExtendSim model was introduced, and its operations were explained. Additionally, the concept of model verification was expanded upon, and the results of the model verification were discussed. Then, DOE was introduced and the specific DOE used for the ExtendSim model was explained. Finally, the methods for estimating cost and a cost benefit analysis of various configurations were completed.

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VI. SUMMARY

This chapter discusses the findings of the higher-fidelity modeling and simulation of the USV maintenance process. These findings are discussed in the context of the rest of the report such as the overall USV Sustainment needs and requirements. Risk management is discussed in this chapter to illustrate risks identified throughout the project. Lastly, recommendations for future work to refine the modeling and simulation are discussed.

A. FINDINGS

Throughout the project, the USV Sustainment Capstone team conducted risk identification, analysis, and management. Risks were managed in accordance with the *Department of Defense Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs* published January 2017. The guide provided information on how to "plan for and manage risks, issues, and opportunities" (Office of the Deputy Assistant Secretary of Defense for Systems Engineering 2017, 3) and was used throughout the risk management process. The risks identified by the capstone team were as a result of the maturity of program. The team also provided a mitigation strategy for each risk to reduce the consequence and probability of occurrence. The USV Sustainment Capstone team's risk management process and outputs can be found in Appendix B.

Following the execution of multiple ExtendSim simulations, it was found that the most significant factor influencing USV availability rates is the availability of corrective maintenance resources. Decreasing the availability of corrective maintenance facilities initiated a cascading effect, leading to backlogs throughout the USV sustainment and deployment cycle. Reducing the accessibility of preventative maintenance facilities had minimal impact, as backlogs were easily addressed due to the brief maintenance times associated with preventative maintenance. The outcomes of multiple ExtendSim simulations highlight the pivotal role of corrective maintenance availability in influencing the USV sustainment life cycle and deployment. While the impact of decreased maintenance availability on USV availability rates was found to be minor, the overall finding highlights the importance of prioritizing efficiency and seamless operation of USVs throughout their sustainment and deployment cycle.

B. PROJECT SUMMARY

The USV Sustainment Capstone team set out to develop recommendations for USV sustainment with a special focus on OCONUS maintenance. The team began this work by identifying and categorizing stakeholders. Through a review of prior work, meetings with relevant stakeholders, and brainstorming sessions, stakeholder needs, and corresponding requirements were generated for USV sustainment. These requirements were captured in an MBSE environment and were traced to activities to be completed which satisfy the requirements. These activities can be used to supplement USV program office sustainment planning. Two of the USV sustainment requirements are for A_M and A_O which are required metrics to include in the JCIDS process for the sustainment KPP and thus were selected as the MOEs for detailed analysis of USV maintenance. The USV MBSE model was expanded to include a BOE model which output A_M and A_O given initial assumptions. The model results were limited as the model is deterministic and did not simulate over time but was used to verify a higher-fidelity ExtendSim model which was stochastic, modeled individual vessels over time, and additionally produced cost data. In the end, ExtendSim configuration 4 seemed the best fit overall, as it required the least amount of cost to maintain OCONUS facilities while satisfying A_O, A_M, and deployment requirements.

C. RECOMMENDATIONS FOR FUTURE WORK

There are many opportunities for future work to expand on this report. Real numbers for average time to perform corrective and preventative maintenance, as well as real cost data can be used in the high-fidelity model. The results of the model using this real data could then be validated against maintenance costs and facility needs for existing ship classes to see if the high-fidelity model closely predicts real-world maintenance results. The model could then be fine-tuned as necessary until it accurately predicts historical results when provided with historical input data. The model then could be used to output expected USV A_M and A_O to see if it meets the parameters in the CDD. Additional maintenance concepts such as alternate OFRP profiles could be implemented to see their effects on A_M and A_O. Furthermore, major upgrades and further details of the OFRP profile such as vessel training and workups could be added to see what percent of the time the vessel could support active operations.

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APPENDIX A. SYSTEM LEVEL SUSTAINMENT PRODUCTS

Activity/Task Name	Activity Steps/Product Name
Design interface and ILS Planning	Design Interface Review
Design interface and ILS Planning	Develop Logistics Strategy
Design interface and ILS Planning	Perform Business Case Analysis
Design interface and ILS Planning	Prepare Performance Base Logistics (PBL) Decision
Design interface and ILS Planning	Create Program Support Data (PSD)
Design interface and ILS Planning	Life Cycle Sustainment Plan (LCSP)
Supply Support	Provisioning
Supply Support	Produce Allowance Parts List
Supply Support	Produce Allowance Components List
Supply Support	Produce Allowance Equipment List
Supply Support	Develop Users Logistics Support Summary (ULSS)
Supply Support	Register Configuration and Logistics Products in CDMD-OA
Supply Support	Diminishing Manufacturing Sources and Material Shortages (DMSMS)
Tech Manual	Perform Job Task Analysis
Tech Manual	Develop Interactive Electronic Technical Manual (IETM)
Tech Manual	Register Tech Manual in TDMIS
Tech Manual	Register Tech Manual in CDMD-OA
Training	Prepare Training Planning Process Methodology (TRPPM) Report
Training	Develop Training Strategy
Training	Develop NTSP
Training	Develop Man Power Estimate
Training	Develop Training Products
Training	Register Training Productss in CANTRAC
Maintenance Planning	Assign System MIP#
Maintenance Planning	Reliability Centered Maintenance (RCM) Analysis
Maintenance Planning	Fleet Technical Support Center Validation
Maintenance Planning	Register Maintenance Planning Products in CDMD-OA
Maintenance Planning	Identify Depot Maintenance Inter-service (DMI) Support

Maintenance Planning	Validate DMI Candidates
Maintenance Planning	Register Study Conduct Analysis and Recommend Depot Source of Repair (DSOR)
Maintenance Planning	Resolve Issues and Approve DSOR
Maintenance Planning	Fund Organic or Commercial Depot
Support Equipment	Develop SPETE
Support Equipment	Develop GPETE
Support Equipment	Update Ship Portable Electrical Test Equipment List

APPENDIX B. RISK MANAGEMENT PROCESS

The USV Sustainment Capstone team began with the risk management process where risks were identified throughout the timeframe of the project. Risks were managed in accordance with the *Department of Defense Risk, Issue, and Opportunity Management Guide for Defense Acquisition Programs* published January 2017. Table 24 describes the identified risk for the USV sustainment capstone project.

Table 24. Risk Identification and Description for USV Sustainment

Risk Identification	Description
R1	USV programs are still in development. The USV Sustainment Capstone team made various assumptions about USV sustainment planning that have not been confirmed by the program office or fleet. If the program office of fleet make decisions that deviate from the USV Sustainment Capstone team's assumptions, the model will require updates and changes to produce representative data.
R2	The USV sustainment model depended on inputs to obtain data for analysis. The USV Sustainment Capstone team was not able to obtain real historical data for USVs as they are not developed programs or from other platforms that would represent USV infrastructure closely. Because of this, the USV Sustainment Capstone team had to assume data for the model and simulation as open-source data could not be found. If the data used for the USV sustainment model is not representative of real-world data, the output metrics of the simulation will not provide valid results.

In order for the USV Sustainment Capstone team to manage the identified risks, an analysis was conducted utilizing a standard risk matrix. Figure 35 displays a risk matrix for the purpose of rating risks based on probability of occurrence and consequence level (Guevara 2023). The color-coding of the matrix is necessary as it "represents the combination level of probability and impact of the identified risks" (Guevara 2023). In the matrix, green means the risk had a low impact, yellow identified as moderate impact, and red means the risk had a high identified impact.

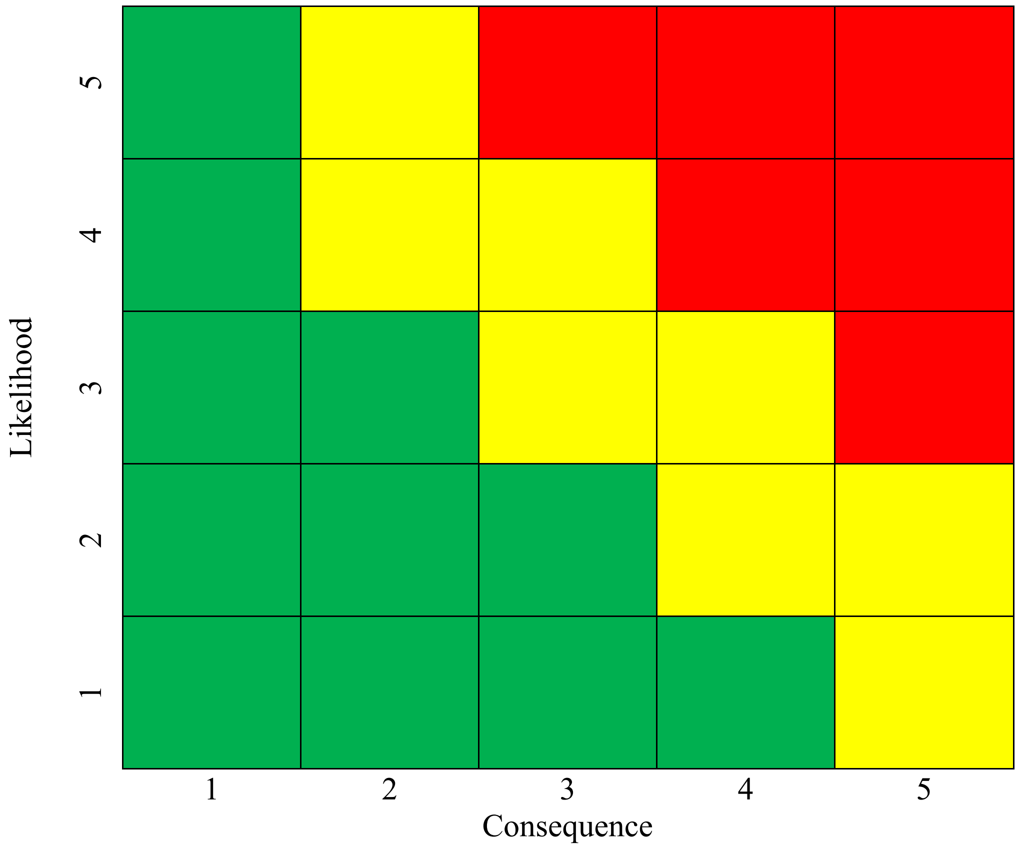

Figure 35. Standard Risk Matrix. Adapted from Office of the Deputy Assistant Secretary of Defense for Systems Engineering (2017, 30).

The DOD Risk, Issue, and Opportunity Management Guide provided a baseline "for establishing the initial assessment of likelihood of a risk occurring" (Office of the Deputy Assistant Secretary of Defense for Systems Engineering 2017, 26). Table 25 identifies the criteria the USV Sustainment Capstone team used to analyze the likelihood of risk occurrence. The levels selected were kept the same as those in the referenced DOD guide.

Table 25. Likelihood Criteria. Source: Office of the Deputy Assistant Secretary of Defense for Systems Engineering (2017, 26).

Level	Likelihood	Probability of Occurrence
5	Near Certainty	>80% to < 99%
4	Highly Likely	>60% to ≤ 80%
3	Likely	>40% to ≤ 60%
2	Low Likelihood	>20% to ≤ 40%
1	Not Likely	>1% to ≤ 20%

The USV Sustainment Capstone team also evaluated the consequence of the risks identified utilizing the referenced DOD Guide as a baseline for the risk consequence. Each consequence was evaluated for cost, schedule, and performance of the overall project. The USV Sustainment Capstone team determined cost would not be a key consequence to the scope of the USV Sustainment project. However, for future work, the USV Sustainment Capstone team recommends adding cost as a consequence for future identified risks. Table 26 provides consequence level criteria.

Table 26. Consequence Criteria for USV Sustainment Team. Adapted from Office of the Deputy Assistant Secretary of Defense for Systems Engineering (2017, 25).

Level	Consequence	Cost	Schedule	Performance
5	Critical Impact	10% or greater cost to project	Schedule will slip and will require major schedule re-baseline	Critical consequence to meeting MOEs and MOPs based on KPPs and KSAs
4	Significant Impact	5% – <10% increase cost to project	Significant schedule slip and impact objectives and key events	Significant impacts to project. Workarounds required to meet objectives

Level	Consequence	Cost	Schedule	Performance
3	Moderate Impact	1% – <5% increase cost to project	Moderate Schedule will slip impact objectives and key events	Unable to meet low tier MOEs and MOPs
2	Minor Impact	Cost increase, but can be managed internally	Some schedule slip, but can meet objectives and key events	Minor impact to meeting technical performance or supportability requirements.
1	Minimal Impact	Minimal impact. Cost expected to meet approved funding levels	Minimal schedule impact	Minimal consequence to meeting technical performance or supportability requirements. Meets MOEs and MOPs based on KPPs of KSA

Based on likelihood and consequence criteria, the USV Sustainment Capstone team gave a rating to each identified risk shown in Table 27. The risks were then plotted in the risk matrix in Figure 36.

Table 27. USV Sustainment Risk Rating of Likelihood and Consequence

Risk ID	Description of Risk	Likelihood	Consequence
R1	The USV program is still in development. The USV Sustainment Capstone team made various assumptions about the USV CONOPS sustainment planning that have not been determined by the program office or Fleet. If the program office or Fleet make future decisions to the USV program that deviates from the USV Sustainment Capstone team’s assumptions, the model will require updates and changes to produce representative data	5	2

Risk ID	Description of Risk	Likelihood	Consequence
R2	The USV sustainment model depended on inputs to obtain data for analysis. The USV Sustainment Capstone team was not able to obtain real historical data for USVs as they are not developed programs or from other platforms that would represent USV infrastructure closely. Because of this, the USV Sustainment Capstone team had to assume data for the model and simulation as open-source data could not be found. If the data used for the USV sustainment model is not representative of real-world data, the output metrics of the simulation will not provide valid results.	5	2

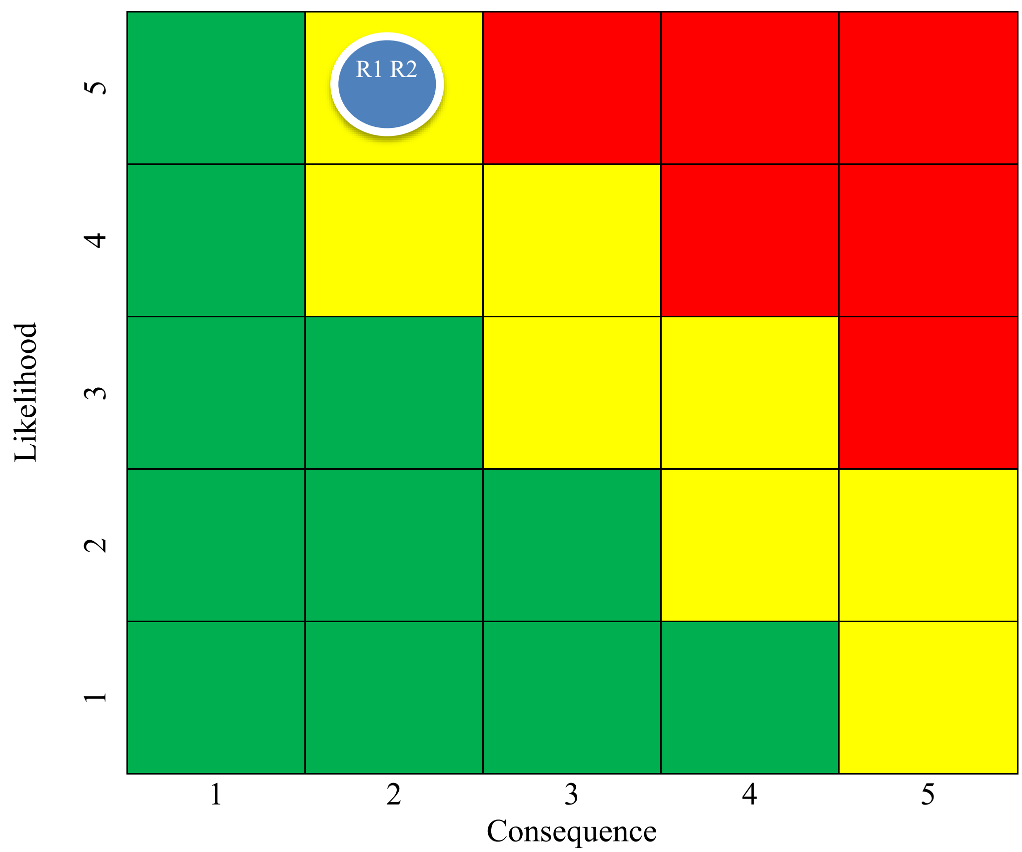

Figure 36. USV Sustainment Risk Matrix

As part of the risk management, the USV Sustainment Capstone team provided mitigation steps to reduce the respective risk consequence shown in Table 28.

Table 28. USV Sustainment Risk Mitigation Strategy

Risk ID	Description of Risk	Mitigation Strategy
R1	The USV program is still in development. The USV Sustainment Capstone team made various assumptions about the USV CONOPS sustainment planning that have not been determined by the program office or fleet. If the program office of fleet make decisions the USV programs deviating from the USV Sustainment Capstone team's assumptions, the model will require updates and changes to produce representative data	1. Program Office and Fleet to determine the state of USV Sustainment 2. Sustainment Plan is utilized by the RMCs and ISEAs to obtain information and to support the USV 3. Make updates to the USV sustainment model 4. Run model to obtain data to make further decisions
R2	The USV sustainment model depended on inputs to obtain data for analysis. The USV Sustainment Capstone team was not able to obtain real historical data for USVs as they are not developed programs or from other platforms that would represent USV infrastructure closely. Because of this, the USV Sustainment Capstone team had to assume data for the model and simulation as open-source data could not be found. If the data used for the USV sustainment model is not representative of real-world data, the output metrics of the simulation will not provide valid results.	1. Obtain historical data for representative platforms 2. Attempt to validate the model with new input values against the historical data. 3. Make updates to the USV sustainment model if needed 4. Analyze the output information for cost and high stress areas within the model

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