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NAVAL ASW COMBAT SYSTEM PRODUCT LINE ARCHITECTURE ECONOMICS

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Monterey, CA; Naval Postgraduate School

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NAVAL ASW COMBAT SYSTEM PRODUCT LINE ARCHITECTURE ECONOMICS

by

Nolan D. Fraine, Tiffany Jackson-Henderson,
and Vimaliz Manfredo

June 2019

Advisor: John M. Green
Co-Advisors: Raymond J. Madachy

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ABSTRACT

Navy combat systems are currently ship class dependent and are acquired as stovepipes. There exist economic consequences to this approach considering various components on the combat system types share commonality. This part of the research will address cross-domain applicability of the antisubmarine warfare (ASW) combat system. This research will include the product line potential for ASW systems to include air, surface, and subsurface applications—light airborne multipurpose system (LAMPS) MK III (SH-60 Helicopters), AN/BYG-1 (Virginia class), SQQ-89 (FFG 7, DDG 51, and CG 47 class). Commonality is assessed for ASW-capable systems to determine the product line approach suitable for the reduction of cost, increase in mission effectiveness, and generation of rapidly deployable combat systems. The product line investigation encompasses air, surface, and subsurface systems for applicability across the domain to establish variations points based on referenced architecture. Product line models provide analysis of the economic consequences of alternative system acquisition approaches. Constructive Product Line Investment Models (COPLIMO) are utilized, with a three-pronged strategy, for system and software to explore numerous architectural possibilities for the derived combat systems. High return on investment were yielded for an adapted ASW system for "most likely" scenarios for both system and software.

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LIST OF ACRONYMS AND ABBREVIATIONS

ALFS	Airborne Low Frequency SONAR
AN/BYG-1	Submarine Combat Control System
AN/SQQ-89	Surface Ship ASW Combat System
APB	Advanced Processing Build
ASW	Anti-Submarine Warfare
AGM	Advanced Guided Missile
APB	Advanced Processing Build
ASuW	Anti-Surface Warfare
BLK	Block
COPLIMO	Constructive Product Line Investment Model
COTS	Commercial off the Shelf
CSE&I	Combat System Engineering and Integration
DoD	Department of Defense
DoDAF	Department of Defense Architecture Framework
HSI	Human System Integration
IDE	Integrated Development Environment
JETDS	Joint Electronics Type Designation System
LAMPS	Light Airborne Multi-Purpose System
LML	Life cycle Model Language
LMRS	Long-Term Mine Reconnaissance System
LOS	Line of Sight
MAD	Magnetic Anomaly Detection
MBSE	Model Based System Engineering
MH-60R	Sikorsky Seahawk model 60R
MK	Mark
N/A	Non-applicable
NAVAIR	Naval Air Systems Command
NUWC	Naval Undersea Warfare Center

OA	Open Architecture
PCS	Payload Control System
PLA	Product Line Architecture
PLE	Product Line Engineering
PLM	Product Life-Cycle Management
PMA	Program Management Agency
R&D	Research & Development
RAN	Royal Australian Navy
RCR	Relative Cost of reuse
RCWR	Relative cost of writing for reuse
ROI	Return-on-investment
SH-60	Sikorsky Seahawk model 60
SLOC	Source Lines of Code
SONAR	Sound and Navigation Radar
SOS	System of Systems
SSBN	Ohio-class ballistic-missile submarine
SSGN	Ohio-class guided-missile submarine
SySML	System Modeling Language
TACCO	Tactical Coordinating Officer
TCS	Tactical Control System
TI	Technology Insertion
TOC	Total Ownership Cost
US	United States
VA	Virginia (Class Submarine)
VLS	Vertical Launch System
VMS	Voyage Navigation System
VP	Variation Point
VPM	Variation Point Model
WAA	Wide Aperture Array

EXECUTIVE SUMMARY

The United States Navy, along with the Department of Defense (DoD), maintains a system of systems (SoS) approach to the development of combat systems leading to architecture being inflexible by design (Guertin 2019). Such an approach allows for practices that lead to ship-class dependency for combat systems that support Antisubmarine Warfare (ASW). Discussed in the Leading Edge's Combat Systems Engineering & Integration (CSE&I) publication, "the vision for enterprise combat systems solutions is the development of reusable product line components into a single combat system architecture" through product line architecture (PLA) application (Dahlgren 2013). This vision is distinct of the traditional "stove-pipe" development currently executed.

The characteristics of ASW are shared throughout U.S. Naval combat systems and across multiple domains comprised of air, surface, and subsurface. There are various configurations of combat system suites that are utilized to perform comparable objectives. Light Airborne Multipurpose System (LAMPS) MK III Weapons System is the integrated combat system of the SH-60R helicopter to support ASW missions in. AN/BYG-1 Combat Control System is integrated into the Virginia (VA) class submarines. It is support by an open architecture (OA) concept. AN/SQQ-89 combat system, utilizing commercial off the shelf (COTS), is integrated into various U.S. fleet surface vessels with acknowledged cost savings (Pike 1998). Development of multiple combat systems fulfilling similar missions is essentially not conducive for technical design if commonality and modularity can be assessed to identify benefits of a single combat system designed for a plethora of platforms across multiple domains.

The focus on this capstone project was to investigate the application of product line engineering (PLE) for the development of combat system design that integrates into various systems that span multiple domains. A breakdown of the functional areas for the Navy's existing combat systems provides an outline to address commonality. We performed an economic analysis of the product line, for system and software, by applying the System Constructive Product Line Investment Model (COPLIMO) and explored various architectural possibilities for the derived combat system.

The data derived from COPLIMO, utilizing a three-pronged strategy, provided the return on investment (ROI) for the adaptation of the ASW system and software for a PLE approach. High ROI were yielded for both system and software COPLIMO granted a "most likely" scenario for product line saving efforts. With an optimistic "best case" scenario, a slight increase in ROI was shown with relative cost to adapt and reuse code and components presenting estimations 20% lower than the most likely scenario. However, if estimations in the relative cost to rewrite adapted and reused components are 50% higher than expected, the ROI would be much lower and not increase at the same rate as the most likely and best case scenarios in product line saving efforts. From the data, it can be recognized that the ROI for the Navy in investing in a generic combat system for ASW mission is positive, and it may be worth pursuing.

Today's acquisition strategy is both slow and inefficient. Although some strides have been made to expedite the process, it still takes years, if not decades, to field new systems to the fleet. In order to successfully integrate a common combat system across the fleet, this acquisition process will need to be modified, from a stovepipe, closed community, to one of information and resource sharing. Additional investigation should be done into these processes to identify the process in which the acquisition community can be modernized into one that is no longer slow to react to the world's combat environment, but maintains itself at the forefront of new technology acquisition and insertion. Information sharing, cooperation, and high velocity learning will have to become a principal tenet of each program office to achieve the desired outcome and streamline the combat system development.

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From Ms. Jackson-Henderson: Thank you to my family, who has fully supported and encouraged my educational endeavors.

From Mr. Fraine: Thank you to my fiancée and my family who have supported me throughout my career and inspire me to improve every day.

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I. INTRODUCTION

A. BACKGROUND

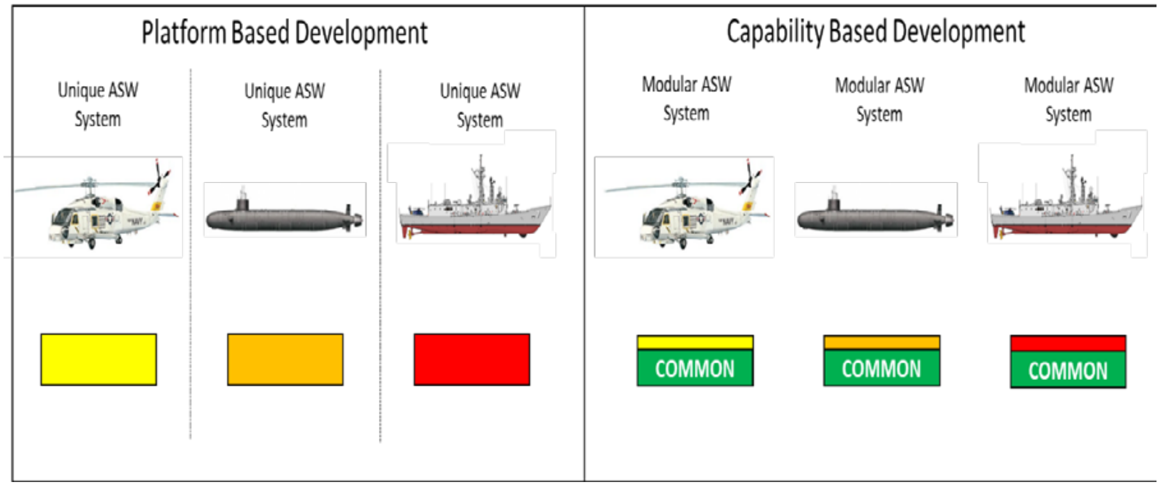
Current U.S. Navy combat system suites are ship-class dependent (Hall 2018); this is reflective of the stovepipe nature in which current combat systems are developed. The development of an individual system is distinct in the current process and failure to assess the commonality that is present across multiple systems is counterproductive to the efficiency that can be implemented in the developmental process. Anti-submarine warfare (ASW) characteristics are recognized as shared across the U.S. Navy; however, the development and implementation of combat systems is currently done in a stovepipe manner, without reaching across ship-classes for commonality purposes. This capstone project addresses cross-domain applicability of the ASW combat system and includes the product line potential for ASW systems to include air (LAMPS MK III), surface (AN/BYG-1), and subsurface (AN/SQQ-89) applications. As a note, General Dynamics provides the definition for the AN/BYG-1 acronym "the AN/ BYG-1 acronym is derived from the Joint Electronics Type Designation System (JETDS): AN refers to Army/Navy, B indicates underwater systems, Y refers to data processing, and G indicates Fire Control or Searchlight Directing" (General Dynamics Mission Systems 2018). Similar to AN/BYG-1, AN/SQQ-89 is not an acronym, but it is the name for Surface Ship's ASW combat system. AN/SQQ-89 stands for Army/Navy, S indicates Surface Ship, Q refers to SONAR and Underwater Sound, and finally the last Q is for Special or Combination (Parsch 2008).

The LAMPS MK III is used by the SH-60 U.S. Navy helicopter, also known as the Sikorsky Seahawk, is capable of handling ASW and Anti-Surface Warfare (ASuW) operations as well as many types of operations (United States Navy 2019c). The Seahawk's combat system is the upgraded LAMPS MK III Weapons System (Block (BLK) II in the MH-60R Seahawk) developed by Naval Air Systems Command (NAVAIR) under the Program Management Activity 299 (PMA299) program office. The primary missions of the LAMPS MK III are those of ASuW and ASW engagements (Pike 1999).

The SSBNs, SSGNs, VA-class, and other submarine classes use the AN/BYG-1 Combat Control System, originally developed by Raytheon. As mentioned in the U.S. Navy program's fact sheet "AN/BYG-1 is an open-architecture submarine combat control system for analyzing and tracking submarine and surface ship contacts, providing situational awareness, as well as the capability to target and employ torpedoes and missiles. AN/BYG-1 replaces central processors with COTS computer technology" (Office of Operational Test and Evaluation 2012).

Finally, AN/SQQ-89 is used in the U.S. surface fleet, and will be the combat system for the Zumwalt-class destroyer (DD-21), among others. The AN/SQQ-89 integrates ASW capabilities to the surface force, and brings the use of COTS products to ease technology refreshment. Some of the surface vessels using AN/SQQ-89 include the Frigates, Spruance destroyers, Ticonderoga-class cruisers, and Arleigh class destroyers (United States Navy 2019a).

This capstone project assesses the economic consequences related to current U.S. Navy Combat System PLA approaches and future architectural approaches aligned with capabilities for performing ASW. Current platform development is specific to platform types that are present in the ASW domain. Based on the concept in Figure 1, evaluating ASW platforms based on capabilities can provide insight into the commonalities that are shared amongst SH-60 helicopter, VA class submarine, and SQQ-89 along with possible cost benefits to a modular approach.



Current development of combat systems in the ASW domain are platform specific. Development based on capabilities produce modular systems in which commonality is the focus to deviate from stove-pipe development.

Figure 1. Current vs. Future Product Line Approach. Adapted from Dahlgren (2013).

Consideration of an adaptation to the combat systems is led by the specified needs and missions required within the ASW domain and within the operational constraints (Naval Surface Warfare Center, Dahlgren 2013).

B. PROBLEM STATEMENT

The stovepipe nature of the current combat system development is not ideal under today's global climate. This model does not allow for sharing of lessons learned, technology development, and development assets. In order to maintain maritime superiority, the U.S. Navy needs to explore alternative ways of building and maintaining their systems, in a way that can keep up and surpass the development efforts of rival navy commands.

With the aim of addressing some of these alternatives, this capstone project models the return of investment (ROI) for adapting the LAMPS MK III, AN/BYG-1 and SQQ-89 combat systems to generic ASW combat system to use a product line approach. For the purpose of this project, only ASW missions will be used. Taking into consideration the commonalities between the ASW missions of all three combat systems mentioned in Chapter I, Section A , the following strategies are taken to find the ROI:

1. Identify common functional elements found in surface, submarine, and aviation

2. Develop product line concept for an ASW combat system

3. Develop cost model to obtain ROI of developing the combat system reusable product lines

Identifying the common functional elements can be done by analyzing the features and functionalities of each of the combat systems. Each combat system provides unique capabilities tied to the weapons used for ASW engagements. However, a common thread can be extracted when comparing these capabilities, such as the sensors and data that provide the target information to the combat system and the type of weapon used in these engagements.

The product line concept can be developed by a functional analysis of the combat systems provides the information needed to create the reference architecture. After developing the functional breakdown, the combat system common functionality can be identified. This architecture is modeled using Innoslate.

Finally, the two previous strategies are utilized to address the third strategy. A product line concept is built using the common functional elements identified in question one in conjunction with the variability model of question two and performing a cost analysis using a system and software level adaptation of Constructive Product Line Investment Model (COPLIMO) on the proposed architecture (Boehm et al. 2004). COPLIMO is a framework used to assess cost, savings, and return-on-investment (ROI) with product lines. “Constructive” means the user understands why the model gives the estimates it does and the model helps the user plan the job better. System and software COPLIMO utilize this framework. System COPLIMO assesses the ROI throughout the life cycle of the system including research and development (R&D) and military acquisition (Boehm, Lane, and Madachy, 2011). Software COPLIMO assesses cost that relate to new software development and reusable software transverse the product line of comparable applications with a focus on parts of the system for adaption to “product-specific newly-built software" (Boehm et al. 2004, 1). An analysis for best case, most likely and worst case scenarios is used for each ASW software and system to get a range of ROIs.

C. ORGANIZATION

This capstone is organized into four main segments that address a literature review, methodology and approach, results, and future work. Chapters I and II present a background on combat systems currently in use for ASW engagements and the platforms they are used on, and establishes the need for a common ASW combat system. A review of current ASW combat system functionalities, along with the U.S. Navy's view for future ASW introduces the reader to the overall functionalities in the combat system, and their purpose.

Chapter III presents the Architectural Concept and Orthogonal Variability Models used by the capstone team to develop the combat system product line, and its associated cost analysis. The variability models present the variations that the generic ASW combat system needs to accommodate. Detailed system and software COPLIMO are discussed and the inputs required are presented along with the calculations performed by the tools created to calculate results.

Chapter IV presents the detailed system and software COPLIMO results for an ASW combat system common across platforms, a range of expected ROI and the benefits that the U.S. Navy can receive in both compatibility and costs savings across the enterprise.

Finally, Chapter V presents the future work needed to expand the common combat system concept. This capstone is organized in a logical manner, from investigation, development, to final product, enabling the reader to flow between topics.

D. SUMMARY

Current U.S. Navy combat system suites are ship-class dependent (Hall 2018). This is reflective of the stovepipe nature in which current combat systems are developed. ASW characteristics are recognized as shared across the U.S. Navy, however, the development and implementation of combat systems is currently done in a stovepipe manner, without reaching across ship-classes for commonality purposes. This capstone project addresses the cross-domain applicability of the ASW combat system and includes the product line potential for ASW systems to include air (LAMPS MK III), surface (AN/BYG-1), and subsurface (AN/SQQ-89) applications.

Taking into consideration the commonalities between the ASW missions of all three combat systems mentioned the following problems are addressed:

1. Identify common functional elements found in surface, submarine, and aviation

2. Develop product line concept for an ASW combat system

3. Develop cost model to obtain ROI of developing the combat system reusable product lines

The capstone project presented will assess economic consequences related to current U.S. Navy combat system PLA approaches and assessing future architectural approaches aligned with capabilities for performing ASW.

II. LITERATURE REVIEW

Each ASW combat system being evaluated for product line potential has similar functions performed by varying subsystems. Understanding the components that make up each individual combat system is fundamental in the development of models and product lines. The information gathered on the individual combat systems is then able to be utilized using concepts from Model Based Systems Engineering (MBSE) and PLE. The following sections give a description of the LAMPS MK III, AN/BYG-1 and SQQ-89 ASW combat systems, MBSE, and PLE.

A. ASW COMBAT SYSTEM

The U.S. Navy employs the use of surface ships, aircraft and submarines, to detect, identify, and neutralize enemy submarines. The combat systems for each asset: helicopters, surface ships and submarines are discussed in the sections hereafter. In addition, Sound and Navigation Radar (SONAR) are discussed in Section 4 as the primary component used by the combat system to perform detection and analysis of targets.

1. LAMPS MK III

The LAMPS MK III is a naval program that allows for deployed manned helicopters from destroyers, frigates, and cruiser platforms to assist in ASW operations. LAMPS equipped helicopters can operate outside of the fleet’s radar and are equipped to track and engage enemy submarines while feeding information live back to the ship. As Pike mentions on his website Military Analysis Network “the Sikorsky SH-60B helicopter is configured specifically in response to the LAMPS requirement of the U.S. Navy” (Pike 1999).

The twin-engine helicopter, SH-60B, is operational utilizing a three-person crew. The naval operators include a pilot, responsible mission assistance via helicopter operations, an airborne tactical coordinating officer (TACCO), responsible for the management of tactical aspects for mission coordination, and a sensor operator, responsible for data collection to support the mission. The system has a range of 450 nautical miles, with a mission endurance of 4 hours. The helicopter also has a maximum speed of 146 knots and a service ceiling of 12,000 feet. The SH-60B can be equipped with a 30mm gun and two MK-46/50 torpedoes, or one Advanced Guided Missile (AGM) 119B Penguin for air to surface strikes (Pearl Harbor Aviation Museum n.d.).

A 2004 report from Forecast International defines the key subsystems to the LAMPS MK III as:

- ALQ-142: Electronic support measures system that can detect radar signals and identify the point of origin
- APS-124: Radar system housed in the cockpit that provides 360-degree coverage
- ARQ-44 Datalink Combat information: airborne datalink terminal that provides data telemetry to host ship's Combat Information Center.
- ARR-75 Sonobuoy Receivers: Radio receiving set for operation and management of anti-submarine sonobuoys.
- ASQ-81(V)4 Magnetic Anomaly Detection (MAD): MAD system used to refine the position plot and confirm classification of below-surface targets.
- ASQ-164 Control Indicator Set: System designed to furnish control for the airborne tactical operator and the sensor operator.
- ASQ-165 Armament Control Indicator Set: Controls torpedoes, practice multiple bomb racks with sound underwater sources and air-launched sonobuoys.
- AYK-14(V) Airborne Digital Computer: Variable-configuration, general-purpose 16-bit computer.
- UYS-1 Advanced Signal Processor: Perform multisensory acoustic analysis.

- AN/AQS-22 Airborne Low Frequency SONAR (ALFS): Dipping SONAR system utilized for target interrogation, communication, and environmental data collection (Forecast International 2004).

In addition to its primary mission of anti-submarine warfare, there are many secondary missions of the LAMPS MK III equipped SH-60 Helicopter. Pike describes the supported missions as “search and rescue, medical evacuation, vertical replenishment, naval gunfire support and communications relay” (Pike 1999). Vertical replenishment missions involve the LAMPS MK III moving material and information across ships in the fleet or from ships to the shore. As part of naval gunfire support, the SH-60B can spot and control naval gunfire from the parent ship or from other units. Finally, the aircraft can serve as a receiver and transmitter relay station in communications relay missions.

2. AN/BYG-1

AN/BYG-1 is an acquisition program for the submarine combat and weapon control system with the purpose of providing the utilization of tools meant for the identification of subsurface, surface, and air platforms (United States Navy 2019b). As indicated previously, AN/BYG-1 is open architecture and is composed of various subsystems used to support submarine mission sets in the area of ASuW and ASW. Through incremental development, modifications are made to applicable submarine platforms with advanced processing builds (APB) which focus on the software component of the build and technical insertions (TI) which focuses on the hardware component. This TI/APB process is “run on a two-year development cycle that are offset by a year so that engineers can develop software on hardware that is in the final stages of production and vice versa” (Zimmerman, 2016). Figure 2 describes the TI/APB process from fleet requirements to upgrade implementations on platforms.

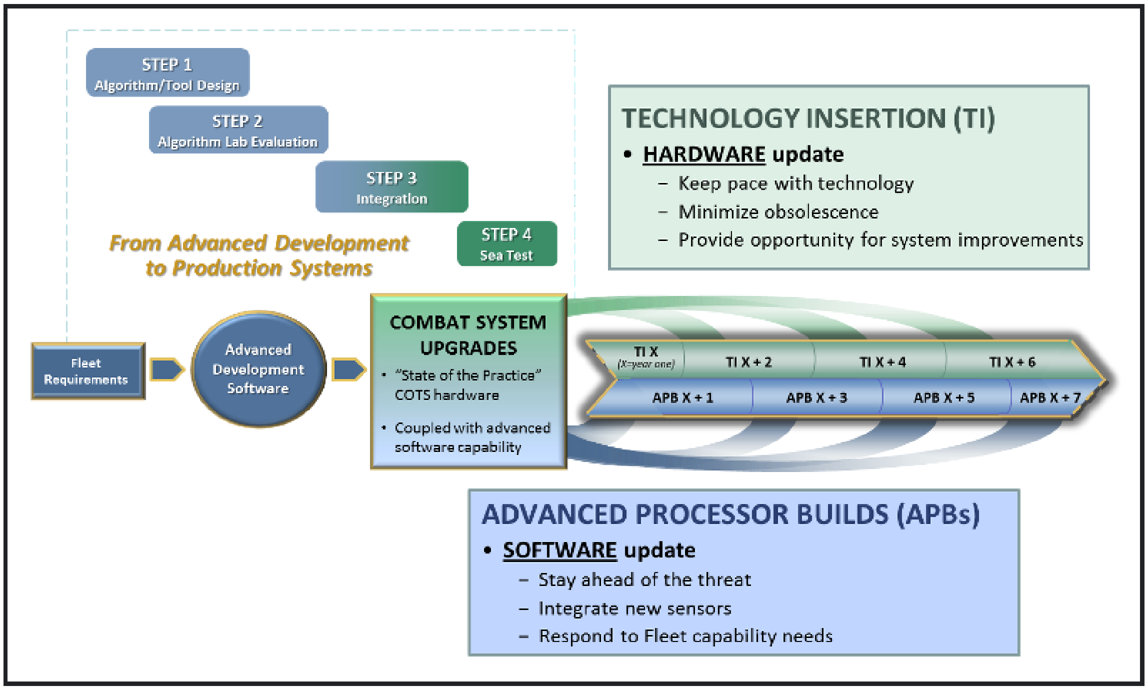


Figure 2. TI/APB Process for Tactical Control System. Source: Zimmerman (2016).

The submarine classes that employ AN/BYG-1 include VA (BLKs I, II, III, IV), Los Angeles (688i), Los Angeles with and without a vertical launch system (VLS), SSBN Trident, Seawolf, SSGN, and the RAN Collins. The main difference between each class of submarine, besides available sensor types, are weapons and tube structures. The focus of this capstone project centers on the VA class Submarine as each submarine class has varying sensor suites.

The VA class Submarine was introduced as a post-cold war attack submarine, first commissioned in 2004 and built by General Dynamics Electric Boat. The application of open architecture, COTS components, and modular construction allows for prompt introduction of additional VA submarines with an increased life cycle and other submarine class.

The AN/BYG-1 VA class submarine is equipped with various sensors used to support the mission. These sensors and components include (Naval Technology n.d.):

- Wide Aperture Array (WAA)**:** Passive fiber-optic panel arrays mounted to the hull used for acoustic detection produced by Northrup Grumman.

- TB-16/TB-29 Towed Arrays**:** Fat line and thin lined, respectively, passive acoustic detection towed arrays.

- AN/BPS-16(v)4/5/17(v)1 RADAR**:** Navigational radar system, developed by Sperry Marine, used in conjunction with the voyage navigation system (VMS). VMS provides acoustic detection of active platforms and broadcasted information.

- AN/BQQ-10(V4) SONAR Processing System: Processor used for submarine array receivers used for detection and identification of sound.

- AN/BVS-1 Photonic Masts: Submarine periscope

- Long-Term Mine Reconnaissance System (LMRS): Used for the detection of mines in the form of unmanned vehicles.

Currently, several variations exist between the various VA class Submarine BLK builds. These variations are a factor of the structured layout of the missile tubes and missile types contained on each block. These modifications are outside of the scope of this capstone project.

3. AN/SQQ-89

AN/SQQ-89 is an acquisition for the Naval Surface Fleet and the combat system for the DD-21. This combat system provides surface ships the ability to detect, localize, classify and target the enemy. Additionally, the system processes and displays the data collected and sent by the SH-60B LAMPS Mk III sensors. Like AN/BYG-1, AN/SQQ-89 is open architecture thus allowing the combat system to change with emerging fleet performance requirements.

AN/SQQ-89 is used on surface vessels including Oliver Hazard Perry Frigates (FFG-7), Spruance destroyers (DD-963), Ticonderoga-class cruisers (CG-47), and Burke class destroyers (DDG-51). The primary weapons these surface vessels are the MK 46 Mod 5A(S) MK 50 torpedo (Sea Technology 1997).

Pike mentions on the website Military Analysis Network the different components that compose of the configuration for Burke class destroyers:

- AN/SQS-53C Hull Mounted SONAR: Computer-controlled surface-ship SONAR with active and passive operating capabilities

- AN/SQR-19 Towed Array SONAR: Cable towed a mile behind ship for long-range passive detection

- AN/SQQ-28 LAMPS MK III Sonobouy Processing System: Provides shipboard support for LAMPS MK III to detect submarines

- ASWCS MK 116 MOD 7 Anti-Submarine Warfare Control System: Combines all tracking data from SONARs to provide targets course and speed (Pike 1998).

As Pike alludes to, AN/SQQ-89 is developed by integrating substantially cost saving COTS components into surface combat systems that support ASW (Pike 1998). The system architecture of AN/SQQ-89 is open to allow the system to grow with fleet requirements. The components that make up AN/SQQ-89 can be seen in Figure 3.

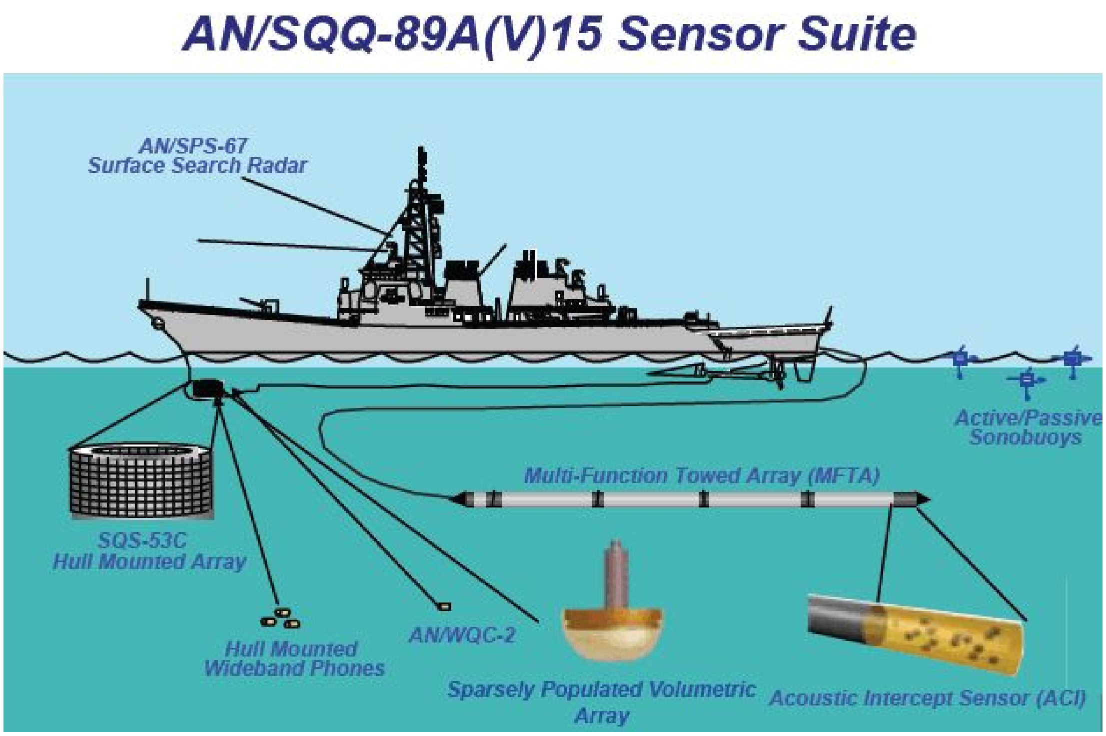
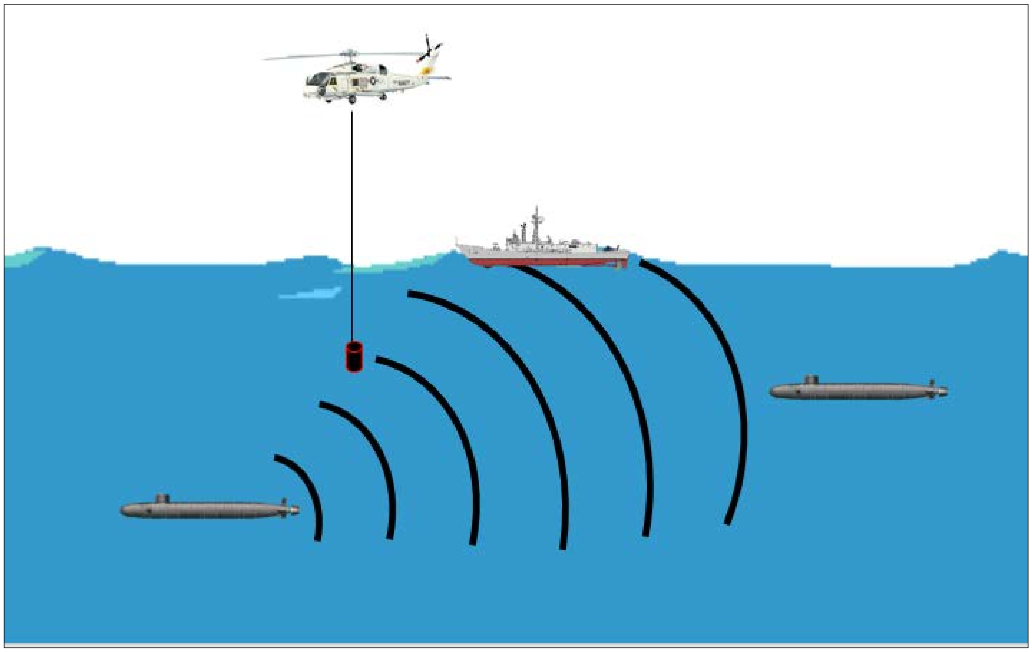


Figure 3. SQQ-89 OV-1. Source: Maritime Security News (2019).

4. SONAR

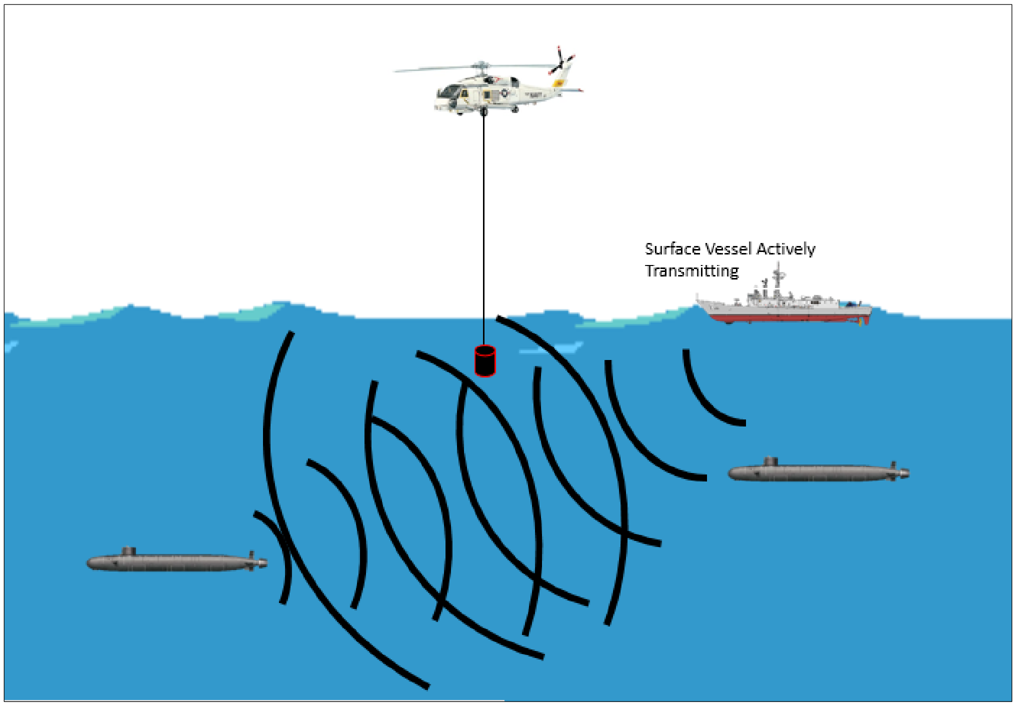
SONAR is a component of the combat system utilized perform detection and analysis of targets. It assures not only ship safety, but also a means to engage with objects external to the combat system. All combat systems are equipped with technology that assists with detections whether it is an array mounted to the combat system or arrays that are external the combat system (towed, sonobuoys, etc.).

The propagations of waves to and from combat systems as it reaches a receiver are the means by which SONAR is performed. There are two types of SONAR systems that comprise underwater acoustics that are used in the ASW domain. These system types include passive and active SONAR. In passive systems, energy is illuminated in the water (target, organic, biological) and is received at the combat system as a target detection as in Figure 4. Active, as shown in Figure 5 is different in which energy (frequency) is emitted from a transmitter, propagates through the water, bounces of an object, and is received back at the combat system of origin. There are two additional types of SONAR systems called daylight and ambient in which energy is given off by the environment, but these systems are not relevant to the context of the combat system being developed.



Submarine emits energy (noise) that is received by various arrays on the SQQ-89, VA submarine, and dipping array on the SH-60 helicopter.

Figure 4. Passive SONAR

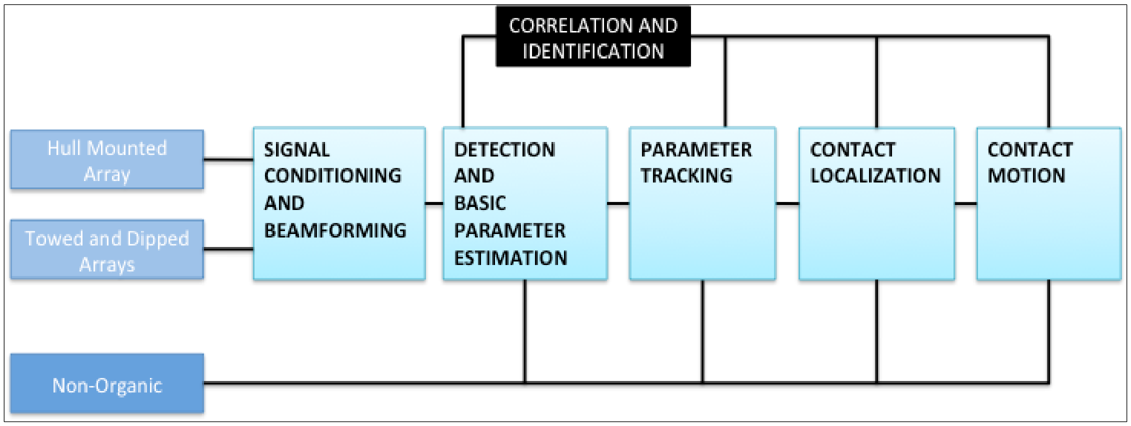


SQQ-89 Actively transmits energy (ping, noise) into the water. The energy reflects off the submarine and is received at the host SQQ-89, and both the VA submarine and SH60-Helo.

Figure 5. Active SONAR

Considering the combat system is a militarized system, the following definition holds for SONAR, "in military applications, SONAR systems are used for detection, classification, localization, and tracking of submarines, mines, or surface contacts, as well as for communication, navigation, and identification of obstructions or hazards (e.g., polar ice)" (Hodges 2010, 1).

For combat systems SONAR is performed by the various arrays available to the system. Figure 6 details an overview of the signal and data process that is performed by the combat system (Hassab 1989).The combat system is utilized to process the signals and data received.



Signal and data processing for the combat systems. Displays energy arrive on various arrays are conditioned when received on the combat system. The combat system processes the detections to gather information such as bearing, bearing rate, range, and frequency. The detections are track and localized to determine target behavior.

Figure 6. Signal and Data Processing. Source: Hassab (1989).

Algorithms, embedded in tactical/fire control, assist in the processing of information to perform analysis of the energy that is received. From the receiver, the signals are conditioned, defined as detected, processed with parametric estimations, tracked, localized, and analyzed for contact motion. Any correlation that can be made by various arrays pinpointing the same target can be identified at different points in the process.

B. MODEL BASED SYSTEMS ENGINEERING

"MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." (Systems Engineering Vision Working Group of INCOSE 2007, 15). The authors use MBSE throughout the design of a generic combat system. MBSE allows the authors to focus on value added models and properly scoping the work needed. Figure 7 depicts the system life cycle using MBSE. This paper concentrates on the system requirements and architecture model of the process, as highlighted. This paper presents system requirements as part of the reference architecture model (Chapter III, Section C - Reference Architecture), which is decomposed from the ASW combat system Domain Model (Chapter III Section B - ASW Domain Model). These two main models become the foundation for the cost modeling in Chapter IV.

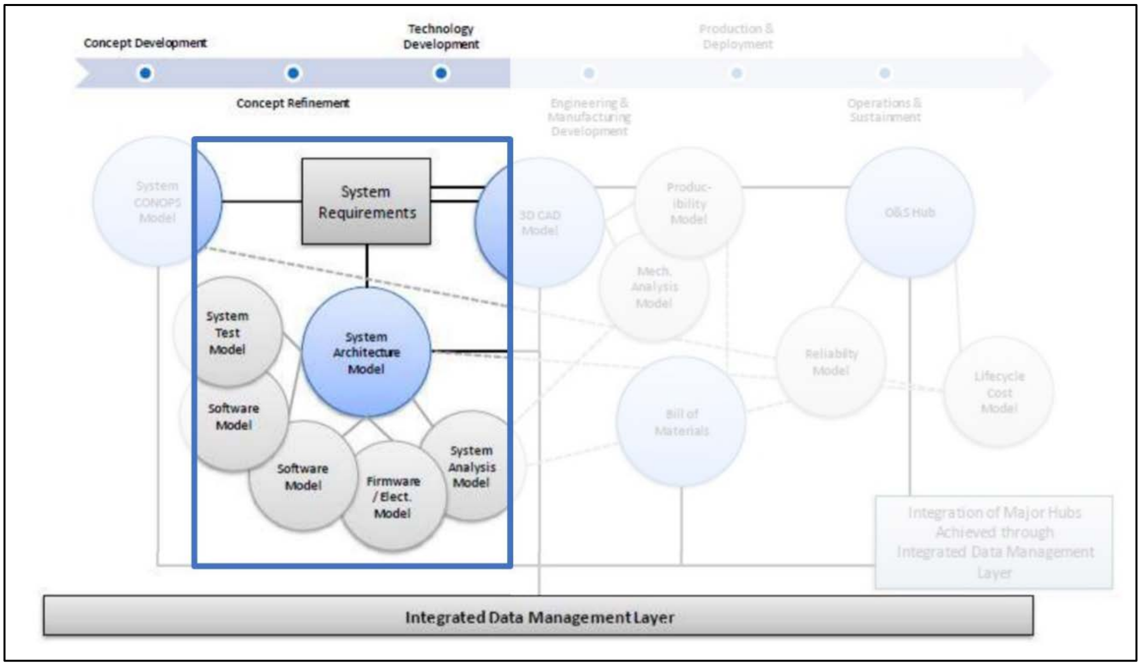


Figure 7. MBSE System Life Cycle Source: Hart (2015).

C. PRODUCT LINE ENGINEERING

PLE is a concept in software development using mass customization and common platforms to create a specific solution that can be applied to large-scale production. It allows for the developer of a solution to create a system that is able to manage the variability in potential products by modeling the system in a common way. The two keys to product line engineering, as defined by Klaus Pohl, Gunter Bockle, and Frank van der Linden in Software Product Line Engineering, are domain engineering and application engineering. The definitions for both as defined by Klaus Pohl et al., are provided:

- **Domain Engineering**: The process of software product line engineering in which the commonality and the variability of the product line are defined and realized

- **Application Engineering**: the process of software product line engineering in which the applications of the product line are built by reusing domain artefacts and exploiting the product line variability. (Pohl, Bockle and van der Linden 2005).

In domain engineering, the key tasks are to identify the commonality and variability in the system, define the scope of the system and construct parts of the system that can meet the variability requirements (Pohl, Bockle and van der Linden 2005). This in turn feeds into the application engineering side of the solution as application engineering looks to reuse domain assets as much as possible when developing the application, exploit commonality and variability during development, document the systems components, and estimate the impacts on the differences between the domain requirements and application requirements (Pohl, Bockle and van der Linden 2005).

Variability modeling is used in product line engineering to "support the development and the reuse of variable development artefacts" (Pohl, Bockle and van der Linden 2005, 58). When variability is defined in system architecture, it can help identify similar components between systems that can be reused.

D. SUMMARY

ASW combat systems for air, surface and subsurface applications are unique in the components that constitute them. The functions performed by each, however, possess many similarities. All systems have a method to detect, track and engage a target. The SONAR subsystems, for example, for each combat system is different: LAMPS MK III uses AN/AQS-22 ALFS, AN/BYG-1 uses TB-16/TB-29 Towed Arrays and AN/SQQ-89 uses AN/SQS-53C Hull Mounted SONAR and AN/SQR-19 Towed Array SONAR. Each SONAR subsystem, however, performs similar functions for their mission scenarios. Using MBSE and the information collected on ASW systems, a reference architecture can be created that shows both the physical and functional hierarchy of a general ASW combat system. Each physical component has a variation where the differences in products are shown. The LAMPS MKIII, AN/BYG-1 and AN/SQQ-89 systems can then map to those variations to gain an understanding of what components of each combat system can be reused, what components are unique to a particular ASW combat system, and what components can be adapted.

III. METHODOLOGY

The following sections describe the approach to develop a combat system product line model. It details the criteria for selecting architecture modeling software, assessing the domain requirements for constructing an ASW combat system domain model, establishing a reference architecture derived from the domain assessment, and identifying variations points for the combat system.

A. ARCHITECTURE MODEL SOFTWARE

The capstone team investigated the qualities between two different products to be used to build the architecture models, Innoslate and Arcadia Capella. Both products offer distinct advantages to the investigation.

Capella is an open source software created by Polarsys, which resides on the Eclipse Integrated Development Environment (IDE). Capella is used mostly on complex systems such as aerospace, transportation, and automotive. One main advantage of Capella is its ability to be used offline, without the need of an internet connection or access to cloud systems. However, this disconnected capability hinders collaboration, as Capella does not allow an easy way to share work with team members. In addition, the software provides no easy way to connect functions and physical attributes to requirements.

Innoslate is a Product Life-cycle Management (PLM) tool that supports system engineering efforts by providing features to perform requirements analysis and management, functional analysis and allocation, solution synthesis, test/evaluation, and simulation (SPEC Innovations 2017). Innoslate has tools that apply System Modeling Language (SysML), Life cycle Model Language (LML), DoD Architecture Framework (DoDAF), in addition to Monte Carlo simulations. The main advantage in using Innoslate for this capstone project is the connectivity to other team members. Changes to documentation and models can be done real time, through the use of their cloud system.

After weighing both software solutions, the team chose Innoslate to generate the necessary architecture models for the project. The benefit of having a cloud based system was the main factor in this decision as the team needed a system that would allow everyone to share access to all architecture models generated in real time.

B. COMBAT SYSTEM DOMAIN MODEL

Using Innoslate, the first model created is a general combat system class diagram or domain model which captures the concept of an ASW scenario with the physical subsystems of a combat system involved, the operations of the subsystems, how the subsystems interacted with each other, and external interactions with the subsystems. Figure 8 shows the domain model created using a class diagram template on Innoslate. Here, the relationship between the combat system subsystems are shown. Reading from left to right, SONAR detects contacts which could either be an enemy ship, friendly ship, or the environment. SONAR then sends that information over to signal processing where it is confirmed by the SONAR Technician. If an enemy ship is detected, signal processing sends information to fire control where a solution for attack can be calculated. Fire control then connects to weapon control to fire. The combat system technician performs the necessary actions for both fire control and weapon control by creating the weapon route, selecting the weapon/tube to fire, and firing the weapon. The operator can select from a torpedo, missile or gun. Finally, weapon control communicates with the selected weapon that then executes the planned route and sends status back to weapon control. Additional functions for combat systems outside of firing a weapon are included here as well; targets can be classified as biological if the SONAR detects a natural object (e.g., whale pods), weapon checks can be performed to ensure weapons are functioning as intended, and casualty procedures for when issues arise.

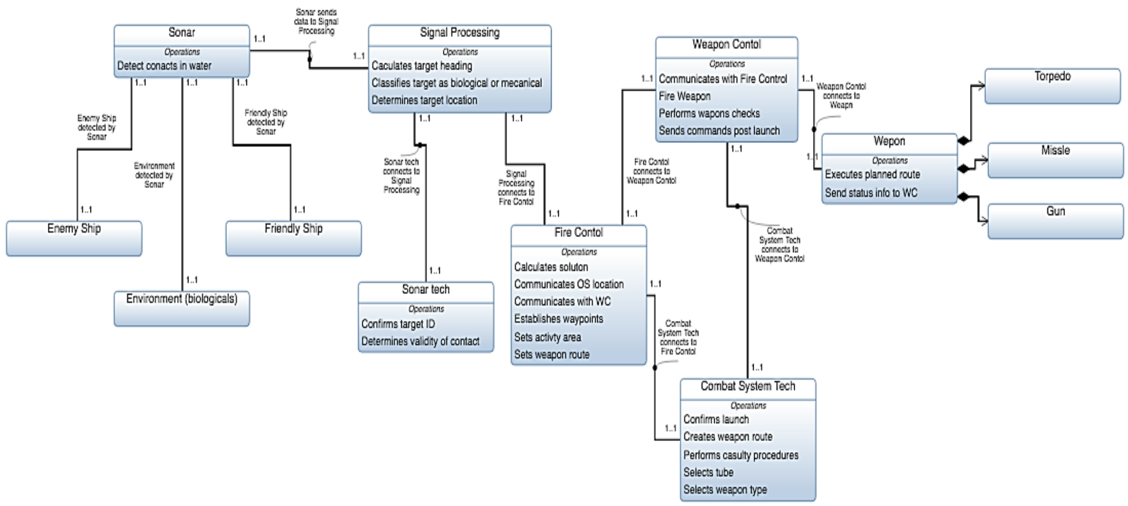


Figure 8. Combat System Domain Model

From the domain model, the main subsystems for a combat system are identified as SONAR, Signal Processing, Fire Control, Weapon Control, and Weapon. Each of the platforms, discussed in Chapter II, have some form of ability to detect an enemy target, calculate a solution, command a launch, prepare a weapon, and send a weapon towards the target. These functions underline the basic capabilities needed for a combat system to complete an ASW mission.

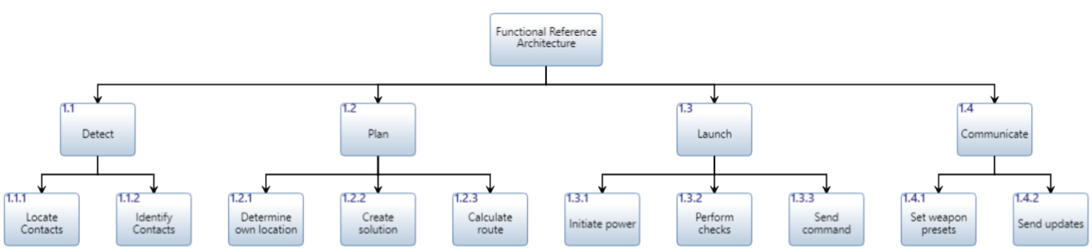
Additional considerations in the domain model include the technicians required to operate specific subsystems. For SONAR, Fire Control and Weapon Control, there are technicians or ‘techs’ required to confirm targets, confirm launches, select weapons route, select tubes, and select weapon type. Each of these tasks are required to be done by an operator to allow for checks in the process so the system does not attack a friendly ship as well as user input to what method of attack is selected.

C. REFERENCE ARCHITECTURE

Reference architecture is used to determine the most suitable solution for domain application for the combat system. The reference architecture is derived from the domain model and consisted of a block diagram of components of the combat systems utilized in a modified “kill-chain,” and a functional block diagram that consists of the functions detect, plan, launch, and communicate. The modification supports current ASW for combat systems with cross-domain consideration and the referenced functional block diagram displays sufficient support of a full extension of a "kill-chain." Each system, individually, fulfills the functions related to the sequence, but use varying components to perform the kill-chain. The top-level functions can be defined as:

- **Detect**: Identification of contacts internal and external to the operational area theatre.
- **Plan**: Determination of location, the development of solutions to contacts, and the calculation of route/distance to target.
- **Launch**: Initializing weapons, performing safety checks, and the transmittal of the command to launch weapons.
- **Communication**: Establishing weapon presets and continuous updates sent between the combat system and weapon.

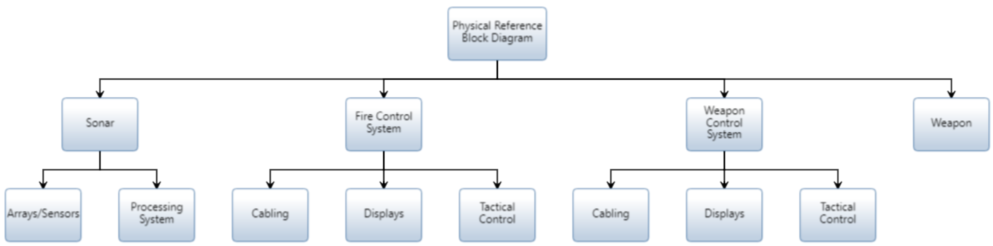
Represented in the top level, functions are mapped to a second level to allocate objectives to top-level components. The conceptual development of the reference functional block diagram, in Figure 9, focuses on the capabilities available to the combat system in level two.



Reference functional block diagram that displays the function level and capabilities level of the developed combat system. This is developed from the current required functionality of the existing referenced combat systems.

Figure 9. Functional Reference Block Diagram

Functional component processes are provided to the ASW system from physical entities and the identification of attributes represented in Figure 10. The application of a reference architecture contributes to identifying components in both the functional block diagram and physical block diagram that pinpoint variations, which can be associated with the combat system.



The reference physical architecture is developed from the components that comprise the combat system.

Figure 10. Physical Reference Block Diagram

D. VARIATIONS

Variation points are identified from the combat system reference architecture described in Chapter III Section C. The premise of developing variations points is to build variants of a system that are distinct from each other (Webber and Gomaa 2004). One or more variants can be identified from a variation point to express the dynamic variability of the system. There are multiple advantages to variability modeling using variant points. When applied to the product line approach the core assets required for the identification of variants incorporate architecture, domain models, requirements, and specifications (Webber and Gomaa 2004). When applied to the product line approach the core assets required for the identification of variants incorporate

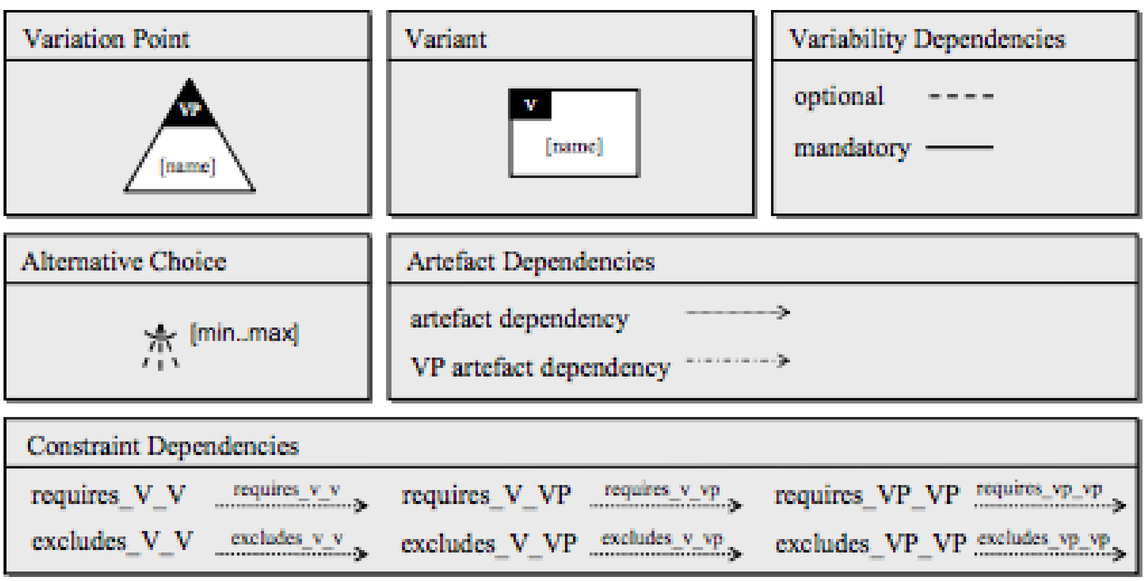
- Referenced Architecture
- Domain Models
- Requirements and Specifications

There are various approaches that comprise the Variation Point Model (VPM), which evaluates multiple levels of the system to identify variants. Since VPM is mostly used to identify variants for software incorporated into a system, the specific approach utilized for the product line combat system is modeling variability using variation points. There are multiple advantages to variability modeling using variant points. VPM has the following qualities for modeling with variation points (Webber and Gomaa 2004):

- Variant points visualization
- Variation points mapped to requirements
- Variation points mapped to reference architecture

Variation points in the reference architecture are marked in Figure 10 with "VP" in the top left corner. Variation diagrams were created using the following notation described in Table 1.

Table 1. Graphical Notation for Variability Models. Source: Pohl, Bockle, and Van Der Linden (2005).



Variation diagrams for each variation point are identified in the following subsections.

1. Array/Sensor Variations

In ASW scenarios, a combat system deploys one or several methods to try to detect an enemy submarine. Any combination of these arrays or sensors send data to be processed and sent to fire control. For the purpose of this paper, only the functionality of detecting submarines is used. The requirements of the sensor variation are detailed in Table 2.

Table 2. Requirement Variations for SONAR

Variation Point	The sensors shall…
Variant	… conduct underwater search and tracking,
Variant	… detect mechanical contacts in the water,
Variant	… track contacts,
Variant	… and provide high-resolution imagery for identification and targeting. (Hall 2018).

Figure 11 identifies the variation diagram for the arrays and sensors.

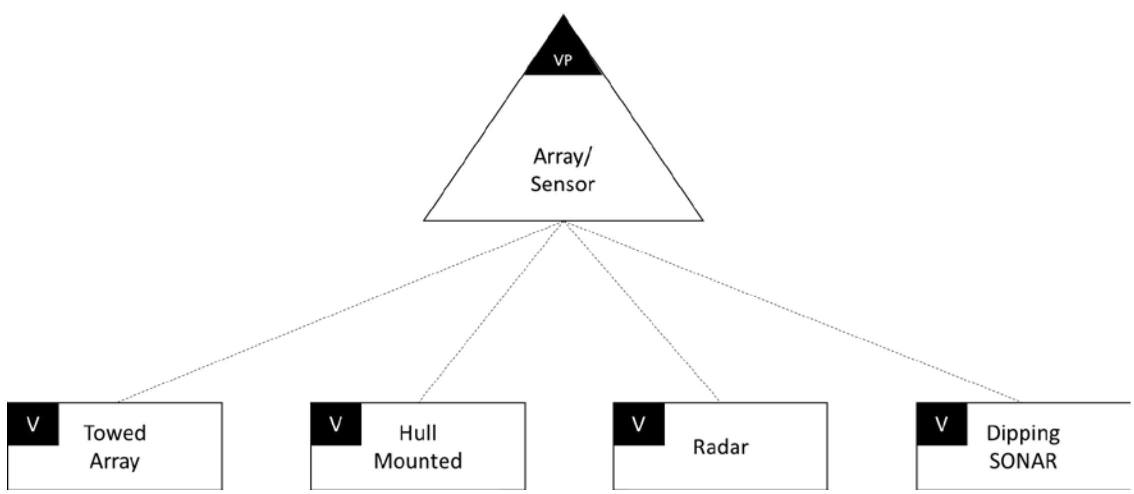


Figure 11. Array/Sensor Variability Diagram

2. Weapon Variations

Each combat system is equipped with a variation of weapons, including vertical and horizontal launched systems. The ability to hold different weapons allows the platforms to be prepared for a variety of ASW scenarios. Both surface ships and submarine platforms hold horizontal weapons (torpedoes), and vertical weapons (missiles). In addition, surface ships have the capability to hold rail guns and similar weapons. Finally, the helicopter platform cannot hold missiles for ASW missions. Regardless of the weapon used, Table 3 describes the requirements that the weapon systems should be able to accomplish.

Table 3. Requirement Variations for Weapons

Variation Point	The weapons shall…
Variant	…target and engage ASW targets at long range,
Variant	…target and engage ASW targets at short range,
Variant	… provide supportability for future weapons technology (Hall 2018),
Variant	… and provide defensive capability to ownship.

Figure 12. Identification of Variation diagram for the weapons on combat systems.

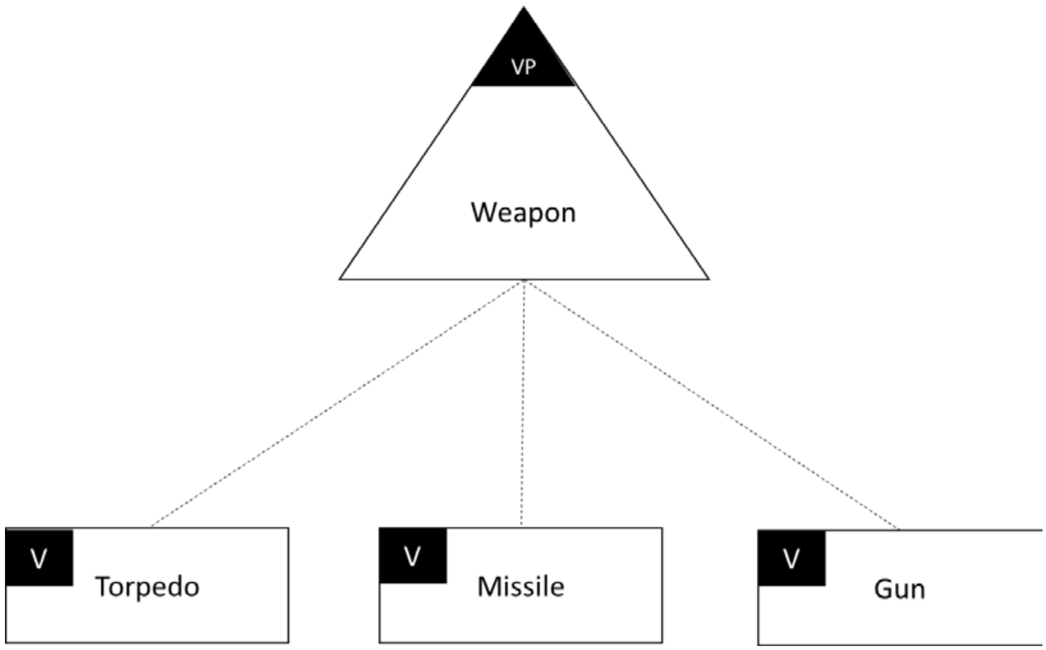


Figure 12. Weapons Variability Diagram

3. Tactical Control Variations

The tactical control subsystem for each of the combat systems is necessary to control the system's ability to launch weapons. For each weapon defined in Chapter II, the tactical control subsystem provides the necessary indications and signals for a successful launch. The requirements for the variation of the tactical control subsystem are identified in Table 4.

Table 4. Requirement Variation for Tactical Control

Variation Point	The tactical control subsystem shall…
Variant	… control launch from the systems torpedo tube,
Variant	… control launch from the systems vertical launch system,
Variant	… control firing of the systems guns.

Figure 13 identifies the variation diagram for the tactical control subsystem.

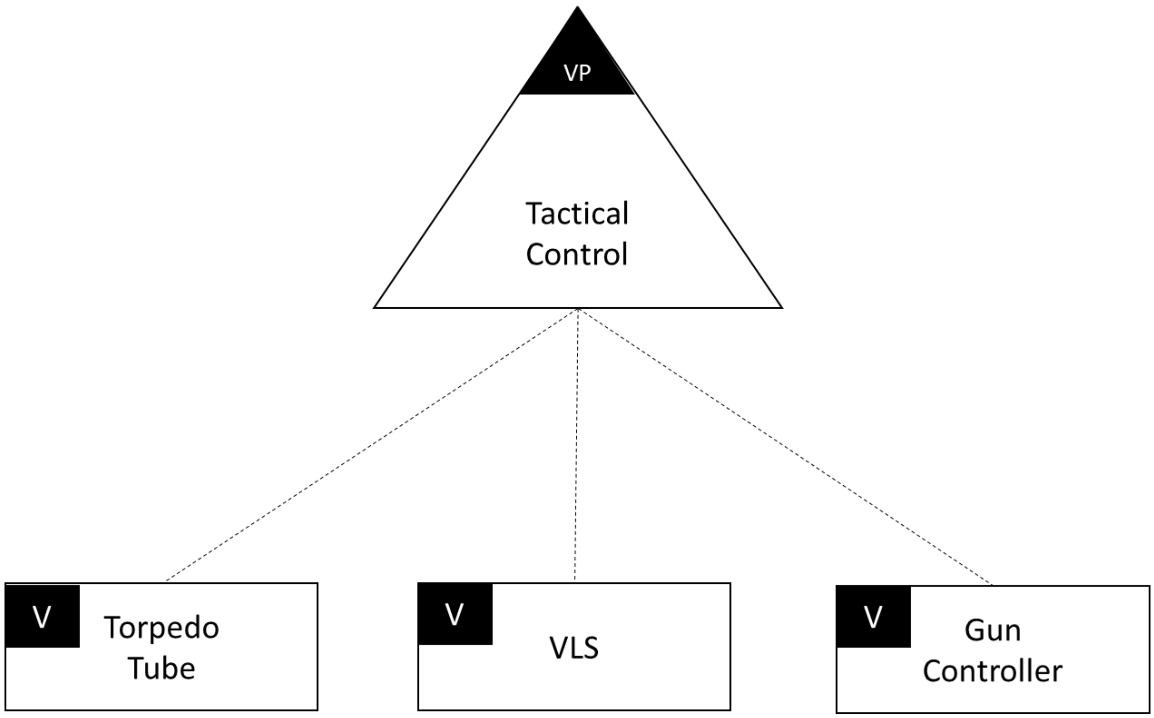


Figure 13. Tactical Control Variability Diagram

4. Data Link Variations

There are two ways a platform obtains the data necessary to execute its ASW mission, organically and via external sources. The variations on organic sensors are covered in Chapter III.C.1. Combat systems can obtain precise mission strike data for ASW missions via different data links including terrestrial line of sight (LOS), terrestrial beyond LOS using relays, and satellites. The data links provide mission data to the platforms that can be executed with any of the variant weapon systems (see in Chapter III.C.1). Table 5 provides the requirement variations for the data links.

Table 5. Variation Requirements for Data Links. Source: Hall (2018).

Variation Point	Data links shall…
Variant	… transfer data with assets within the LOS,
Variant	… transfer data with assets beyond LOS,
Variant	… transfer data via satellite.

Figure 14 identifies the variation diagram for the data links on combat systems.

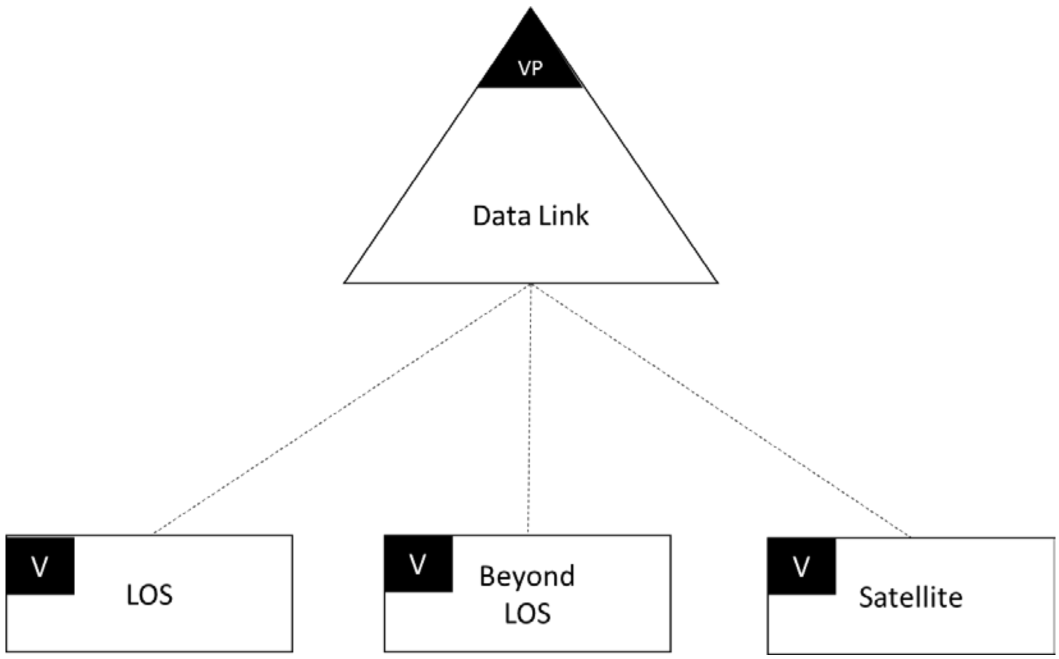


Figure 14. Data Link Variability Diagram. Adapted from Hall (2018).

5. Human System Integration (HSI) Variations

As Hall mentions on his thesis, Utilizing a model-based system engineering approach to develop a combat system product line, "The HSI variation points offer five optional variants as alternative choices that are focused on the consoles and displays for the combat systems" (Hall 2018, 45). These variation points enable the generic combat system model to be adapted to a variety of platforms with different display and arrangement requirements. As an example, a combat platform may have only one console with two displays, or three consoles with one display each, where the middle display is double the size of the other two. Table 6 provides the requirement variations for the HSI variations.

Table 6. Variation Requirements for Combat System. Source: Hall (2018).

Variation Point	Display console be equipped with…
Variant	… either single…

Variant	… or multiple consoles…
Variant	… and single…
Variant	… or multiple displays…
Variant	… and allow for various display sizes.

Figure 15 identifies the variation diagram for the HSI displays on Combat Systems.

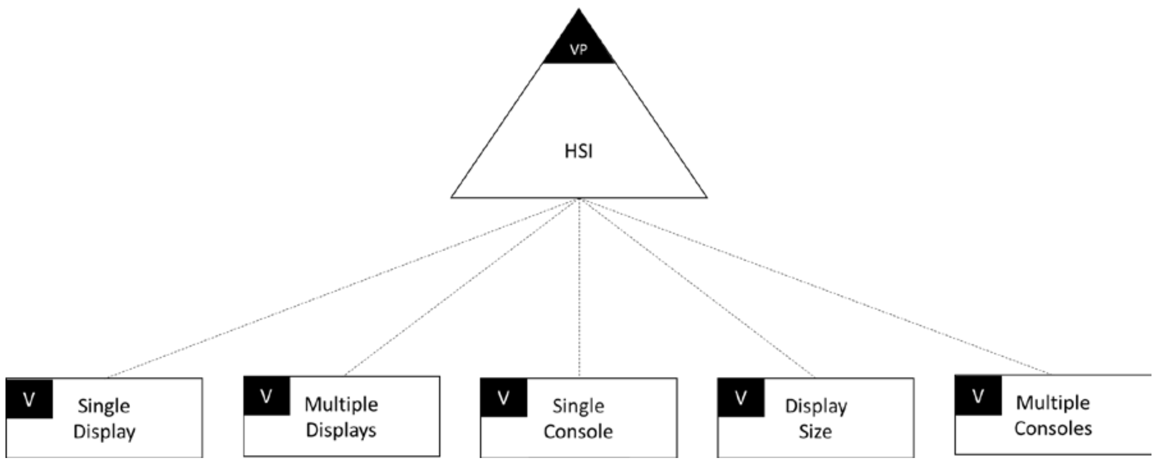


Figure 15. HSI Variability Diagram. Source: Hall (2018).

E. ASW ORTHOGONAL VARIABILITY MODEL

The combat system orthogonal variability model describes the combat systems used by three ASW systems proposed for the product line. The variation points defined in the previous sections, Array/Sensor, Weapon, Tactical Control, Data Link, and HSI are included in the model. Each combat system has dependencies with the other variations, which are marked in accordance with Figure 16. Depending on the functionalities of the combat system, each system may require or exclude different variations. These variations allow the combat system to perform the basic functions required in an ASW scenario defined in Figure 8.

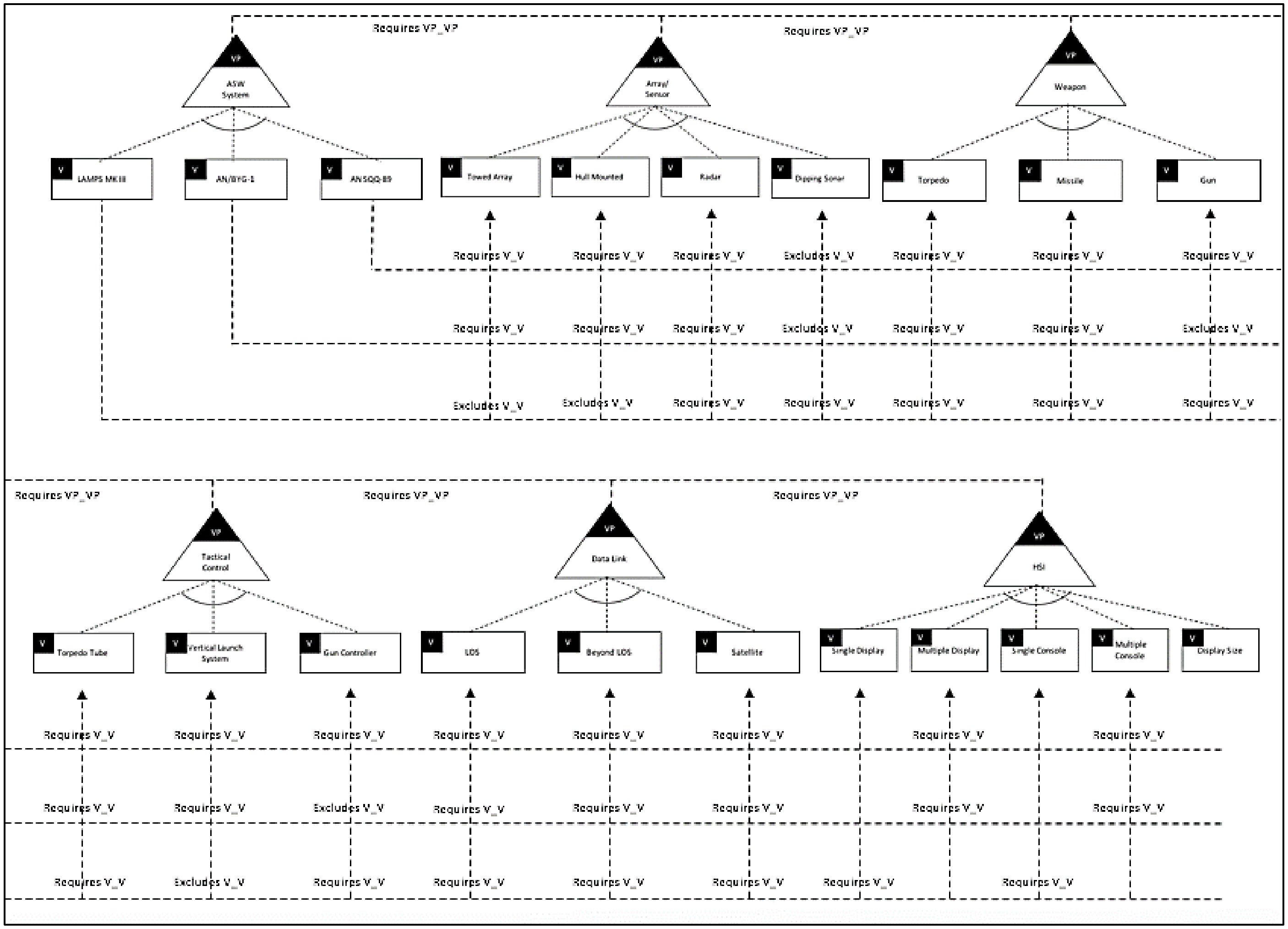


Figure 16. Combat System Product Line Orthogonal Variability Model

F. SYSTEM CONSTRUCTIVE PRODUCT LINE INVESTMENT MODEL

System COPLIMO is a variation of the Basic COPLIMO used in software that models product line investment at the system-level. It includes maintenance costs such that it can be used to assess the Total Ownership Cost (TOC) to research, develop, acquire, own, operate, maintain and dispose of a system (Boehm, Lane and Madachy 2011). The inputs required to the System COPLIMO are:

1. System Cost
2. Product Line Percentages
3. Relative Cost of Reuse
4. Investment Cost
5. Ownership Time
6. Annual Change Percentage

A model is created with system COPLIMO using a reference combat system as a baseline product and the LAMPS MK III, AN/BYG-1 and SQQ-89 combat systems as products in the product line. The average product development cost for the LAMPS MK III and SQQ-89 combat systems are $189 million (Forecast International 2004) and $262.4 million (Defense Acquisition Management Information Retrieval 2015) respectively. For AN/BYG-1, two of the three main components (Tactical Control System (TCS), Payload Control System (PCS) and Information Assurance application) are found. The costs of PCS and TCS are found to be $54.7 million (Keller 2016) and $74 million (U.S. Department of Defense 2015) respectively. Using these two values, the third is estimated to come to a total estimate development cost of $212.5 million for AN/BYG-1.

The total ownership time for the LAMPS MK III combat system in its current state is estimated to be 25 years, with a service life of 20,000 flight hours (Pike 1999), while the total ownership time of both AN/BYG-1 and SQQ-89 combat systems is estimated to be the same at 40 years (Defense Acquisition Management Information Retrieval 2015). The annual interest rate is given by the Bureau of the Fiscal Service as 3.625 percent (Bureau of the Fiscal Service 2019).

The product line percentages to be entered into COPLIMO are a percentage of three categories of system components: Unique, Adapted and Reused. These three labels are given to classify each variant defined in Chapter III, Section D along with supporting rationale. The 18 variants are listed in Table 7 with their assigned classification and supporting rationale.

Table 7. Product Line Variant Classification

Variation Point: Array/Sensor		
Product Line Classification	Variant	Supporting Rationale
Adapted	Towed Array	Array only used for surface and subsurface platforms
Adapted	Hull Mounted Array	Array only used for surface and subsurface platforms
Reused	Radar	Standard across all systems
Unique	Dipping SONAR	SONAR only used for LAMPS MK III
Variation Point: Weapon		
Product Line Classification	Variant	Supporting Rationale
Unique	Torpedo	Weapon dependent on ship size and mission
Unique	Missile	Weapon dependent on ship size and mission
Adapted	Gun	Size of the gun varies between air and surface ship ASW systems
Variation Point: Tactical Control		
Product Line Classification	Variant	Supporting Rationale
Adapted	Torpedo Tube	Torpedo tube varies between systems
Adapted	Vertical Launch System	Vertical launch system varies between systems
Adapted	Gun Controller	Guns vary between systems
Variation Point: Data Link		
Product Line Classification	Variant	Supporting Rationale
Reuse	LOS	Standard across all systems
Reuse	Beyond LOS	Standard across all systems
Reuse	Satellite	Standard across all systems
Variation Point: HSI		
Product Line Classification	Variant	Supporting Rationale
Reuse	Single Display	Displays common across systems
Reuse	Multiple Display	Displays common across systems
Reuse	Single Controller	Controllers common across systems
Reuse	Multiple Controller	Controllers common across systems
Adapted	Display Size	Size specified by restrictions of the system

The percentages for the combat system baseline product and the products after are then broken into Table 8, Table 9, Table 10 and Table 11. Each of the combat systems has the percentage of components that can be reused, adapted, or uniquely designed.

Table 8 used the total amount of reused and adapted components identified in Table 7 as the Developed for Product Line Reuse Count, and the total amount of unique components in Table 7 for the Unique Count. Percentages are based of the count for each row divided by the total possible components (i.e., for Developed for Product Line Reuse Percentage, the value is found by taking the count, 16, divided by the total possible components, 18).

To determine what components will be reused, adapted, or unique for following products in the product line, Figure 16 was utilized for each ASW system. Looking at LAMPS MK III as an example going from left to right, towed array and hull mounted variants are not included for the LAMPS MK III Package Variant since Figure 16 "excludes" these variants from LAMPS MK III. Radar and Dipping Sonar are identified as "required" by Figure 16 and are therefore included in the LAMPS MK III Packaged Variant. To determine if the Radar and Dipping Sonar are reused, adapted, or unique, Table 7 was used where the Radar component is identified as a product to be developed for reuse while Dipping Sonar is identified as a unique product. The remaining variants are also evaluated for LAMPS MK III in the same way, and for AN/BYG-1 and SQQ-89. The total counts for reused, adapted, and unique components using this methodology are identified in Table 9, Table 10 and Table 11. Percentages are based on the count for each system component type divided by the total possible components identified for the packaged variant as defined in the top row of each table.

Table 8. Combat System Reference Baseline Architecture

ASW Reference Architecture (18 Total Possible Components)		
System Component Type	Count	Percentage
Developed for Product Line Reuse	16	88.8%
Unique	2	11.1%

Table 9. LAMPS MK III Packaged Variant Product Line Percentages

LAMPS MK III Packaged Variant (15 Total Possible Components)		
System Component Type	Count	Percentage
Reuse	8	53.3%
Adapted	5	33.3%
Unique	2	13.3%

Table 10. AN/BYG-1 Packaged Variant Product Line Percentages

AN/BYG-1 Packaged Variant (15 Total Possible Components)		
System Component Type	Count	Percentage
Reuse	8	53.3%
Adapted	5	33.3%
Unique	2	13.3%

Table 11. SQQ-89 Packaged Variant Product Line Percentages

SQQ-89 Packaged Variant (17 Total Possible Components)		
System Component Type	Count	Percentage
Reuse	8	47%
Adapted	7	41%
Unique	2	12%

1. System COPLIMO Inputs

System COPLIMO inputs are derived from the tables and information detailed in in Section E. The inputs to the System COPLIMO model are identified for the three products to follow the baseline. The product line percentages and other inputs are entered into the input table in Table 12.

Table 12. System COPLIMO Input Table

System COPLIMO Input Summary		
Input	Value	Rationale
System Cost		
Average Product Development Cost	$221,300,000	Average cost of LAMPS MK III, AN/ BYG-1 and SQQ-89
Annual Charge Cost	10%	Estimation
Ownership Time	25 years (LAMPS)	(Pike, 1999).
	40 years (BYG-1, SQQ-89)	(Defense Acquisition Management Information Retrieval 2015).
Interest Rate	3.63%	(Service, 2019).
Product Line Percentages for Baseline Product		
Unique	11.1%	Table 8
Developed for Product Line Reuse	88.8%	Table 8
Product Line Percentages for Product 1 (LAMPS MK III)		
Unique	13.3%	Table 9
Adapted	33.3%	Table 9
Reused	53.3%	Table 9
Product Line Percentages for Product 2 (AN/BYG-1)		
Unique	13.3%	Table 10
Adapted	33.3%	Table 10
Reused	53.3%	Table 10
Product Line Percentages for Product 3 (SQQ-89)		
Unique	12.0%	Table 11
Adapted	41.0%	Table 11
Reused	47.0%	Table 11
Relative Cost of Reuse		
Relative Cost of Reuse for Adapted	40%	COPLIMO default
Relative Cost of Reuse for Reused	5%	COPLIMO default
Investment Cost		
Relative Cost of Developing for PL Flexibility via Reuse	1.7	COPLIMO default

The values listed in Table 12 are then input into the System COPLIMO model. In order to account for the varying ownership times and varying unique, adapted and reused percentages, updates to the basic system COPLIMO used by Boehm, Lane and Madachy are necessary. The system COPLIMO runs computes the Development Cost, Ownership Cost, Investment, Savings, Avoidance, and ROI for each product in the product line.

Development cost is calculated using product equivalent size and the product cost for each product to show the cost expected to develop each product in the product line. The average product cost is an input provided while the product equivalent size is different depending on the product in the product line. The baseline product uses the following equation to determine product equivalent size, which accounts for the extra effort in creating components that can be reused and adapted by following products in the product line:

$$Product\ Equivalent\ Size\ Baseline\ =\ Unique\ \% + RCWR * (Adapted\% + Reused\%) \quad (1)$$

The products that follow use a different equation to determine product equivalent size, which accounts for the lower cost of reusing and adapting existing components to LAMPS MK III, AN/BYG-1 and SQQ-89 combat systems:

$$\begin{aligned} Product\ Equivalent\ Size = & \left(RCRUnique * Unique\%\right) + \left(RCRAdapted\ * Adapted\%\right) \\ & + (RCRReused * Reused\%) \end{aligned} \quad (2)$$

Using the product equivalent size for a product found with either equation 1 for the baseline product or equation 2 for following products, and the associated product cost, the development cost for each product can be found using the equation:

$$Development\ Cost\ =\ \frac{Product\ Equivalent\ Size}{100} *\ Average\ Product\ Cost \quad (3)$$

Ownership cost for a product in the product line finds the cost of owning a product in the product line by accounting for the ownership time and the annual change cost along with the cost to develop the product. Ownership cost is found using the equation:

$$Ownership\ Cost\ =\ \frac{Development\ Cost * Annual\ Change\ Cost}{100} * Ownership\ Time \quad (4)$$

Investment for a product in the product line also varies depending on the product. The baseline product investment show the investment required to develop components of a system to be capable of being adapted and reused by other products in the product line. Non-product line equivalent size for the baseline system is found by taking the sum of its unique, adapted and reused percentages. The investment for a baseline product is found using the following equation:

$$Investment = \frac{(Product\ Equivalent\ Size - NonProduct\ Equivalent\ Size)}{100} * Product\ Cost \quad (5)$$

For products following the baseline product, the investment is zero since there are no new components being created requiring design for adaptation or reuse.

The savings of the product in the product line shows the amount of money saved by a developer for each product using the product line compared to if a non-product line product was developed. An ownership cost multiplier is applied to account for the life of the product using the following equation:

$$Ownership\ Cost\ Multiplier = \frac{(Development\ Cost + Ownership\ Cost)}{Development\ Cost} \quad (6)$$

Using the ownership cost multiplier from equation 6, along with the other inputs mentioned, savings for a product is found using the equation:

$$Savings = \frac{(NonProduct\ Line\ Equivalent\ Size - Product\ Equivalent\ Size)}{100} * Product\ Cost * Ownership\ Cost\ Multiplier \quad (7)$$

Using the Non-Product Line Product Cost of LAMPS MK III, AN/BYG-1 and SQQ-89 combat systems, a cost avoidance is also calculated by the models using the equation:

$$Cost\ Avoidance = \frac{(NonProduct\ Line\ Product\ Cost - Development\ Cost)}{NonProduct\ Line\ Product\ Cost} \quad (8)$$

The non-product line cost for the baseline combat system is found using the average cost of all three combat systems to be $221 Million. The mission unique and developed for product line reuse percentages along with the relative cost weight (both inputs to the system COPLIMO model defined in Table 12) can then be used to find the mission unique and developed for product line reuse adjusted costs. The sum of those costs represents the additional cost of designing 88.8% of products in the system to be reused and adapted by following products. This results in a higher total cost for the product line adjusted cost. The cost avoidance of the baseline product is therefore a higher value than the non-product line cost due to this additional investment.

Illustrated, in both Table 13 and Table 14, are the essential cost COPLIMO calculations for the baseline system and LAMPS MK III. Table 13 shows the process for finding cost avoidance for the baseline product.

Table 13. Baseline Combat System with Investment Cost Estimate

Baseline Combat System			
Non-Production Line Cost ($M)	221		
Category	**Percent**	**Relative Cost Weight**	**Adjusted Cost ($M)**
Mission Unique	11.0%	1.0	24.3
Developed for Production Line Reuse	89.0%	1.7	334.3
		Total Adjusted Cost ($M)	358.6

For a product in the product line following the baseline product, the products of the percent mission unique/adapted/reused components, the relative cost (both inputs to the system COPLIMO model defined in Table 12) and the non-product line cost form the adjusted cost for mission unique, adapted and reused components. The sum of these adjusted costs is then subtracted from the non-product line cost for LAMPS MK III combat system over the non-product line cost for LAMPS MK III combat system to get a 76% cost avoidance in the cost of LAMPS MK III combat system by using a product line. Table 14 depicts the process for determining cost avoidance for LAMPS MK III combat system.

Table 14. LAMPS MK III Combat System Cost Estimate

LAMPS MK III Combat System			
Non-Production Line Cost ($M)	189		
Category	**Percent**	**Relative Cost Weight**	**Adjusted Cost ($M)**
Mission Unique	13.3%	1.00	25.1
Adapted	33.3%	0.40	25.2
Reused	53.3%	0.05	5.0
Cost Avoidance	85%	**Total Adjusted Cost ($M)**	55.3

Finally, the ROI is a cumulative value calculated using the cumulative savings and investment of a product; meaning the sum of the savings and the sum of the investment costs for the product in the product line and all the products before it. The equation for ROI is:

$$ROI = \frac{(Cumulative\ Savings - Cumulative\ Investment)}{Cumulative\ Investment} \quad (9)$$

Equations 3, 4, 5, 7, 8 and 9 are all used in the excel tool to calculate Development Cost, Ownership Cost, Investment, Savings, Cost Avoidance, and ROI. The excel tool is shown in Figure 17, Figure 18 and Figure 19 as part of Chapter IV.

G. SOFTWARE CONSTRUCTIVE PRODUCT LINE INVESTMENT MODEL

The Software COPLIMO, also called Basic COPLIMO, is a framework designed to assess the cost and savings associated with developing new software and reusing software from a product line across similar applications. The Software COPLIMO focuses on parts of the system "that involve product-specific newly-built software, fully reused product line software and product line software that are reused with some modification" (Boehm et al. 2004, 1). In order to use the Software COPLIMO model, the following inputs are required:

1. Average Software Productivity

2. Average Product Size

3. Expected Reuse Category Percentages

4. Expected Relative Cost of Reuse

5. Expected Relative Cost of Writing for Reuse

The average software productivity, expected relative cost of reuse, and expected relative cost of writing for reuse are all estimated using standards provided by the COPLIMO model. An estimate of 150 source lines of code (SLOC) provides an average for “outcome-critical real-time control applications” (Center for Systems and Software Engineering n.d.). Additionally, COPLIMO uses an expected relative cost of reuse value for unique, adapted and reused software of 100%, 40%, and 5% respectively. Finally, a standard value for relative cost of writing for reuse is 1.7.

The other inputs for COPLIMO are based on the software that is being analyzed. The average ,product size and the percent of software that is unique, adapted, and reused for the product line needs to be determined for software of all three combat systems.

1. Software COPLIMO Inputs

When deriving estimates for SLOC for combat systems, there is a difficulty of running into the classification of the systems. For SQQ-89 and for LAMPS MK III, there is a lack of public information on the codes. The cost for each system found in the previous section as system COPLIMO inputs and the SLOC for AN/BYG-1 are used to calculate the SLOC for LAMPS MK III and SQQ-89.

With the development cost of each system found previously, the SLOC is next to be determined. An estimate from the website of In-Depth Engineering at the time of development, a principle partner in the design and development of AN/BYG-1, had approximately 63% of the code baseline at 1.3 million SLOC (In-Depth Engineering 2014) or roughly 2 million SLOC for AN/BYG-1. The SLOC for LAMPS MK III and SQQ-89 are interpolated using development cost and SLOC for AN/BYG-1. The SLOC for LAMPS MK III and SQQ-89 are estimated to be 1.8 million SLOC and 2.5 million respectively.

The assumptions and inputs from Table 15 are used as inputs to the software COPLIMO.

Table 15. Software COPLIMO Inputs

Software COPLIMO Input Summary		
Input	Value	Rationale
Average Productivity and Size		
Average SW Productivity (SLOC/PM)	150	COPLIMO Default
Average Product Size (SLOC)	2089072	Average of LAMPS MK III, AN/BYG-1 SQQ-89
Expected Reuse Category Percentages for Baseline Product		
Unique	11.1%	Table 8
Developed for Product Line Reuse	44.4%	Table 8
Expected Reuse Category Percentages Product 1 (LAMPS MK III)		
Unique	13.3%	Table 9
Adapted	33.3%	Table 9
Reused	53.3%	Table 9
Expected Reuse Category Percentages Product 2 (AN/BYG-1)		
Unique	13.3%	Table 10
Adapted	33.3%	Table 10
Reused	53.3%	Table 10
Expected Reuse Category Percentages (Product 3 (SQQ-89)		
Unique	12.0%	Table 11
Adapted	41.0%	Table 11
Reused	47.0%	Table 11
Expected Relative Cost of Reuse		
Unique	100%	COPLIMO Default
Adapted	40%	COPLIMO default
Reused	5%	COPLIMO default
Expected Relative Cost of Writing for Reuse (RCWR)		
RCWR	1.7	COPLIMO Default

The basic COPLIMO models used by Boehm, Brown, Madachy and Yang was updated to allow for variation in the SLOC for each product in the product line and variation in the unique, adapted, and reuse percentages for each product. The results of the detailed software COPLIMO are the amount of unique, adapted and reused SLOC, the Total Non-PL SLOC, the Non-PL Effort, 1-Product Equivalent SLOC, 1-Product Equivalent Effort, Cumulative Equivalent PL SLOC, Cumulative PL Effort, PL Effort Savings, PL Reuse Investment and ROI.

Unique, Adapted and Reused SLOC is found by multiplying the unique, adapted, and reused percentages by the size, all of which are provided as inputs. These values are cumulative, the number of unique, adapted and reused SLOC for a product is the sum of that product and all products before it. Total SLOC is the sum of unique, adapted, and reused SLOC. Non-PL Effort uses the total SLOC divided by the average productivity provided as an input for a product finds the effort in person-months. For the baseline product, the percentages of reused and adapted SLOC are not actually being reused and adapted, rather this represents the amount of SLOC being generated to be adapted and reused later on by following products in the product line. The adapted and reused SLOC for the baseline product is represented in the software COPLIMO as “Developed for Product Line Reuse” which shows the total amount of SLOC developed as part of the baseline product for reuse and adaption by the following products.

The 1-Product Equivalent SLOC and Cumulative Equivalent PL SLOC look at the SLOC for 1 product in the product line and cumulative SLOC respectively. Cumulative Equivalent PL SLOC uses a different equation for the baseline product in the product line using the unique, adapted and reused SLOC and Relative Costs of Writing for Reuse (RCWR) to account for the extra effort of writing code that can be reused and adapted by following products. The equation for baseline Cumulative Equivalent PL SLOC is:

$$Cum. Equiv. PL\ SLOC\ Baseline = Unique\ SLOC + RCWR * (Adapted\ SLOC + Reuse\ SLOC) \quad (10)$$

Following the baseline product, Cumulative Equivalent PL SLOC values are found using unique, adapted and reused SLOC with their expected relative cost of reuse (RCR) values since the code written for the baseline can now be reused and adapted at reduced costs. The equation for the Cumulative Equivalent PL SLOC for products after the baseline product is:

$$Cum.\ Equiv.\ PL\ SLOC\ =\ \frac{(UniqueSLOC * RCRUnique) + (AdaptedSLOC * RCRAdapted) + (Reuse\ SLOC * RCRReuse)}{100} + Previous\ Cum.\ Equiv.\ PL\ SLOC \qquad (11)$$

The 1-Product Equivalent SLOC can be found from Cumulative Equivalent PL SLOC for the product in question subtracted by the Cumulative Equivalent PL SLOC of the product before the product in question.

The 1-Product Equivalent Effort and the Cumulative PL Effort have a similar relationship. The Cumulative PL Effort divides the Cumulative Equivalent PL SLOC by the average productivity provided as an input to the model, while the 1-Product Equivalent Effort divides the 1-Product Equivalent SLOC by the average productivity.

The PL Effort Savings is found by taking the difference of the Non-PL Effort and the Cumulative PL Effort. The inverse of the PL Effort Savings determines the PL Reuse Investment for the baseline product. For following products, the PL Reuse Investment is zero.

Finally, the ROI found by COPLIMO is found by taking the PL Effort Savings of a product and dividing it by the cumulative PL Reuse Investment up to that product.

Equations 10 and 11 are utilized by the excel tool to calculate Cumulative Equivalent PL SLOC for both the baseline product and the products that follow. The Software COPLIMO Excel tool is shown in Figure 20, Figure 21 and Figure 22.

H. SUMMARY

Innoslate, a MBSE tool, is chosen to not only develop and characterize the combat system domain model, but also the reference architecture. The combat system domain model encompasses the ASW scenario with physical subsystems that perform the functions along with external interactions for information that is passing between the systems boundaries. The reference architecture is reflective of the suitable solution for a combat system utilizing existing components used in the functional “kill-chain” sequence. The functions supported are detect, plan, launch, and communicate. These functions are fulfilled by the three combat systems, but contain varying components.

The reference functional architecture is mapped to physical entities diagramed in the reference physical architecture. From the reference physical architecture, variation points are identified to develop variants of a combat system. The points of variation assist in the visualization, requirements mapping, and architectural mapping of the derived system. Different variations exist based on arrays/sensors, weapons, tactical control, datalink, and HSI. From the variations, an orthogonal variability model assists in the proposal of combat systems for product line engineering and accounts for the dependencies of the variations. The purpose is to have a system that is fully capable of performing the requirements of an ASW combat system.

The Software COPLIMO, also called Basic COPLIMO, is a framework designed to assess the cost and savings associated with developing new software and reusing software from a product line across similar applications. The Software COPLIMO focuses on parts of the system "that involve product-specific newly-built software, fully reused product line software and product line software that are reused with some modification" (Boehm et al. 2004, 1). On the other hand, System COPLIMO is a variation of the Basic COPLIMO used in software that models product line investment at the system-level. It includes maintenance costs such that it can be used to assess the Total Ownership Cost (TOC) to research, develop, acquire, own, operate, maintain and dispose of a system (Boehm, Lane and Madachy 2011). A model is created for both system and software COPLIMO using a reference combat system as a baseline product and the LAMPS MK III, AN/BYG-1 and SQQ-89 combat systems as products in the product line.

IV. ECONOMIC ANALYSIS

A. SYSTEM ECONOMIC ANALYSIS

The results for the System COPLIMO run are shown in Figure 17. The outputs from the System COPLIMO are plotted as points in the product line with the net development effort savings over the number of products in the product line. The equations in Chapter III, Section E are used on each product in the product line with the system inputs and product specific inputs shown with the results.

Summary of Inputs

	Baseline Product	Product 1 (LAMPS MK III)	Product 2 (AN/BYG-1)	Product 3 (SQQ-89)
Product Cost ($M)	$221.30	$221.30	$221.30	$221.30
Ownership Time (years)	40	25	40	40
Annual Change Cost (%)	10	10	10	10
Interest Rate (%)	3.63	3.63	3.63	3.36
Unique (%)	11.1	13.3	13.3	12
Developed for Product Line Reuse (%)	88.8	0	0	0
Adapted (%)	0	33.3	33.3	41
Reused (%)	0	53.3	53.3	47
RCR-Unique (%)	100	100	100	100
RCR-Adapted (%)	40	40	40	40
RCR-Reused (%)	5	5	5	5
RCWR	1.7	1.7	1.7	1.7
Non-Product Line Cost ($M)		189	212.5	262.4

Summary of results

Product #	Development Cost ($M)	Ownership Cost ($M)	Investment	Savings ($M)	Cost Avoidance	Cum. ROI
0	$358.64	1434.56	$137.56	($687.80)		-6.00
1	$64.81	162.02	0	$546.95	85%	-2.02
2	$64.81	259.23	0	$781.35	83%	3.66
3	$97.74	390.98	0	$766.25	68%	9.23

Figure 17. Most Likely Scenario System COPLIMO

The model in Figure 17 provides the estimated product line effort savings for the most likely scenarios of all three product lines. Optimistic “best case” and pessimistic “worst case” approaches are adapted from Alain Abran’s textbook “Software project estimation: the fundamentals for providing high quality information to decision makers” (Abran 2015) to provide a range of where the true return on investment for adapting combat systems to a product line approach.

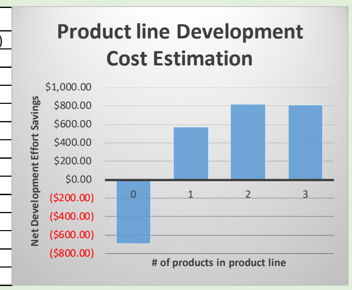
A best case scenario shows the results if the actual relative cost to rewrite for adapted and reused components was overestimated by 20% resulting in an RCR-Adapted and RCR-Reused of 32% and 4% respectively.

The worst case scenario for the system COPLIMO run was found using a pessimistic estimation of 50% higher RCR-Adapted and RCR-Reused resulting in 60% and 7.5% respectively.

By estimating the best and worst case scenarios, the best and worst case ROIs can be compared to the most likely scenario to understand the range of outcomes in adapting the combat system to a product line approach. The best case scenario system COPLIMO run shown in Figure 18 and the worst case scenario system COPLIMO run is shown in Figure 19 show points in the best and worst scenarios of adapting the combat system into a product line.

Summary of Inputs

	Baseline Product	Product 1 (LAMPS MK III)	Product 2 (AN/BYG-1)	Product 3 (SQQ-89)
Product Cost ($M)	$221.30	$221.30	$221.30	$221.30
Ownership Time (years)	40	25	40	40
Annual Change Cost (%)	10	10	10	10
Interest Rate (%)	3.63	3.63	3.63	3.36
Unique (%)	11.1	13.3	13.3	12
Developed for Product Line Reuse (%)	88.8	0	0	0
Adapted (%)	0	33.3	33.3	41
Reused (%)	0	53.3	53.3	47
RCR-Unique (%)	100	100	100	100
RCR-Adapted (%)	32	32	32	32
RCR-Reused (%)	4	4	4	4
RCWR	1.7	1.7	1.7	1.7
Non-Product Line Cost ($M)		189	212.5	262.4



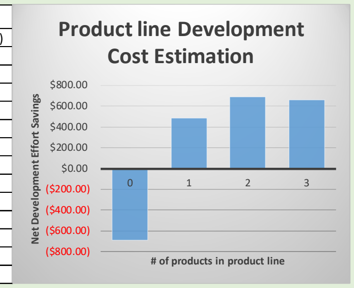
Summary of results

Product #	Development Cost ($M)	Ownership Cost ($M)	Investment	Savings ($M)	Cost Avoidance	Cum. ROI
0	$358.64	1434.56	$137.56	($687.80)		-6.00
1	$57.73	144.33	0	$571.71	86%	-1.84
2	$57.73	230.93	0	$816.73	85%	4.09
3	$95.90	383.60	0	$807.75	68%	9.97

Figure 18. Best Case Scenario System COPLIMO

Summary of Inputs

	Baseline Product	Product 1 (LAMPS MK III)	Product 2 (AN/BYG-1)	Product 3 (SQQ-89)
Product Cost ($M)	$221.30	$221.30	$221.30	$221.30
Ownership Time (years)	40	25	40	40
Annual Change Cost (%)	10	10	10	10
Interest Rate (%)	3.63	3.63	3.63	3.36
Unique (%)	11.1	13.3	13.3	12
Developed for Product Line Reuse (%)	88.8	0	0	0
Adapted (%)	0	33.3	33.3	41
Reused (%)	0	53.3	53.3	47
RCR-Unique (%)	100	100	100	100
RCR-Adapted (%)	60	60	60	60
RCR-Reused (%)	7.5	7.5	7.5	7.5
RCWR	1.7	1.7	1.7	1.7
Non-Product Line Cost ($M)		189	212.5	262.4



Summary of results

Product #	Development Cost ($M)	Ownership Cost ($M)	Investment	Savings ($M)	Cost Avoidance	Cum. ROI
0	$358.64	1434.56	$137.56	($687.80)		-6.00
1	$82.50	206.24	0	$485.04	80%	-2.47
2	$82.50	329.98	0	$692.92	78%	2.56
3	$102.36	409.42	0	$662.52	66%	7.38

Figure 19. Worst Case Scenario System COPLIMO

B. SOFTWARE ECONOMIC ANALYSIS

The results of the software COPLIMO run are shown in Figure 20. The outputs from the Software COPLIMO, like the outputs from the System COPLIMO, are plotted as points in the product line with the net development effort savings over the number of products in the product line. The point estimations for the product line net development effort savings only reflect the average value expected for net development effort savings.

Basic COPLIMO Output Summary

Summary of Inputs:

	Baseline	Product 1 (LAMPS MK III)	Product 2 (AN/BYG-1)	Product 3 (SQQ-89)	
AVPROD	150	150	150	150	
Size (SLOC)	2089072	2089072	2089072	2089072	SLOC
Unique %	11.4	13.3	13.3	12	(%)
Adapted %	44.4	33.3	33.3	41	(%)
Reused %	44.4	53.3	53.3	47	(%)
RCR-UNIQ	100	100	100	100	(%)
RCR-ADAP	40	40	40	40	(%)
RCR-RUSE	5	5	5	5	(%)
RCWR	1.7	1.7	1.7	1.7	

Product Line Effort Savings:

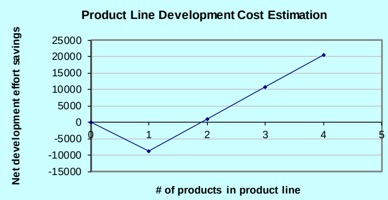


Table of Results:

# of Products	0	1	2	3	4
Unique SLOC	0	238154	516001	793847	1044536
Developed for Product Line Reuse	0	1855096	0	0	0
Adapted SLOC	0	0	1623209	2318870	3175389
Reused SLOC	0	0	2041023	3154499	4136363
Total Non-PL SLOC	0	2093250	4180233	6267216	8356288
Non-PL Effort (PM)	0	13955.00096	27868.22048	41781.44	55708.58667
1-Product Equiv. SLOC	0	3391817.299	633667.7644	626373.421	630377.476
1-Product Equiv. Effort	0	22612.11533	4224.451763	4175.82281	4202.516507
Cum. Equiv. PL SLOC	0	3391817.299	4025485.064	4651858.48	5282235.961
Cum. PL Effort	0	22612.11533	26836.56709	31012.3899	35214.90641
PL Effort Savings	0	-8657.114368	1031.653389	10769.0501	20493.68026
PL Reuse Investment	0	8657.114368			
Return on Investment	N/A	-1.00	0.12	1.24	2.37

Figure 20. Most Likely Scenario Software COPLIMO

While the model shown in Figure 20 provides the estimated product line effort savings for the most likely scenarios of all three product lines, the amount of unique SLOC may have been overestimated. Optimistic "best case" and pessimistic "worst case" approaches are again adapted to provide a range of where the true return on investment for adapting combat system software to a product line approach.

A best case scenario shows results if the actual relative cost to rewrite for adapted and reused components was overestimated by 20% resulting in an RCR-Adapted and RCR-Reused of 32% and 4% respectively. The worst case scenario for the system COPLIMO run is found using a pessimistic estimation of 50% higher RCR-Adapted and RCR-Reused resulting in 60% and 7.5% respectively. By estimating the best and worst case scenarios, the best and worst case ROIs can be compared to the most likely scenario to understand the range of outcomes in adapting the combat system software to a product line approach. The best-case scenario is displayed using software COPLIMO in Figure 21. The worst-case scenario is shown in Figure 22.

Basic COPLIMO Output Summary

Summary of Inputs:

	Baseline	Product 1 (LAMPS MK III)	Product 2 (AN/BYG-1)	Product 3 (SQQ-89)	
AVPROD	150	150	150	150	
Size (SLOC)	2089072	2089072	2089072	2089072	SLOC
Unique %	11.4	13.3	13.3	12	(%)
Adapted %	44.4	33.3	33.3	41	(%)
Reused %	44.4	53.3	53.3	47	(%)
RCR-UNIQ	100	100	100	100	(%)
RCR-ADAP	32	32	32	32	(%)
RCR-RUSE	4	4	4	4	(%)
RCWR	1.7	1.7	1.7	1.7	

Product Line Effort Savings:

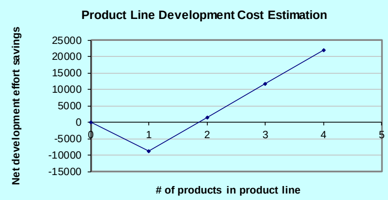


Table of Results:

# of Products	0	1	2	3	4
Unique SLOC	0	238154	516001	793847	1044536
Developed for Product Line Reuse	0	1855096	0	0	0
Adapted SLOC	0	0	1623209	2318870	3175389
Reused SLOC	0	0	2041023	3154499	4136363
Total Non-PL SLOC	0	2093250	4180233	6267216	8356288
Non-PL Effort (PM)	0	13955.00096	27868.22048	41781.44	55708.58667
1-Product Equiv. SLOC	0	3391817.299	558534.2899	554021.894	556528.7808
1-Product Equiv. Effort	0	22612.11533	3723.561933	3693.4793	3710.191872
Cum. Equiv. PL SLOC	0	3391817.299	3950351.589	4504373.48	5060902.264
Cum. PL Effort	0	22612.11533	26335.67726	30029.1566	33739.34843
PL Effort Savings	0	-8657.114368	1532.543219	11752.2834	21969.23824
PL Reuse Investment	0	8657.114368			
Return on Investment	N/A	-1.00	0.18	1.36	2.54

Figure 21. Best Case Scenario Software COPLIMO

Basic COPLIMO Output Summary

Summary of Inputs:

	Baseline	Product 1 (LAMPS MK III)	Product 2 (AN/BYG-1)	Product 3 (SQQ-89)	
AVPROD	150	150	150	150	
Size (SLOC)	2089072	2089072	2089072	2089072	SLOC
Unique %	11.4	13.3	13.3	12	(%)
Adapted %	44.4	33.3	33.3	41	(%)
Reused %	44.4	53.3	53.3	47	(%)
RCR-UNIQ	100	100	100	100	(%)
RCR-ADAP	60	60	60	60	(%)
RCR-RUSE	7.5	7.5	7.5	7.5	(%)
RCWR	1.7	1.7	1.7	1.7	

Product Line Effort Savings:

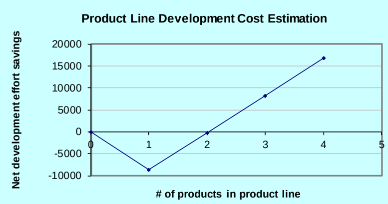


Table of Results:

# of Products	0	1	2	3	4
Unique SLOC	0	238154	516001	793847	1044536
Developed for Product Line Reuse	0	1855096	0	0	0
Adapted SLOC	0	0	1623209	2318870	3175389
Reused SLOC	0	0	2041023	3154499	4136363
Total Non-PL SLOC	0	2093250	4180233	6267216	8356288
Non-PL Effort (PM)	0	13955.00096	27868.22048	41781.44	55708.58667
1-Product Equiv. SLOC	0	3391817.299	821501.4506	807252.239	814999.214
1-Product Equiv. Effort	0	22612.11533	5476.676337	5381.68159	5433.328093
Cum. Equiv. PL SLOC	0	3391817.299	4213318.75	5020570.99	5835570.202
Cum. PL Effort	0	22612.11533	28088.79167	33470.4733	38903.80135
PL Effort Savings	0	-8657.114368	-220.5711853	8310.96674	16804.78532
PL Reuse Investment	0	8657.114368			
Return on Investment	N/A	-1.00	-0.03	0.96	1.94

Figure 22. Worst Case Scenario Software COPLIMO

C. SUMMARY

The cost models for the combat system software and systems provide the expected savings and ROI if a product line approach is used for the LAMPS MK III, BYG-1, and AN/SQQ-89 combat systems.

System models show how the overall cost of developing each combat system can drop with the addition of each product to the product line. The best case, most likely and worst case scenarios all show a positive ROI using the product line and the most likely scenario nearly reaches 10.0. The Software COPLIMO ROI for LAMPS MK III, AN/BYG-1 and AN/SQQ-89 combat systems all show a positive ROI for the best case and most likely scenarios to provide strong rationale for having a product line approach for the combat system software.

Both system and software COPLIMO illustrates the savings and ROI when developing a product line for software development, and the overall system development; as more products are created by the product lines, the larger the savings over the program. It should be noted that these estimations have been done with publicly available information only. Chapter V, Section A - Recommendations provides details into recommendations to expand on this work.

The most likely, best case and worst-case scenarios shown for software and system COPLIMO can be used to show an expected ROI by using a product line approach to developing a combat system and how the savings can be impacted if estimations were altered to reflect a higher or lower relative cost to rewrite adapted and reused components or SLOC. Increasing the RCR-adapted and RCR-reused by 50% leads to a much lower ROI.

V. CONCLUSION

The stovepipe nature of the current combat system development is not ideal under today's global climate. This model does not allow for sharing of lessons learned, technology development, and development assets. In order to maintain maritime superiority, the U.S. Navy needs to explore alternative ways of building and maintaining their systems, in a way that can keep up and surpass the development efforts of rival navy commands. Appling the product line architecture concept is one of the ways the U.S. Navy can achieve its mission. This capstone project presented the models for ROI for a generic ASW combat system. This ROI was constructed using a three pronged strategy presented in Chapter I:

1. Identify common functional elements found in surface, submarine, and aviation

The literature review in Chapter II presents an overall description of the surface, submarine, and aviation systems, specifically, the LAMPS MK III, AN/BYG-1 and SQQ-89 combat systems. From the literature review, it is evident that the current U.S. Navy combat system development is ship-class dependent. LAMPS MK III, AN/BYG-1 and SQQ-89 are all developed, maintained, and upgraded without considering the need for commonality between each of them, even though there exists commonality in their mission profiles, such as their ASW and ASuW missions, among others.

This commonality provides the foundation to analyze the features and functionalities of each of the combat systems. As mentioned in Chapter II, all three combat systems in the fleet use a type of SONAR to detect contacts, a type of tactical control system for planning the ASW mission, a weapon control system to set the parameters of the selected weapon, and an ASW weapon to engage the target. Table 16 categorizes some of the commonalities.

Table 16. Current ASW Combat System Commonality

Current ASW Combat System Commonality			
Function	**Aviation**	**Submarine**	**Surface Vessel**
Detect contacts	Dipping SONAR	Hull mounted Sonar Towed Array Radar	Hull mounted Sonar Towed Array Radar
Plan ASW Mission	Advanced Signal Processor	SONAR Processing System	ASW Control System
Set weapon presets	Armament Control Indicator Set	Weapon Control System	Weapon Control System
Launch Weapons	Torpedo Gun	Torpedo Missile	Torpedo Missile Gun

The information gathering in Chapter II also provides the groundwork to address the next two strategies in answering the problem statement. In addition, the information presented aids in the construction of the variation models, which are then used to construct the orthogonal variability modeling of the generic ASW combat system architecture.

2. Develop product line concept for an ASW combat system

In order to develop a product line concept for ASW combat system, a generic model based architecture must be constructed first. Chapter III introduces the methodology, ASW combat system domain model, reference architecture, the variation points, and later on, the product line models for both system and software for this generic, combat system centric, architecture. This reference combat system is constructed utilizing concepts from the combat systems from the three platforms mentioned before, LAMPS MK III, AN/BYG-1 and SQQ-89.

Using Innoslate, the first model created is a general ASW combat system domain model, which captures the concept of an ASW scenario with the physical subsystems involved, the operations of the subsystems, how the subsystems interacted with each other, and external interactions with the subsystems. This domain model maintains the ASW combat system’s mission as its central purpose, concentrating on the subsystems and external interfaces needed to properly execute the mission. The main subsystems identified are Signal Processing, Fire Control, and Weapon Control, SONAR and the weapons.

A reference architecture is used to determine the most suitable solution for domain application for the combat system. The reference architecture is derived from the domain model and consists of a block diagram of components of the combat systems utilized in a "kill-chain" and a functional block diagram that consists of the functions detect, plan, launch, and communicate. Each system, individually, fulfills the functions related to the sequence, but use varying components to perform the kill-chain.

The ASW combat system domain model and reference architecture provide the structure for defining the variation points necessary for the orthogonal variability modeling of the generic combat system architecture construct. Five (5) variation points are identified, Sensors/Arrays, Weapons, Tactical Control, Data Link, and HSI. The variation points also serve as the entrance points on which new technology is inserted into the development and maintenance cycle. The variants of each variation point are presented in Variability Diagrams, which serve as the basis for the product line model development of the generic ASW combat system. The combat systems for LAMPS MK III, AN/BYG-1 and SQQ-89 are mapped to each variation in an Orthogonal Variability Model to identify the variations required and excluded for each of the three products.

3. Develop cost model to obtain ROI of developing the combat system reusable product lines

This capstone presents software and system COPLIMO results of best case, most likely, and worst case scenarios after investing in a product line. The Software COPLIMO focuses on parts of the system that involve product-specific newly-built software, fully reused product line software and product line software that are reused with some modification (Boehm et al. 2004). COPLIMO is adjusted to be used at a system level as well. The Orthogonal Variability Model is used with the product line variant classification table to identify which parts of the system are unique versus reused, represented as variants. Comparison is done with the results of the three scenarios for the ASW combat system product line.

In the case of the System COPLIMO, the best case for the product line approach looks at the ROI if a program experienced 20% lower RCR-Adapted and RCR-Reused while the worst case for the product line approach looks at the ROI if a program experienced 50% higher RCR-Adapted and RCR-Reused. Table 17 shows the result comparison between the most likely and worst case scenarios ROI. This ROI is cumulative, adding a new product line to the previous one.

Table 17. System COPLIMO Result Comparison

System COPLIMO Result Comparison			
Product	Cumulative Return on Investment (Best Case)	Cumulative Return on Investment (Most Likely)	Cumulative Return on Investment (Worst Case)
Reference Architecture	-6.00	-6.00	-6.00
LAMPS MK III	-1.84	-2.02	-2.47
AN/BYG-1	4.09	3.66	2.56
SQQ-89	9.97	9.23	7.38

Based on the ROI comparison in Table 17, the best and most likely case scenarios generate a high cumulative return on investment when adapting all three combat systems to a product line. Even in the worst case scenario, where the cost to adapt and reuse components is 50% higher than estimated, there is still a significant ROI of 7.38.

For the Software COPLIMO, the most likely scenarios for the ASW combat system software also assume 40% RCR-adapted and 5% RCR-reuse. The best-case scenario for the combat system software looks at the additional ROI if the estimations were 20% lower. The worst case for the product line approach looks at the ROI if a program underestimated the RCR-adapted and RCR-reused resulting in 50% higher values. Table 18 show side-by-side comparisons of the ROI for the most likely, best and worst-case scenarios. As before, this ROI is cumulative, adding a new product line to the previous one.

Table 18. Software COPLIMO Result Comparison

Software COPLIMO Result Comparison			
Product	Cumulative Return on Investment (Best Case)	Cumulative Return on Investment (Most Likely)	Cumulative Return on Investment (Worst Case)
Reference Architecture	-1.00	-1.00	-1.00
LAMPS MK III	0.18	0.12	-0.03
AN/BYG-1	1.36	1.24	0.96
SQQ-89	2.54	2.37	1.94

Based on the ROI comparison in Table 18, the best and most likely case scenarios generate a positive cumulative return on investment when adapting any of the three combat systems to a product line and a high ROI when adapting all three. Even in the worst case scenario, where the cost to adapt and reuse components is 50% higher than estimated, there is still a significant ROI once all three combat systems were adapted with a value of 1.94.

Both ROI comparison tables show a positive ROI once the last two products in the product lines, AN/BYG-1 and AN/SQQ-89, are developed. From this data it can be concluded that the ROI for the Navy in investing in a generic combat system for ASW mission is positive, and is worth pursuing.

A. RECOMMENDATIONS

This capstone concentrates on the ASW portion of the combat systems for the U.S. Navy fleet; however, the U.S. Navy's mission goes beyond ASW mission sets. As such, further investigation into a generic combat system should include additional mission capabilities, such as ASuW, land strikes, strategic deterrence, and defensive capabilities, among others. Any generic combat system developed needs to be able to address the mission scenarios that each platform and ship-class currently does and may need in the future. This generic combat system must be adaptable, and needs to not be designed with current limitations in mind but remain open to further expansion or upgrades. The challenge with this adaptability lies not on the system development, but in the change that needs to be done to the current acquisition paradigm.

Today's acquisition strategy is both slow and inefficient. Although some strides have been made to expedite the process, it still takes years, if not decades, to field new systems to the fleet. In order to successfully integrate a common combat system across the fleet, this acquisition process will need to be modified, from a stovepipe, closed community, to one of information and resource sharing. Additional investigation should be done into these processes to identify the process in which the acquisition community can be modernized into one that is no longer slow to react to the world's combat environment, but maintains itself at the forefront of new technology acquisition and insertion.

Finally, applying the engineering product line methodology and model-based system engineering should be done at the earliest stages of the combat system design, with the cooperation of all the program offices in charge of the each of the platforms. Starting from the ground up, but utilizing the lessons learned from the years of separate combat system development. Relying in communities of interest that have the background knowledge in their respective platforms and mission sets. Information sharing, cooperation, and high velocity learning will have to become a principal tenet of each program office to achieve the desired outcome and streamline the combat system development.

B. FUTURE WORK

The scope of this capstone is limited to the ASW missions of the combat system. Future work can be conducted to develop cost models and generic architectures for additional missions of the combat systems, such as ASuW, electronic warfare, cyber warfare, and strategic deterrence, among others. The methodology presented on this paper can be used also in other applications, such as ground vehicles, integrated air and missile defense, etc.

Cost models for both software and overall system are introduced on this capstone. These models are constructed at a high level, with limited details due to the nature and classification of the information needed. Additional cost modeling, especially at a classified level, with a more detailed set of data points will provide greater insight into setting input values for the COPLIMO system and software models, providing greater accuracy in its results. The cost models additionally only show a single point estimation of ROI; additional modeling can be done with ranges of inputs to perform a statistical analysis and obtain a confidence interval of what the true values for each ROI in a product line are. This can help a program to get an understanding of the risk and reward of implementing a product line for a combat system.

The best and worst case scenarios run with the models only look at the impact to ROI if the amount of unique, adapted and reused SLOC and components were altered. There are many other factors in the COPLIMO models that can impact the ROI for a software or system. Further work on varying inputs like the relative cost of reuse and investment costs should be done to get more detail on the variance in the models. A Monte Carlo simulation can be done to gain a confidence interval of ROI for a software or system.

Finally, combining the efforts of this capstone, along with the recommendations of the models for other mission sets should be used to create an overarching combat system. As mentioned before, additional investigations should also be done in the acquisition processes currently used for combat system development, fielding and maintenance, to identify the process in which a generic combat system can be fielded to different platforms across the U.S. Navy, and later on, allied communities.

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