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ECONOMIC TRADEOFF ANALYSIS OF A PRODUCT LINE ARCHITECTURE APPROACH THROUGH MODEL-BASED SYSTEMS ENGINEERING: A CASE STUDY OF FUTURE MINE COUNTERMEASURES UNMANNED UNDERWATER VEHICLES

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by

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September 2022

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The defense sector often develops systems to operate for at least 15 years, which can reach 40 or even 50 years. Those systems tend to be cheaper, more rapidly developed, and reliable when developed on product lines (PL). Product line architecture surges with potential to improve the acquisition process, resulting in a more rapid insertion of cost-effective warfighting capabilities. This thesis investigates the impact of the PL approach by analyzing the future generation of mine countermeasure (MCM) unmanned underwater vehicle (UUV) architecture alternatives, employing a detailed reuse model based on the COPLIMO framework. The research integrates parametric cost modeling with model-based systems engineering (MBSE), feeding the existing baseline knowledge regarding PL architecture. Furthermore, this can improve systems acquisition processes, deliver more agile capability, and reduce total life cycle costs (LCC). The integration of models highlights significant differences among the architectural variations considered early in the acquisition process before substantial financial commitments. Early decisions determine most of the total LCC and establish a baseline for long-term system performance. Hence, the choice of favorable design alternatives is crucial to program success. The results demonstrate that up-front investments in product lines generate a significant return on investment (ROI).

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LIST OF ACRONYMS AND ABBREVIATIONS

ASW	anti-submarine warfare
AUV	autonomous underwater vehicle
AUVSI	Unmanned Vehicle Systems International
BN	Brazilian Navy
CC	constant communication
CER	cost estimating relationships
CN3	navigation network nodes
CNO	Chief of Naval Operations
CONOPS	concept of operations
COPLIMO	Constructive Product Line Model
DC	direct-current
DE	digital engineering
DOD	Department of Defense
DoDAF	Department of Defense Architecture Framework
DON	Department of the Navy
DVL	doppler velocity log
EEZ	exclusive economic zone
EMD	engineering and manufacturing development
FOC	full operational capability
GDP	gross domestic product
GPS	Global Positioning System
HC	human-control
HIL	human-in-the-loop
HMHS	His Majesty’s Hospital Ship
HOL	human-on-the-loop
IC	intermittent communication
ICE	independent cost estimates
IDEF	integrated definition methods
INCOSE	International Council on Systems Engineering
IO	information operations

IOC	initial operational capability
ISPA	International Society of Parametric Analysts
ISR	intelligence, surveillance, and reconnaissance
JCIDS	Joint Capabilities Integration and Development System
JROC	Joint Requirements Oversight Council
LCC	life cycle costs
LCS	Littoral Combat Ship
LML	life cycle model language
MBSE	model-based systems engineering
MCM	mine countermeasure
MCM-1	Avenger-class vessel
MDA	mine danger area
MDAP	major defense acquisition program
MDD	material development decision
MILEC	mine-like echo
MIW	mine warfare
MSA	material solution analysis
O&S	operation and sustainment
OMG	Object Management Group
OUSD(R&E)	Office of the Under Secretary of Defense for R&E
OVM	orthogonal variability model
P&D	production and deployment
PEO USC	Program Executive Office Unmanned and Small Combatants
PLE	product line engineering
PLM	product life cycle management
PMA	post mission analysis
PMI	Program Management Institute
PMO	Program Management Office
R&E	research and engineering
RAM	reliability, availability, and maintainability
RDT&E	research, development, test and evaluation
RFP	request for proposals

ROI	return on investment
ROV	remotely operated vehicle
SEP	systems engineering process
SLOC	sea lines of communication
SoS	system of systems
SysML	system modeling language
TCS	time critical strike
TMRR	technology maturation and risk reduction
TPM	technical performance measures
U.S.	United States
UMAA	unmanned maritime architecture
UML	unified modeling language
UMS	unmanned maritime systems
UUV	unmanned underwater vehicle
UWIED	underwater improvised explosive device
V&V	validation and verification
VP	variation point
WTO	World Trade Organization
WWI	World War I
WWII	World War II

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I. INTRODUCTION

A. OVERVIEW

In summary, this thesis evaluates how investing in a product line approach can benefit acquisitions of defense systems, reducing the total life-cycle costs (LCC). The research also highlights the importance of unmanned systems for mine countermeasures (MCM) operations, especially unmanned underwater vehicles (UUV), exploring them as the object of the study.

Deshmukh et al. (2010) state that several costs may be involved in developing product lines. The foremost step is identifying similar characteristics (commonalities) and variabilities. Creating reusable components requires a certain degree of up-front investment, which later can generate savings from a family of a systems perspective. In this context, it is possible to estimate the effort/cost through parametric tools in order to develop components with a certain degree of reuse and adaptability. The first does not require variations among systems, characterized as a black-box, and the second would be subject to adaptation that needs to be reused, being called adapted.

This thesis assesses the possible benefits of reusing components in a family of systems compared to the investments needed to develop individual stovepipe systems. Although the reuse-driven investments approach was initially more used for software-intensive systems, some authors have demonstrated that it can be used for hardware-intensive systems with the same effectiveness (Deshmukh et al., 2010; Hall, 2018). The systems engineering process enables identifying similarities among products in order to develop reusable infrastructure and components. In this way, initial projects will likely increase their timelines and costs. On the other hand, the later products of this product line may have their schedules and costs significantly reduced through the reuse of components, in addition to having a simpler integration (Deshmukh et al., 2010).

The product line (PL) approach is evaluated in this research across the integration of parametric cost modeling within the model-based systems engineering (MBSE) approach. A modeling framework based on the Constructive Product Line Investment

Model – COPLIMO (Boehm et al., 2004) may enable the systems acquisition community to analyze an economic tradeoff during the earlier systems design phase, exploring the possible return on investment (ROI). Thus, this analysis demonstrates the relevance of a PL architecture approach through an economic tradeoff analysis in terms of commonality and variability of the future MCM UUVs.

B. BACKGROUND

The Unmanned Integrated Systems Roadmap (DOD, 2017) exposes how the United States Department of Defense (DOD) estimates that autonomous unmanned systems will coordinate with manned systems to optimize decision-making processes during military operations that expose combatants to the risk of life. The DOD comes on a growing curve in developing and integrating unmanned systems into its structure and operations. Its most varied organizations increased efforts in research, acquisition, and support of these systems to meet the demand of each sector. The DOD Roadmap also identifies a range of enablers regarding technologies or policies that "detail the ongoing work, or challenges, that require further effort, investment, and advancement to continue the paradigm shift that unmanned systems offer" of which autonomy stands out (DOD, 2017).

Throughout recent years, the DOD and the U.S. Department of the Navy (DON) assessed several alternatives for modernizing its assets to contradict raising competition in the maritime domain. The U.S. Navy conducted studies and found that unmanned maritime systems (UMS) are crucial to face contemporary and expected threats. Through the Unmanned Campaign Framework (US Navy, 2021) issuance, the DOD established priorities in developing and deploying diverse unmanned vehicles designed to complement the current makeup of its naval assets. The Navy's planning document warns of the crucial role such systems will impact the Navy's future capacities and points out the plan for conceiving them by employing technology that can be used in various air and marine systems. The document highlights that it is essential to aggregate systems acquisition management and technical capabilities to accelerate the development, testing, and production of effective unmanned systems. The acting Secretary of the Navy, Mr. Thomas

W. Harker, exposed that the DON is “moving with purpose to innovate and adapt new technology to build a more lethal and distributed naval force for the future.” (p. 1)

In parallel to this unmanned development effort, the DOD released its Digital Engineering Strategy (U.S. Department of Defense [DOD], 2018), which established relevant goals to create a paradigm shift for how the DOD has to manage its systems across the transition to a Digital Engineering (DE) environment. The DE Strategy also spotlights that the DE integrates program management and systems engineering activities, enabling better results through developing complex systems. From that strategical guide, the DON released its U.S. Navy and Marine Corps Digital Systems Engineering Transformation Strategy (DON, 2020) “to transform systems engineering capabilities, by using common, composable, interactive, model-based systems to store and exchange data, models, and authoritative data to coordinate and integrate all disciplines and phases of work for the life cycle of a platform or system.”

The OMG and INCOSE (n.d.) characterize MBSE as: “the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases.” (webpage) The MBSE methodology is a core aspect of digitalizing the systems engineering process (SEP), enabling researchers to conduct systems analysis and cost estimations when architecting and modeling complex systems. The SEP has a crucial role during the system life cycle since requirements, earlier architecture, and the design phase, widely known as the pre-conceptual phase, often compromise more than 80% of the total LCC. The system’s development will determine the following production and operation and sustainment (O&S) costs, as illustrated in Figure 1.

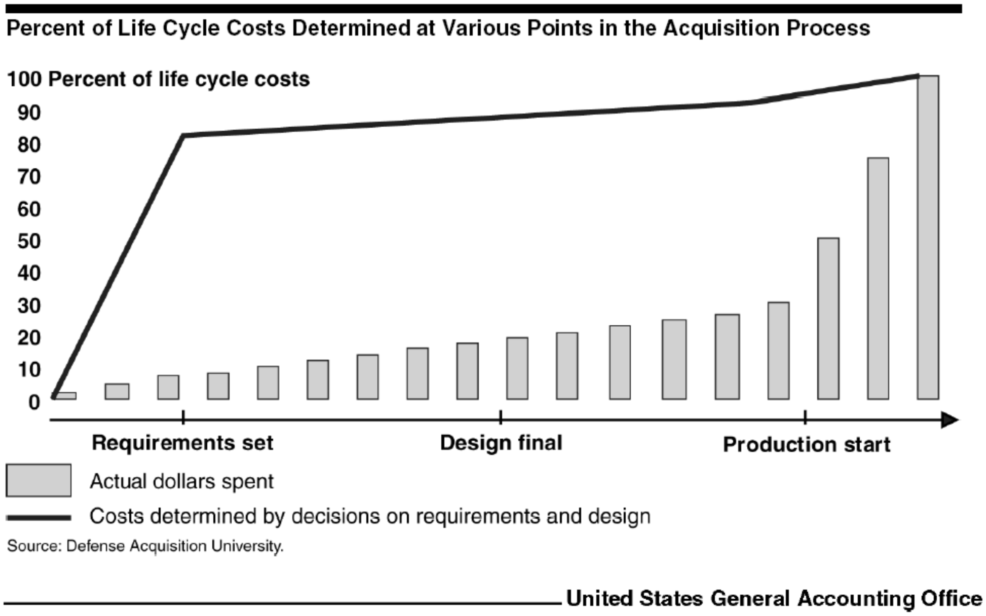

Figure 1. Cost Commitment throughout the Life Cycle. Source: Schinasi (2003).

Hall (2018) stated that systems are usually developed for specific missions and platforms without considering commonality aspects and necessity. Recent research (Hall, 2018; Chance, 2019; Fraine et al., 2019) found that developing hardware and software components to be reused in different programs through a portfolio approach presents a great potential for savings. That occurs not only across the developmental phase (RDT&E) but also during the following system life cycle phases. Furthermore, commonality also has the potential to impact systems suitability aspects such as system reliability, usability, supportability, maintainability, and training, potentially reducing future O&S costs of naval assets.

From the integration of systems engineering and program management perspectives, this thesis explores the relevance of a product line engineering (PLE) approach across an economic tradeoff analysis regarding commonality aspects of future MCM UUVs. Previous studies conducted by Hall (2018), Chance (2019), and Fraine et al. (2019) have already demonstrated how the product line architecture has great potential to bring significant economic results in comparison to a one-off approach. Unlike PL architecture, one-off approach does not consider commonalities and variabilities through the pre-conceptual phase of complex systems, thus promoting an isolated development process, resulting in redundant development efforts, and adding extra costs to defense programs. From this perspective, Madachy and Green (2022) state the importance of applying PL approach during the earlier design phase when architecting and developing the system.

C. RESEARCH OBJECTIVE

This research investigates the benefits of employing a MCM UUVs product line using MBSE methods and parametric cost modeling. The aim is to analyze the impact of the reusability of UUVs' components through the orthogonal variability model – OVM (Pohl et al., 2005). Finally, it searches for individual and cumulative ROI from a model based on the COPLIMO framework.

Camacho et al. (2017) explored the UUV technology and capabilities with a future perspective. They analyzed system and operational performance, providing recommendations to MCM UUVs to support the MCM mission. They assessed the performance of a set of proposed systems architectures using a tailored system engineering process by concentrating the analysis on two main characteristics: communication states and the data processing location. Thus, it culminates into six alternative functional architectures developed using MBSE tools.

From that performance perspective, this study considered those developed alternatives to assess the product line architecture approach using the OVM and find commonalities and variabilities throughout those six possible MCM UUVs architectures. Then, this research explores the potential savings through the systems' life cycle across an economic tradeoff analysis when investing in a product line approach, assessed through the modeling COPLIMO framework for product line cost estimation and investment analysis.

The integration of cost modeling and MBSE aims to point out significant differences among the architectural variations that are being considered early in the acquisition before substantial financial commitments are made. This integration is relevant since it improves the decision-making process. Decisions made earlier in the development of defense systems determine most of the total LCC, as well as establish a baseline for the system's long-term performance; therefore, the choice of favorable design alternatives becomes vital to the program's success. Previous research has already identified that this approach can generate considerable savings in defense systems' total LCC (Hall, 2018; Chance, 2019; Fraine et al., 2019).

D. PROBLEM STATEMENT AND RESEARCH QUESTIONS

There are many defense systems there are developed independently for specific missions and demands, as Hall (2018), Chance (2019), and Fraine et al. (2019) recently demonstrated. Many UUVs programs followed this path without considering the necessity for commonality among them. This lack often generates extra effort and extensive rework during the developmental phase. Consequently, it results in systems and components that can be architected and designed with a focus on the commonality characteristic. Applying the PL approach can provide future savings during the operational and sustainment phase since they would share systems and components, then reduce operating, maintenance, training, and consequently logistics costs.

Recently, the acting Secretary of the Navy, Thomas W. Harker, demonstrated the relevance of moving faster in the right direction regarding cutting-edge technology. He pointed out that: "the Department of the Navy is moving with purpose to innovate and adopt new technology to build a more lethal and distributed naval force for the future" (United States Navy, 2021). However, despite recent progress on unmanned systems, higher risks have evolved during their technologies' maturity. Regarding that rate, some systems occasionally start their O&S phase already outdated.

Consequently, commonality and flexibility are essential features that need to be considered at the earliest system design stage. According to Thomke (1997), both attributes can provide the opportunity to frame the system design better to reach better solutions regarding warfighter needs. Madachy and Green (2019) claim that flexibility is achieved by amplifying the option space and that capability may be reached by integrating a performance-based model and cost tradeoff analysis.

The research investigates the potential benefits of enlarging the product line architecture approach through the systems engineering process of future alternatives for

MCM UUVs. In this sense, this study consists of an approach that employs parametric cost modeling, some empirical data collection from recent research, and the demonstration of MBSE approach to assessing economic savings through systems product line architecture. Then, answering the questions below contributes to the achievement of this objective:

- Can the product line architecture approach benefit the development of the next-generation MCM UUVs designs instead of using non-reusable systems/components?
- Can potential technological changes/solutions be used as performance drivers in the analysis of MCM UUVs product line architecture?
- How can the OVM contribute to the product line strategy?
- How can the product line approach be integrated into a parametric cost model in order to conduct a cost analysis and ROI assessment of MCM UUVs?
- What is the potential ROI for applying a product line architecture when developing MCM UUVs?

E. THESIS METHODOLOGY OVERVIEW

According to Camacho et al. (2017), the current set of U.S. MCM UUVs involved in "detect and classify" portions of the defensive-active MCM missions "rely on a physical transfer of sensor data for processing via capabilities not resident on the UUV – *status quo."* This study considers the *status quo* alternative as the hypothetical system baseline in order to employ the initial investment to investigate potential components for reuse in a product line approach. Hence, the methodology of this study consists of exploring the PLE approach and open architecture to guide a standard system design for the next-generation MCM UUVs to achieve potential savings across their total life cycle costs. Camacho et al. (2017) identified two possible technological changes/solutions that were used as performance drivers to the MCM UUVs' concept of operations: "Data Processing Location" and "Communications Cadence." These two systems' characteristics were combined to generate six future potential solutions/alternatives, which are then assessed across an OVM in this study.

Taking into consideration the likely commonalities among MCM UUVs, the following steps are taken to explore the ROI of product line architecture:

a. Identify System Architecture Alternatives
b. Perform System Variability Modelling
    i. Define Variability from Textual Requirements
    ii. Identify Physical Components/Set of Components
    iii. Build Orthogonal Variability Model
c. Obtain the expected reuse category percentages.
d. Run Economic analysis
    i. Calculate individual and cumulative ROI

Through functional analysis of the future MCM UUVs it is possible to develop a product line concept, providing relevant data to generate the reference architecture. After exploring the functional decomposition of the system, the systems engineering team can identify the MCM UUV core elements. It is relevant to highlight that the system architecture was modeled by Camacho et al. (2017) using Innoslate, a product life cycle management (PLM) tool that aids the systems engineering process and activities across a MBSE approach, demonstrating the importance of the disruptive way to conduct the process. The tool applies system modeling language (SysML) and life cycle model language (LML) to manage the systems engineering process in an integrated way. According to SPEC Innovations Co., Innoslate offers "full life cycle software for MBSE, requirements management, verification, and validation, plus Department of Defense Architecture Framework (DoDAF) with a powerful ontology at its core." (SPEC Innovations, n.d.)

F. THESIS SCOPE

The research limits the scope to the economic analysis of the six architecture alternatives proposed by Camacho et al. (2017), which previous research focused on MCM UUV's performance considerations. This thesis focuses on assessing the ROI of the product line architecture approach applied to the demands arising from the rising employment of UUVs in mine countermeasure operations.

G. SPECIFIC CONTRIBUTIONS AND BENEFITS

These research products can substantially benefit the acquisition community with standardized processes and tools for integrated analysis of unmanned maritime systems through a product line approach, supporting acquisition decisions by crossing measuring systems effectiveness and maximizing cost-effectiveness across product lines.

The main contribution of this research lies in increasing the fundamentals associated with integrating parametric cost modeling with MBSE. The objective is to feed the knowledge that already exists regarding PL architecture through research associated with the future generation of MCM UUV across the employment of a detailed reuse model. Madachy and Green have been working on this approach through recent research (2019, 2022). Furthermore, it can improve systems acquisition processes, optimize budgets, deliver more agile capability, and enhance system product lines' flexibility and prediction.

The integration of models highlights significant differences among the architectural variations considered early in the acquisition process before substantial financial commitments are made. Early decisions determine most of the total LCC and establish a baseline for long-term system performance. Hence, the choice of favorable design alternatives is crucial to program success.

In addition to the benefits associated with savings in LCC, the product line has the potential to accelerate the system's development and provide a flexible characteristic related to mission variations throughout the operation and medium support phase (Deshmukh et al., 2010). Here, it is worth noting that there is currently a broad consensus among policymakers and procurement professionals that instilling greater flexibility into defense systems raises mission success levels and decreases the system's LCC. Models provide a framework of use that allows the realization of a broader system suitability analysis through core design aspects such as reliability, availability, maintainability – RAM, and system affordability.

The defense sector often develops systems to operate for at least 15 years, reaching 40 or even 50 years. Hence, commonality and flexibility design considerations are relevant as early as possible. Product line architecture presents the potential to improve the acquisition process, resulting in a more rapid insertion of cost-effective warfighting capabilities. The resulting fielded systems tend to be cheaper, more rapidly developed, and reliable to fulfill the totality of mission objectives across product lines. Cost models like COPLIMO also enable a better evaluation of distinct architectural choices and support the decision-makers in defining whether a product line approach is feasible (Madachy & Green, 2019). Nolan (2009, p. 255) states that "a good cost model is central to good decision-making and good project management."

H. THESIS ORGANIZATION

This research is organized into five chapters: this introduction, literature review, methodology, economic analysis, and conclusion.

Chapter II presents a broad overview of relevant concepts, conditions, and processes interrelated with the thesis objective. In the beginning, a background of MIW and MCM has shown as well as the use of these systems in the U.S. Navy and Brazilian Navy. Then, it introduces the UUV and its applications. After, the concepts of the systems engineering process and program management, as well as the integration among them and the acquisition process in the U.S. Department of Defense Systems Acquisition, are discussed. Subsequently, concepts such as DE, MBSE, system architecture, and product line approach are presented. The last one focuses on PLE and Parametric Cost Modeling.

Chapter III presents the detailed methodology previously summarized in Section D. This chapter shows the strategies used to identify system architecture alternatives and perform system variability modeling. For the latter, the following steps are used: define variability in textual requirements, identify physical components/set of components and build an OVM. From this, one can obtain the expected reuse category percentages. Finally, run an economic analysis and calculate ROI.

Chapter IV performs an economic tradeoff analysis of the proposed MCM UUVs alternatives through a reused model based on COPLIMO. It presents the product line percentages found for each alternative to the economic analysis based on COPLIMO, ROI analysis, individually and cumulative, as well as a sensitivity analysis regarding a variation of the relative cost of development for reuse (RCDR). At the end of the chapter, there is a brief discussion of the results.

Finally, Chapter V presents the conclusion and a briefly recommendation for future work.

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II. LITERATURE REVIEW

A. BACKGROUND ON MINE WARFARE (MIW) AND MINE COUNTERMEASURES (MCM)

Naval mines have been a relevant threat to many countries that perform naval operations and maritime commerce. For instance, the only four U.S. warships lost in combat during the Korean War in the 1950s were sunk by opponent mines, as pointed out by Marolda (2020). Besides, the author highlights that sea mines had hit four times more U.S. Navy ships than all other origins of attacks throughout World War II (WWII). Recently, the U.S. Navy has faced another kind of mine threat, underwater improvised explosive devices (UWIED), which can be used as an asymmetric weapon by U.S. opponents (Truver, 2007). As such, mine warfare (MIW) has become complex and unpredictable.

Besides naval operations, maritime logistics represent a significant concern for the U.S. and many other countries. For example, maritime logistics represents a major part of Brazil's gross domestic product (GDP), representing 83.3% of total exports and 76.7% of total imports, according to the World Trade Organization (WTO, 2020). Having a harbor closed by some mine threat might cause a massive loss to the Brazilian economy, even during a short period. Thus, it is vital to keep maritime security through its coast by ensuring the sea lanes and harbor entrances are available and safe for the transit of merchant ships, navy warships, and submarines. The Brazilian Navy (BN) performs an important role by protecting Brazil's littoral, a large area of the South Atlantic Ocean, currently denominated as the *Blue Amazon* (Ortiz, 2015). That concept represents Brazil's Exclusive Economic Zone (EEZ), a vast offshore area along the Brazilian coast prosperous in marine biodiversity and many kinds of resources. It received this name since its size is compared to the surface of the famous Amazon rainforest (Almeida Resende & Tavares Cardoso, 2020). To maintain that security level, the BN must continue rapidly and effectively responding to all kinds of mine threats.

1. Briefly Review MIW History

The Chinese inventors were the pioneers in creating naval mines in the 14th century (Bray et al., 2008). The author exposes that Ralph Rabbards developed the first plan for a Western Sea mine years later, introducing that to the Queen of England in the 16th century (Bray et al., 2008). During the 19th century, the United States started to employ those weapons as a priority for shore defense, and later the nation predominantly used them throughout the American Civil War (Naval Mine Warfare, n.d.).

Mines are relatively inexpensive around the world. Government and non-government organizations often purchase or develop them easily, having a highly trustworthy and hard-to-track weapon available. Those weapons have a highly favorable investment return for the miner (Naval Doctrine Command, 1996). Countries widely employed naval mines during World War I (WWI) and World War II (WWII) to defend their shores, ports, and naval bases. In June 1918, many thousands of mines were used at the North Sea's northern doors. Only during WWI more than two thousand naval mines were spread throughout the conflict's seas (Bernaerts, 2005). In November 1916, the naval mine made its most prominent victim, a British hospital ship, the HMHS Britannic. A naval mine of the Imperial German Navy hit the ship causing an explosion sank it less than one hour later (Tikkanen, n.d.).

Truver (2007) argues that sea mines' technology was enhanced throughout the years since WWII. Magnetic mines (e.g.) were widely used during that world conflict, based on the principle of magnetism for their activation, generating a substitution process of contact mines used previously. The author reinforces that the main parts of the conflict, the Allies and Germans, widely employed acoustic mines. It is crucial to advise that even "wooden-hulled ships" are susceptible to that sea mines' technology. Over the next thirty years after the war, hundreds of minesweepers (wooden-hulled vessels) were damaged or sunk when clearing minefields. Mines have damaged more than fourteen U.S. Navy vessels since WWII in contrast to other damages promoted by different weapon types, concluding that naval mines are one of the most affordable weapons available in conventional and asymmetric warfare.

Figure 2 illustrates the advancement in mine technology since the eighteenth century. Melia (1991) produced that study, U.S. Navy Department historian who containerized information about MCM evolution from 1777 to 1991. The findings highlight how the MIW evolved over many decades.

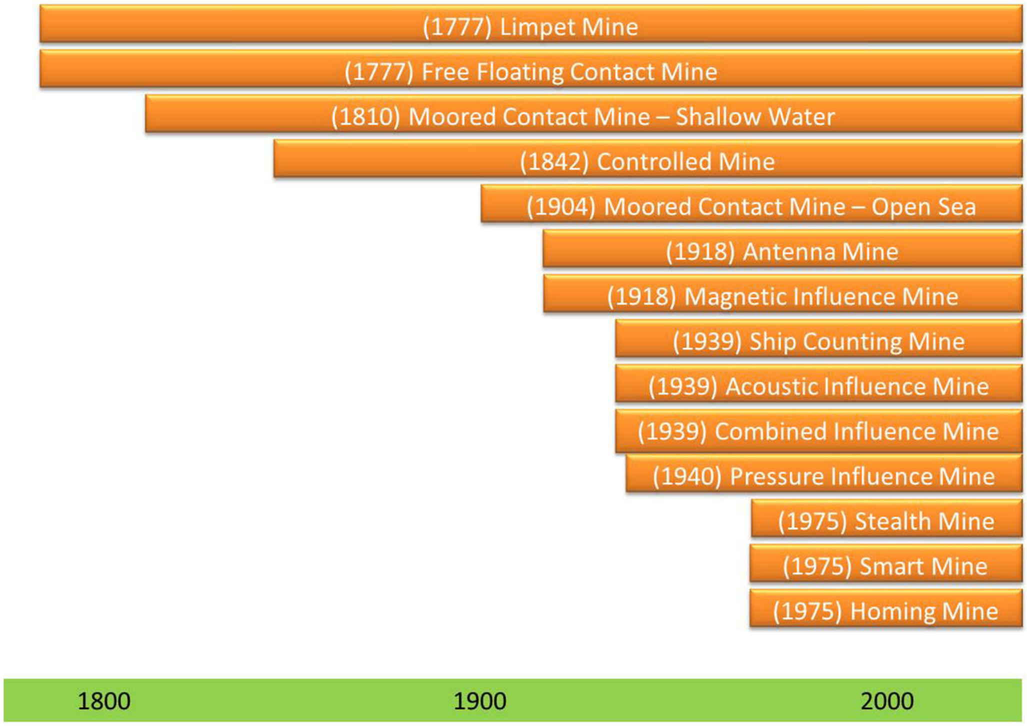


Figure 2. Advances in Mine Technology since the 18th Century. Source: Melia (1991).

2. Mine Types and General MCM Concept of Operations (CONOPS)

Currently, it is possible to classify sea mines into three relevant groups: contact, remote, and influence (Think Defence, 2014). According to the UUV Master Plan (United States Department of the Navy [DON], 2004), their threat spectrum is associated with the depth of the sea, as depicted in Figure 3. Agents often use them to deny movement in a certain area, in contrast to common sense, in which many think the main objective would be the vessel’s sinking. Mine countermeasures operations primarily aim clear sea lines of communication (SLOC) and support amphibious operations (Think Defence, 2014).

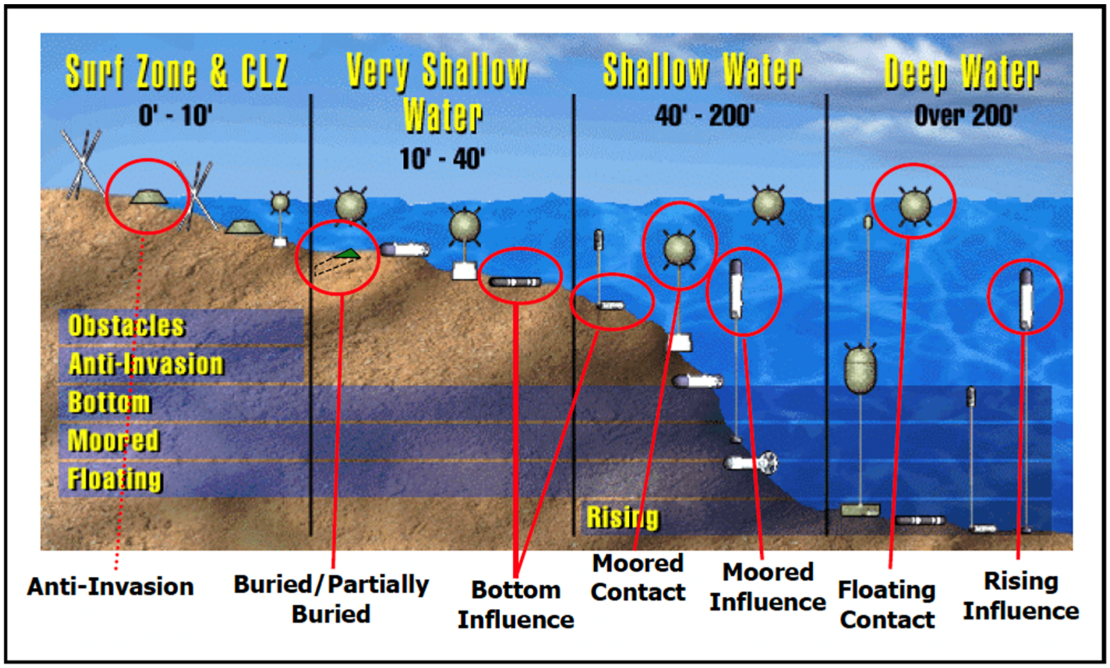


Figure 3. Mine Threat Spectrum. Source: DON (2004).

Frank et al. (2014) researched the wide spectrum of current mine categories. They demonstrate that four primary categories classify mines according to their position in the water: bottom mines, moored mines, drifting mines, and limpet mines. The first type lies on the sea floor. The bottom mine detectability is affected by the depth, seafloor clutter, amount of burial, and sediment type, and hence are usually difficult to detect. Operationally, bottom mines are employed in shallow and deeper water, aiming to hit surface ships and submarines, respectively. With another objective, moored mines are laid floating below the water surface and tethered to an anchor to keep their position. On the other need, drifting mines are laid buoying on the sea surface, capable of moving freely through the sea currents (Frank et. al., 2014). It is important to highlight that international law forbids drifting mines, although they are still employed (Erickson et al., 2009). Lastly, Truver (2007) clarifies that limpet mines are those that agents enclose on the vessel's hull.

UUV Master Plan (DON, 2004) classifies the MCM as one of the most problematic missions when the subject is the deployment of UUVs. Time is paramount during MCM operations and is relevant to reduce risk to ships and submarines navigating through mine fields. All MCM operations in these areas are expected to take seven to ten days to complete, yet shorter is better. Figure 4 exposes a generic concept of operations across MIW mission areas. The UUV Master Plan concludes that MCM mission is one of the most challenging to the U. S. Navy's access requirements since current mines are broadly available to potential opponents and are easy to employ over a vast range of sea depths.

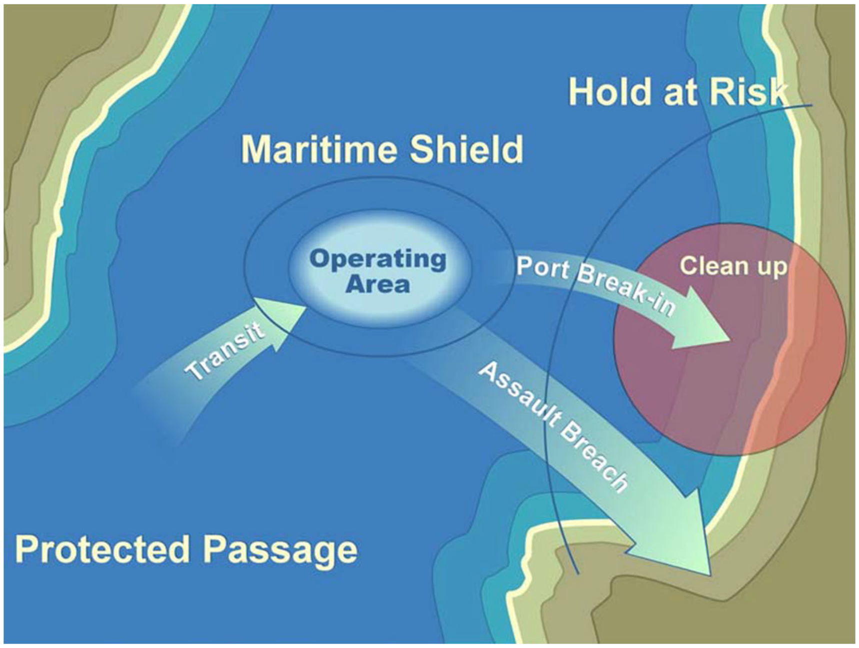


Figure 4. MIW Mission Areas. Source: DON (2004).

The DON (Naval Doctrine Command, 1996, p. 1-2) defines MIW as "the strategic and tactical use of sea mines and their countermeasures. It includes all available offensive, defensive, and protective measures for laying and countering sea mines." Figure 5 decomposes mine warfare functionally, focusing on two broad strategies: offensive and defensive. The first one aims to reduce the capability of opponents to lay sea mines, destroying them before the mines are laid, while a defensive MCM is established an opponent lays the mines. Breaking it down, we can observe two subsets, the passive MCM, which focuses on restricting a vessel's capacity to be perceived by a naval mine; and the active MCM, which Paulo et al. (2016) decompose through five main steps: detection, classification, localization, identification, and neutralization. UUVs are often used from the detection to the identification steps through mine hunting operations since the neutralization usually demands some weapon payload.

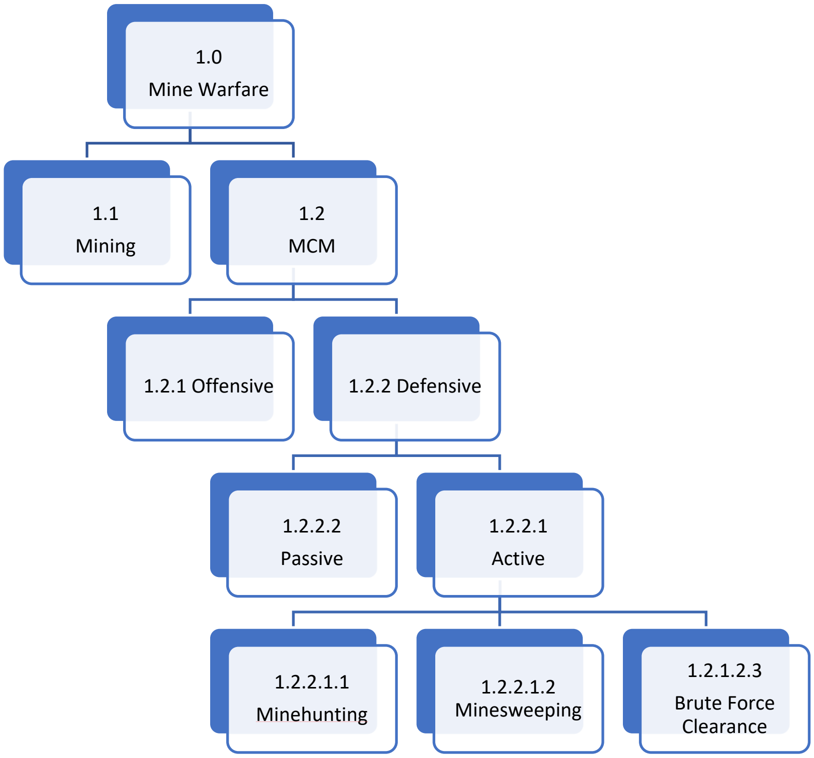


Figure 5. MIW Functional Decomposition Diagram. Adapted from Naval Doctrine Command (1996).

The MCM community widely knows the techniques utilized to perform those missions, minesweeping and minehunting. Minesweeping is often conducted by vessels (sweepers) and helicopters. On the other hand, minehunting operations often employ aerial, surface, or underwater systems and subsystems to perform those five steps of the active MCM. Currently, minehunting using MCM UUVs is considered safer and more effective active MCM since it does not depend on sea conditions as minesweeping does and does not subject sailors to the risk involved in this type of operation (Joint Chief of Staff, 2018). Figure 6 exemplifies a general concept of MCM operations employing UUVs.

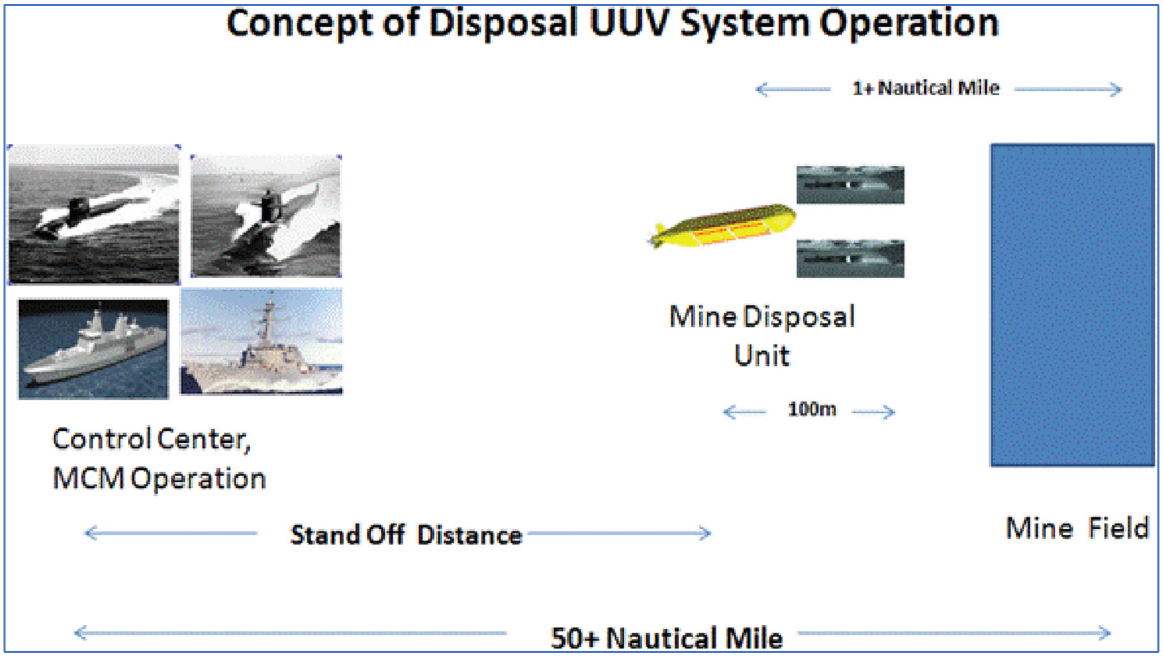
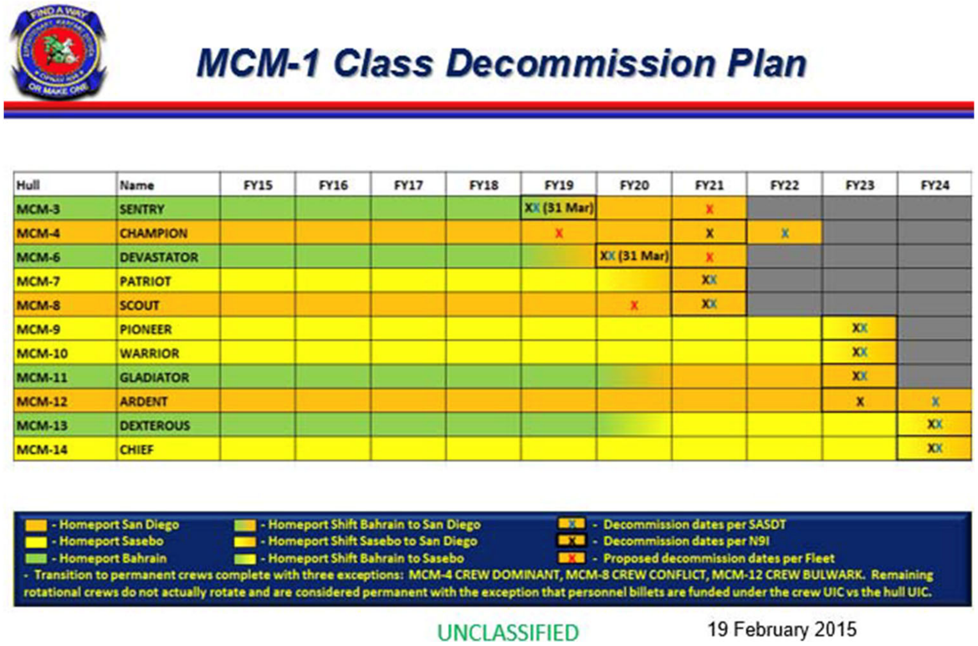


Figure 6. General concept of MCM UUV system operations. Source: Song (2016).

3. Legacy MCM Systems Employed by the U.S. Navy and Brazilian Navy

The U.S. Navy and the BN still use legacy minesweepers ships to perform active MCM operations. The U.S. Navy deploys the *Avenger-class* vessels (MCM-1), designed as minesweepers with focus in moored and bottom mines (Wellach, 2016). They were built of sheathed fiberglass and over a wooden hull not to influence the magnetic activation mechanisms of mines. Eight MCM-1 remain under operation conditions, which will be decommissioned throughout this decade (Dvids, 2020). These ships have been used to perform missions of detection, classification, and neutralization of sea mines since 1987 when the first one was commissioned. During the decommissioning ceremony of three MCM-1 in August 2020, the Commander of the Naval Surface and Mine Warfighting Development Center, Rear Adm. Scott Robertson, spotlighted the importance of MCM capabilities, saying that: “With more than ninety percent of the world’s trade carried by sea, mine countermeasures capabilities underwrite freedom of navigation and global commerce that are essential to the world’s economy.” (Dvids, 2020)

Bowe (2015) depicts the Avenger-class Decommission Plan (Figure 7), which expected the Avenger-class service life for 25–30 years. From that demand for substitution the U.S. Navy planned to replace the Avenger-class ships employing UUVs launched from Littoral Combat Ships (LCS) as part of the MCM Mission Package (Camacho et al., 2017). The last MCM ship will go out of service around 2024.



MCM-1 Class Decommission Plan

Hull	Name	FY15	FY16	FY17	FY18	FY19	FY20	FY21	FY22	FY23	FY24
MCM-3	SENTRY					XX (31 Mar)		X			
MCM-4	CHAMPION					X		X	X		
MCM-6	DEVASTATOR						XX (31 Mar)	X			
MCM-7	PATRIOT							XX			
MCM-8	SCOUT						X	XX			
MCM-9	PIONEER									XX	
MCM-10	WARRIOR									XX	
MCM-11	GLADIATOR									XX	
MCM-12	ARDENT									X	X
MCM-13	DEXTEROUS										XX
MCM-14	CHIEF										XX

- Homeport San Diego
- Homeport Sasebo
- Homeport Bahrain
- Homeport Shift Bahrain to San Diego
- Homeport Shift Sasebo to San Diego
- Homeport Shift Bahrain to Sasebo
X - Decommission dates per SASDT
X - Decommission dates per N9I
X - Proposed decommission dates per Fleet
- Transition to permanent crews complete with three exceptions: MCM-4 CREW DOMINANT, MCM-8 CREW CONFLICT, MCM-12 CREW BULWARK. Remaining rotational crews do not actually rotate and are considered permanent with the exception that personnel billets are funded under the crew UIC vs the hull UIC.

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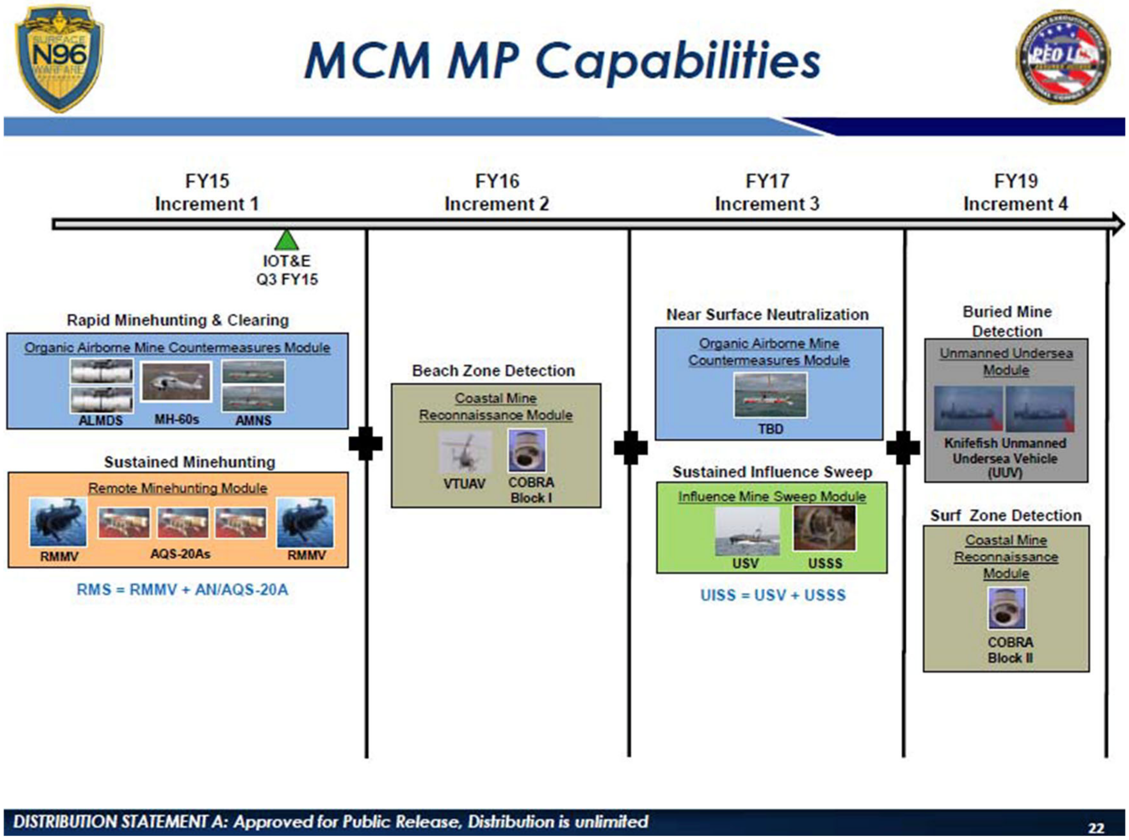
Figure 7. Avenger-Class Decommission Plan. Source: Bowe (2015).

In South Atlantic, the Brazilian Navy currently deploys the *Aratu-class* vessels (Figure 8), built in Germany in the 1970s (*NGB*, n.d.). It is also a wooden-hulled vessel immune to magnetically triggered mines. The remaining three vessels are subordinated to the Mining and Sweeping Force Command – *Comando da Força de Minagem e Varredura*. Since they were commissioned, they have been used to conduct missions through magnetic, mechanical, and acoustic means. Currently, it is widely known that they will be fully decommissioned across this decade, resulting in an emergent demand for replacement by modern MCM assets.

Figure 8. *Aratu*-Class MCM Ship. Source: Wiltgen (2012).

4. U.S. MCM Mission Package Capabilities: The Littoral Combat Ship (LCS)

In 2002, the U.S. Navy started the development of the Littoral Combat Ships (LCS) to shelter interchangeable mission packages (Figure 9), integrating the manned and unmanned maritime systems to perform active MCM (U.S. Navy, 2016). Across an incremental acquisition approach, which represents an evolutionary acquisition, the U.S. Navy has developed an acquisition plan to transition the MCM capabilities to the LCS mine warfare mission package. This DOD's acquisition approach means the capability is developed and delivered in increments. The AcqNotes website (n.d.) exposes that this acquisition strategy: "allows for future capabilities to be added to a system as upgrades in improved technology or other increase in operational capabilities to meet the desired state. Each block upgrade is managed as a separate increment for a fully operational system. Each increment will have its own set of requirements, review cycles, certification and accreditation, milestones, and acquisition strategy." More details about the current DOD acquisition process will be discussed further in this chapter.



MCM MP Capabilities

FY15
Increment 1

FY16
Increment 2

FY17
Increment 3

FY19
Increment 4

IOT&E
Q3 FY15

Rapid Minehunting & Clearing

Organic Airborne Mine Countermeasures Module

ALMDS MH-60s AMNS

Sustained Minehunting

Remote Minehunting Module

RMMV AQS-20As RMMV

RMS = RMMV + AN/AQS-20A

Beach Zone Detection

Coastal Mine Reconnaissance Module

VTUAV COBRA Block I

Near Surface Neutralization

Organic Airborne Mine Countermeasures Module

TBD

Sustained Influence Sweep

Influence Mine Sweep Module

USV USSS

UISS = USV + USSS

Buried Mine Detection

Unmanned Undersea Module

Knifefish Unmanned Undersea Vehicle (UUV)

Surf Zone Detection

Coastal Mine Reconnaissance Module

COBRA Block II

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Figure 9. MCM MP Capabilities. Source: Siel et al. (2014), as cited in Bowe (2015).

Figure 10 provides a graphical depiction of the LCS CONOPS, indicating tasks and features related to MIW mission through the concept of system of systems (SoS). According to (Pei, 2000), SoS integration seeks “the development, integration, interoperability, and optimization of systems to improve performance in future battlefield scenarios” (pp. 574).

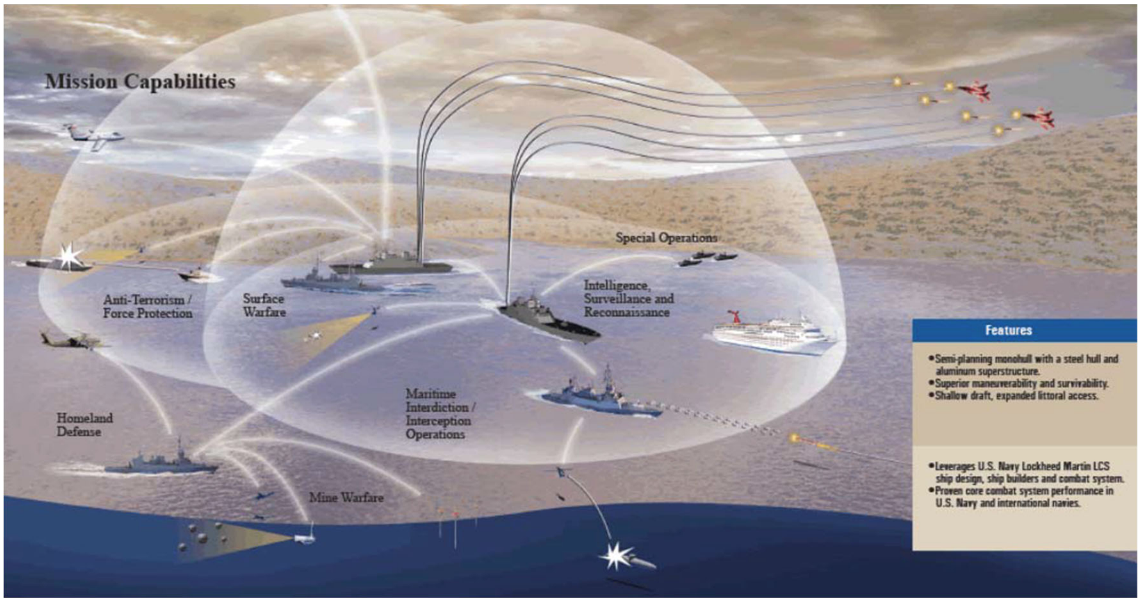


Figure 10. LCS CONOPS. Source: Broughton and Burdon (1998), as cited in Frank et al. (2014).

In this sense, not only the U.S. Navy but many other navies worldwide are raising the use of unmanned maritime systems to perform MCM operations. The next generation of UMS embedded in the LCS interchangeable mission packages was planned to perform a broad range of missions, among them MCM.

B. UNMANNED UNDERWATER VEHICLES

Firstly, it is so important to clarify the difference between remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs), both subcategories of the UUV class. The UUV Master Plan (DON, 2004) clarifies that ROVs are towed or hard-tethered systems; that is, they are permanently connected to the host vessel. The AUVs, the scope of this study, have no physical connection with the host vessel after being launched, allowing them to be controlled remotely or carried out their activities fully autonomously. Nothwang et al. (2016) differentiate the range between human and autonomy control, classifying the following levels of autonomy: “human control (HC),” “human-in-the-loop (HIL),” “human-on-the-loop (HOL),” and “complete autonomy” (p. 2). The author argues that “HIL [happens when] the human [is] actively (often continuously) engaging in control decisions” (p. 2); e.g., when a doctor performs robotic surgery. HC implies that “the human is involved with all kinds of the system’s decision-making process” (p. 2). Finally, his research clarifies that HOL sets when “the human monitors the operation of autonomy, taking over control only when the autonomy encounters unexpected events or when a failure occurs” (p. 2). On the other hand, when the human has minimal or no intervention in the system during the designated task, it is considered complete autonomy.

Unmanned Underwater Vehicle (UUV) platforms are highly advantageous for the warfighter to execute many different missions without risking the loss of life (Haller et al., 2022). The authors also expose that UUVs are beneficial platforms due to their low construction cost, a large range of vehicle sizes, and wide mission versatility. Figures 11 represents a basic UUV mission, and Figure 12 exemplifies commercial UUV design, showing the dominant torpedo-like shape of a broad group of components. They can be easily transported and deployed by several methods such as surface ships, submarines, small combatant crafts, and air platforms.

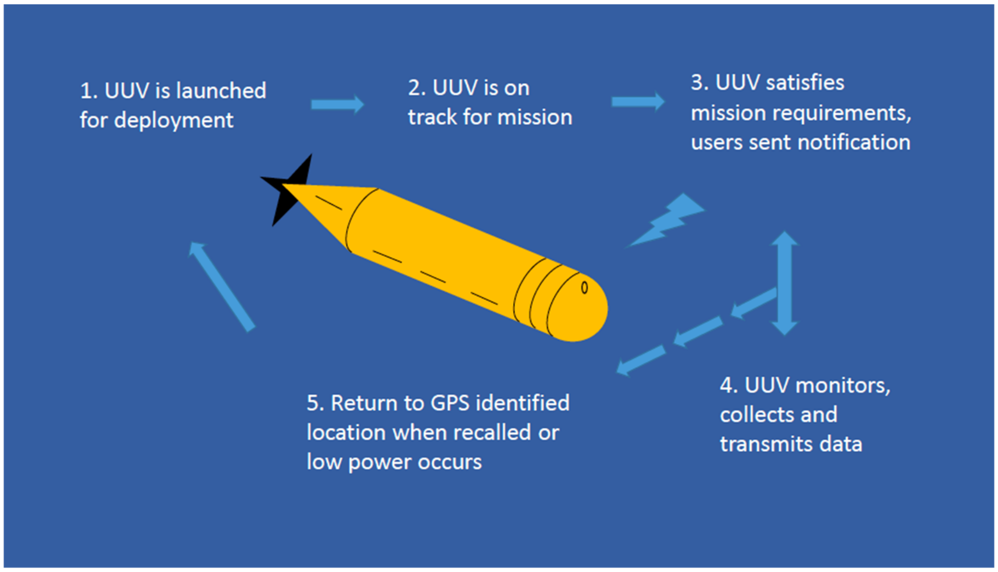
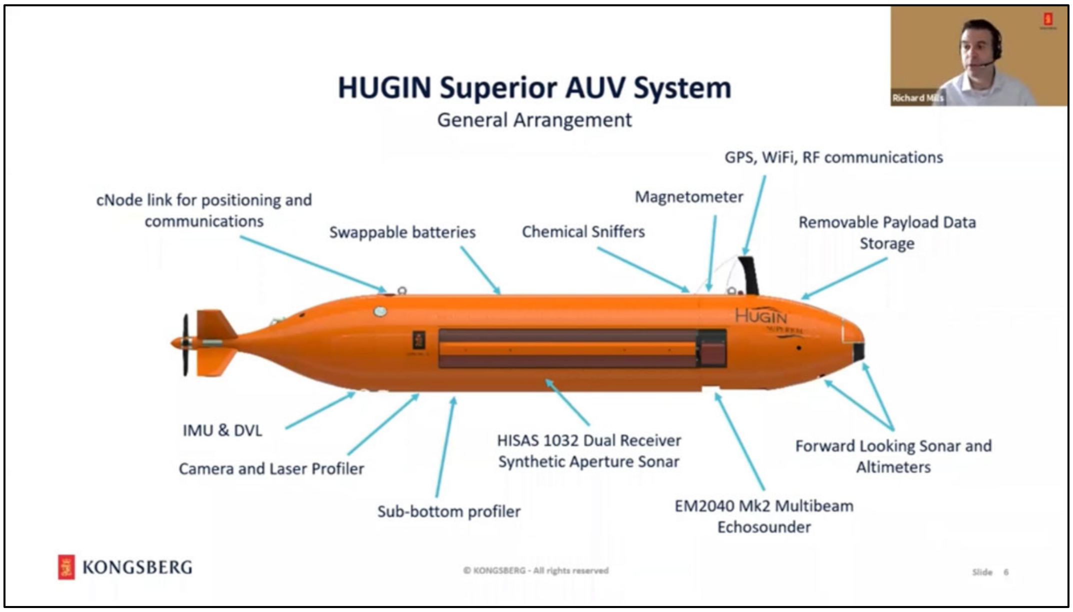


Figure 11. Basic UUV Mission Actions. Source: Haller et al. (2022).



HUGIN Superior AUV System

General Arrangement

cNode link for positioning and communications

Swappable batteries

Chemical Sniffers

Magnetometer

GPS, WiFi, RF communications

Removable Payload Data Storage

IMU & DVL

Camera and Laser Profiler

Sub-bottom profiler

HISAS 1032 Dual Receiver Synthetic Aperture Sonar

EM2040 Mk2 Multibeam Echosounder

Forward Looking Sonar and Altimeters

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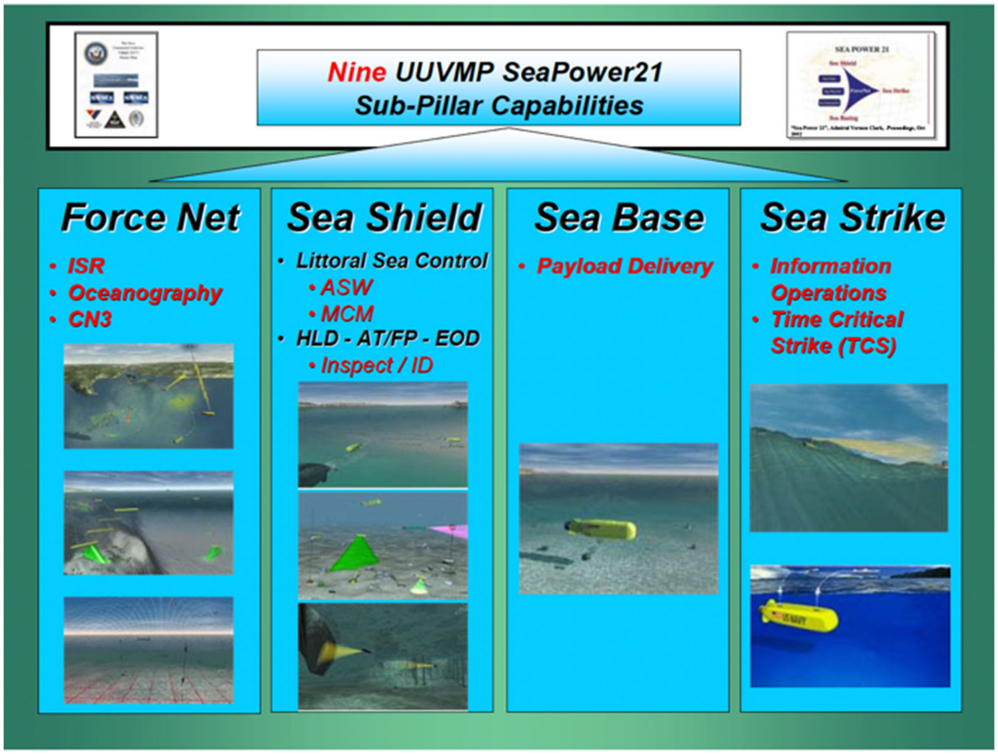
Slide 6

Richard Mills

Figure 12. Commercial Torpedo-like UUV. Source: Kongsberg (n.d.).

The DON UUV Master Plan (2004) specifies the use of unmanned vehicles "as force multipliers and risk reduction agents for the Navy of the future and postulates a host of specific missions for which UUVs are uniquely qualified." (p. 15) It also defined "nine high-priority UUV missions [supporting] four Sea Power 21 Pillars" (Figure 13), decomposed in nine sub-pillars (missions) listed below.

- Intelligence, Surveillance, and Reconnaissance (ISR)
- Mine Countermeasures (MCM)
- Anti-Submarine Warfare (ASW)
- Inspection / Identification
- Oceanography
- Communication / Navigation Network Nodes (CN3)
- Payload Delivery
- Information Operations (IO)
- Time Critical Strike (TCS). (DON, 2004, p.16)



Nine UUVMP SeaPower21 Sub-Pillar Capabilities

Force Net
- ISR
- Oceanography
- CN3

Sea Shield
- Littoral Sea Control
  - ASW
  - MCM
- HLD - AT/FP - EOD
  - Inspect / ID

Sea Base
- Payload Delivery

Sea Strike
- Information Operations
- Time Critical Strike (TCS)

Figure 13. Sea Power 21 Sub-Pillar Groupings. Source: DON (2004).

1. The MCM UUV Subsystems and Components Overview

Button et al. (2009) identified major UUV subsystems, of which this thesis focuses on those marked below. It means that this study explores potential UUV subsystems built with components or a set of components strongly related to the potential architecture's alternatives proposed by Camacho et al. (2017). This study will further analyze them through the identification of the expected reuse category percentages:

- The pressure hull
- The hydrodynamic hull
- Ballasting
- Power and energy*
- Electrical-power distribution
- Propulsion*
- Navigation and positioning*
- Obstacle avoidance*
- Masts*
- Maneuver control*
- Communications* (Button et al., 2009, p. 46)

- Locator and emergency equipment
- Payloads.

a. Power and Energy Systems

Power and energy systems strongly relate to the speed and endurance characteristics of the UUV. According to Button et al. (2009), p. 48, "the power available to a UUV determines how fast it can go, while energy determines how far it can go.." Additional sensors and onboard processing data demand energy as a core resource. In the 1980s, batteries became common AUV power sources, and we can say that it is a reality until nowadays, instead of modern technologies and chemical components, which enhanced their capabilities.

The RAND Corporation and the Association for Unmanned Vehicle Systems International (AUVSI) surveyed many AUV developers in the spring of 2008, exhibiting that "propulsion power and energy are the second-greatest long-term challenge to modern AUV development (after autonomy)." (Button et al., 2009, p. 49)

b. Propulsion System

Button et al. (2009) state that the propulsion for torpedo-like UUVs is typically furnished by an electric motor that drives a propeller. They expose that brushless direct-current (DC) motors are components commercially available and provide several advantages over brushed motors, primarily regarding efficiency, reliability, and power density. It is relevant to complement that recent improvements have been made in glider propulsion systems concerned with achieving higher speeds.

c. Navigation and Positioning System

Current UUVs employ different subsystems, components, and different technologies regarding location capability. Whether navigating on the sea surface, an internal Global Positioning System (GPS) is employed to identify their real-time location. On the other hand, when the UUVs are submerged, they utilize systems such as the doppler velocity log (DVL), which "uses sound to measure velocity along and across the vehicle's track relative to the sea or relative to the bottom.," (Button et al., 2009, p. 51). It works by combining an initial position, compass, or gyro heading across the data from an acceleration sensor.

d. Obstacle Avoidance System

The main objective of the obstacle avoidance system is to prevent the UUV's collision with some undesired object and prevent damage during its operations. It combines active and passive methods, employing sonar (active) and components to prevent the propeller from jamming due to fishing nets or other kinds of obstacles. The active method utilizes acoustic systems through single-beam sounders (only detection capability) or multibeam sonars to detect, track, and classify them.

e. Mast

This structure is closely related to the navigation and the communication systems (IC – intermittent communication alternative), which rely on that to work properly. It is used to stand communication and navigational antennas. It is relevant to punctuate that the platform of opportunity used to launch and recover the UUV can influence the design consideration of have or not mast since it can become an obstacle to deployment from the host platform, such as those UUVs launched or recovered through a submarine torpedo tube. The mast allows the UUV to upload and download data across an IC design. This data includes GPS strings for its real-time position or the data collected by the UUV, such as digital recordings, sample measurements, and any other specific data collected.

f. Maneuver Controls

Maneuvering and controlling the UUVs are accomplished by managing the control planes or multiple thrusters. At the time of Button et al.'s research (2009), maneuvering systems for traditional AUVs and gliders were regarded as mature in opposite to maneuvering biomimetic systems.

g. Communications System

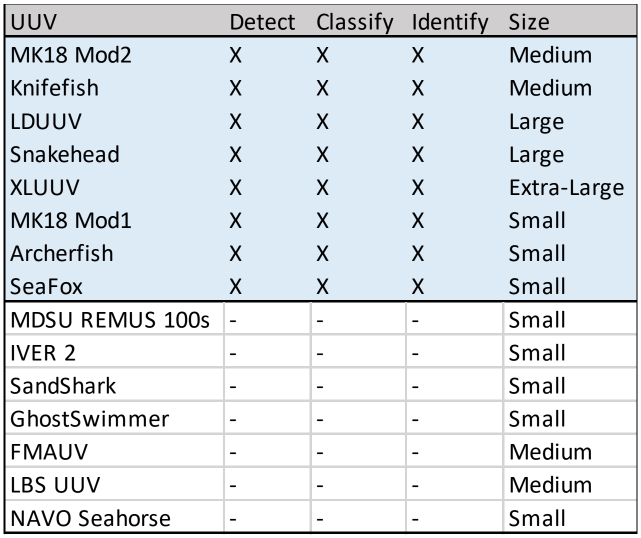
Camacho et al. (2017) proposed six MCM UUVs' architectures. Four depend on data transmission between the UUV and its host vessel or its command-and-control center located at the shore. These four alternatives can be characterized by two types of communication, IC and CC (constant communication). These communication types include mission commands or the data collected during the operation. The CC type relies on acoustic communication methods, which present low data transfer rates and consume power very fast (Button et al., 2009).

C. CURRENT UNMANNED UNDERWATER VEHICLES

1. U.S. Navy UUVs

Camacho et al. (2017) investigated the UUVs currently deployed by the U.S. Navy, depicted in Table 1. They considered that if the UUV could perform detection, classification, and identification operations, it would be included in their study's scope. In order to provide a demonstration to the reader, this thesis will present below two recently developed U.S. UUVs, the Mk18 Mod2, and the Knifefish.

Table 1. U.S. UUVs. Adapted from Camacho et al. (2017).



UUV	Detect	Classify	Identify	Size
MK18 Mod2	X	X	X	Medium
Knifefish	X	X	X	Medium
LDUUV	X	X	X	Large
Snakehead	X	X	X	Large
XLUUV	X	X	X	Extra-Large
MK18 Mod1	X	X	X	Small
Archerfish	X	X	X	Small
SeaFox	X	X	X	Small
MDSU REMUS 100s	-	-	-	Small
IVER 2	-	-	-	Small
SandShark	-	-	-	Small
GhostSwimmer	-	-	-	Small
FMAUV	-	-	-	Medium
LBS UUV	-	-	-	Medium
NAVO Seahorse	-	-	-	Small

a. *Knifefish*

According to Burgess' post (2019) to *SeaPower*, the Navy has recently awarded a contract to start the low-rate initial production (LRIP) for the Knifefish Surface MCM

UUV, a critical mission module for the LCS's MCM Mission Package. The Knifefish (Figure 14) is a medium-class MCM UUV "designed for deployment off the LCS." The system aims to deliver the mine warfare commander enriched minehunting capacity "by detecting, classifying, and identifying buried mines and mines in high clutter environments."

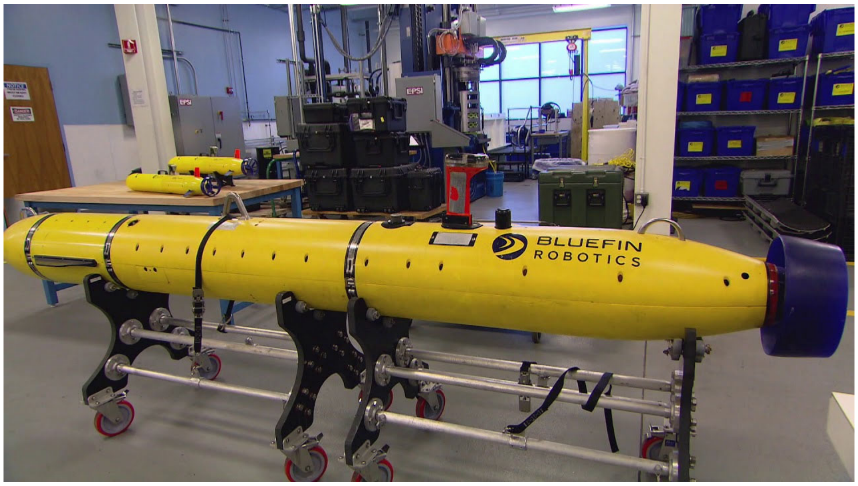


Figure 14. UUV Knifefish. Source: Burgess (2019).

b. Mk 18 Mod 2 Kingfish

The U.S. Navy has employed the Mk 18 Mod 2 Kingfish (Figure 15) since 2013 across mine detection missions for the 5th Fleet, as exposed by Gain (2019). The MK 18 UUV is based on the REMUS 600, with a capacity to descend until 600 meters depth and has the endurance to operate for 24 hours, relying on one battery.

Figure 15. A Mk 18 Mod 2 Kingfish. Source: Gain (2019).

2. Commercial UUVs

Currently, there are also a large quantity and types of UUVs available on the commercial market of unmanned systems. For example, we can cite the AUV Hugin, by Kongsberg Co., depicted in Figure 16, which can operate in many tasks and conditions, including MCM, as described on the company's website. Many companies already employ the product line approach during the development of their products; however, it is still not widely used by the government-defense institutions through their developmental programs. The PL approach can enhance the decision-making process across the requirements definition, architectural, and design phases of UUVs since it can support enhanced requests for proposals (RFPs) when released to the commercial sector.

Figure 16. AUV Hugin. Source: Kongsberg (n.d.).

D. SYSTEMS ENGINEERING PROCESS

Firstly, it is important to define systems, and Blanchard and Fabrycky (2011, p. 3) do very well. They argue that a "system is an assemblage or combination of functionality-related elements or parts forming a unitary whole, such as a river system or a transportation system." They complement the system definition classifying them into natural or human-made, physical or conceptual, static or dynamic, closed or open (Blanchard & Fabrycky, 2011, pp. 6–8). Systems engineering focuses on human-made systems.

The International Council on Systems Engineering – INCOSE defines systems engineering as "a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.," (INCOSE, n.d.). The International Council also defines a transdisciplinary feature as "an approach that crosses many disciplinary boundaries to create a holistic approach." (webpage) Systems Engineering started to surge as an organized, "or at least matured" tool during the 1960s (Rebentisch, 2017, p. 191), when the National Aeronautics and Space Administration – NASA reformulated its way of engineering systems. George Muller, the new Associate

Administrator of the Office of Manned Space Flight (OMSF) designated in 1963, reorganized the Office "in response to slipping schedules." (p. 192)

In order to complement those definitions, Blanchard and Fabrycky (2011) argues that "engineered systems" are the tangible outcome of systems engineering, exposing that they are configured by combined resources, "such as facilities, equipment, materials, people, information, software, and money" (p. 24). Furthermore, they are decomposed into subsystems connected by components with a common objective that conducts their manners, as seen in Figure 17.

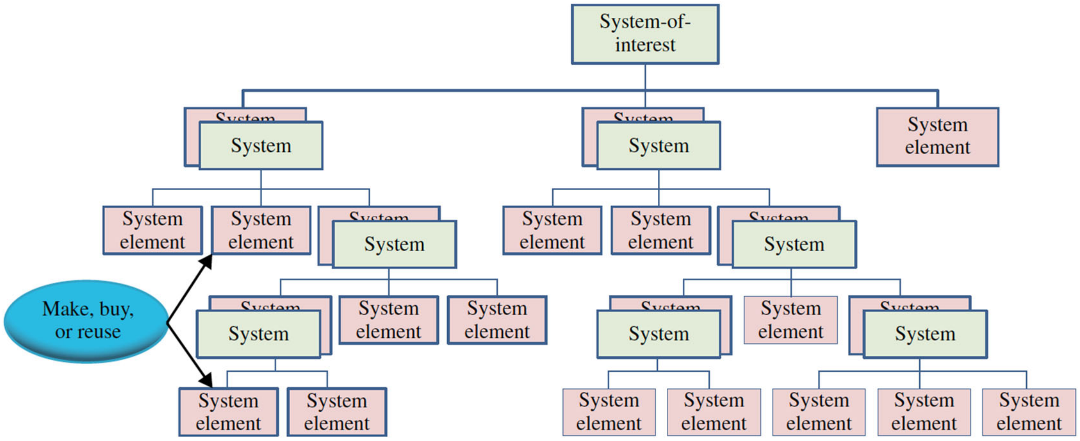


Figure 17. System of Interest (SOI) Hierarchy. Source: Walden et al. (2015).

The Systems Engineering process is often modeled through a life cycle approach. Walden et al. (2015) expose various life cycle models; however, the *Vee* Model, which was originally introduced by Forsberg & Mooz (1991), is currently used by the DOD systems development process (Figure 18). It is a methodological sequence that allows the visualization of several crucial areas through the SE approach, mainly during the system concept and development phases. In summary, the process starts with the operational need definition, known at the DOD as Joint Capabilities Integration and Development System (JCIDS). JCIDS, conducted by the Joint Requirements Oversight Council (JROC), provides "an integrated process to identify new capabilities from a joint perspective based on the national military strategy." (Sawyer, 2021, p. 1) The process involves "identifying, documenting, and prioritizing capability gaps and the weapon system capabilities to address those gaps, generally known as capability requirements.” (p. 1) That is why this process is so important to defense acquisitions since it consistently supports future systems’ needs. Then, the Council defines the system’s requirements, which the Program Managers and Systems Engineers use as a reference to work on the system’s architecture and design. Further, the solution is tested through the validation and verification (V&V) phases until it achieves the initial operational capability (IOC). Finally, the system achieves the last step before comes to the operational field, the full operational capability (FOC), meaning it is ready to be operated by the warfighters.

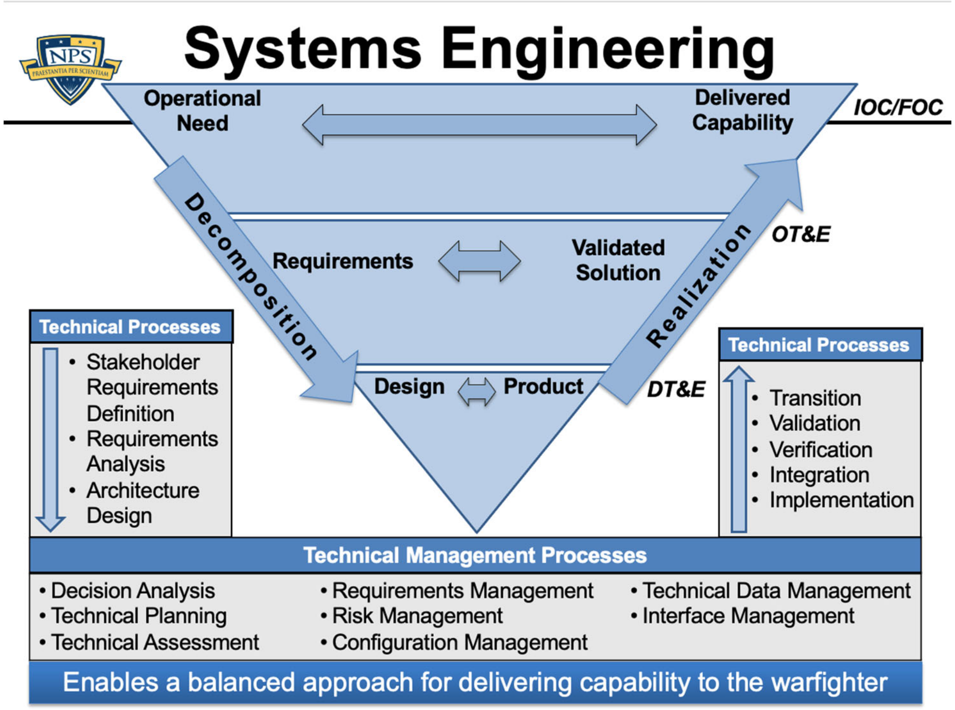


Figure 18. *Vee* model across the DOD systems acquisition. Source: Jones (Winter quarter, 2021).

E. THE IMPORTANCE TO INTEGRATE PROGRAM MANAGEMENT AND SYSTEMS ENGINEERING

Professor Raymond Jones (PowerPoint Slides, Winter, 2021) defined the defense acquisition as a process that involves “the conceptualization, initiation, design, development, test, contracting, production, deployment, and logistic support, modification, and disposal of weapons and other systems, supplies, or services to satisfy defense needs in support of military missions." In order to achieve better results across this complex process, this section argues the importance of integrating program management and systems engineering throughout the systems acquisition.

Rebentisch (2017, p. 54) highlights the Program Management Institute's (PMI) definition of Program Management as "the application of knowledge, skills, tools, and techniques to a program to meet the program requirements and to obtain benefits and control not available by managing projects individually." The author also exposes a conceptual definition of the Integration of those important areas for the acquisition process:

> Integration is a reflection of the organization's ability to combine program management and systems engineering practices, tools and techniques, experience, and knowledge in a collaborative and systematic approach in the face of challenges, in order to be more effective in achieving common goals in complex program environments. (Rebentisch, 2017, p. 93)

Rebentisch (2017) also exposes that the broad program performance management approach will include core metrics from both the management and technical perspective (Figure 19). The image also depicts the key elements that must be present in the program to promote the success of the integration. The Systems Engineering Guidebook (Office of the Under Secretary of Defense for Research and Engineering [OUSD(R&E)], 2022) is a recent initiative that aims to integrate those areas across the DOD programs.

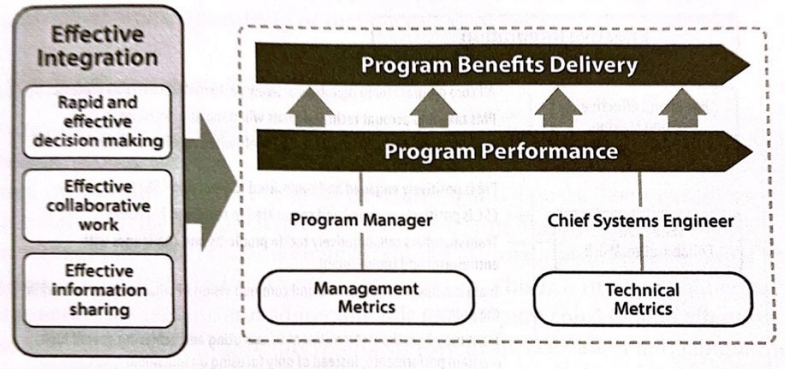


Figure 19. The Impact of Integration on Program Performance. Source: Rebentisch (2017).

F. U.S. DEPARTMENT OF DEFENSE SYSTEMS ACQUISITION

The DOD acquisition process is currently conducted under an integration of program management and systems engineering approach. Figure 20 details the process briefly introduced in Section D. Major Defense Acquisition Program (MDAP) is planned and performed through four main decision-making milestones (Material Development Decision – MDD, A, B, C). The process transitions through five phases after the JCIDS process defines the operational need: Material Solution Analysis (MSA), Technology Maturation and Risk Reduction (TMRR), Engineering and Manufacturing Development (EMD), Production and Deployment (P&D), and finally, O&S. Across these phases and milestones, technical management is performed through a system engineering approach, as previously shown in Figure 18.

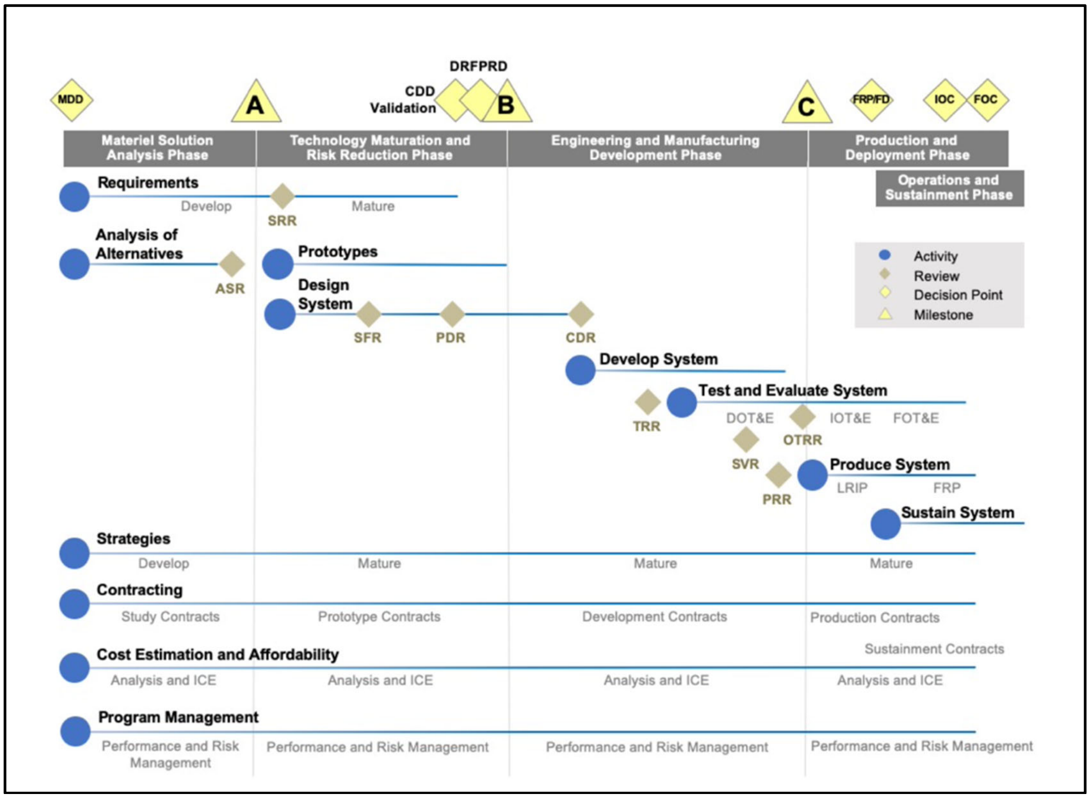


Figure 20. Detailed Life Cycle View of Major Capability Acquisition. Source: Defense Acquisition University [DAU] (n.d.).

Another core characteristic of the U.S. Defense Systems Acquisition is the life cycle management, which begins at the MSA and finishes at the system's disposal. Cost, schedule, and performance, known by the acquisition community as the "triple constrain," must be managed by program managers and highly considered by systems engineers during the developmental phase. Throughout the system's life cycle is possible to realize how technical and management activities are performed in parallel to provide the program's success.

In parallel, the LCC estimation is a great tool to support decision-makers during the entire life cycle, mainly at earlier trade-off considerations. Independent cost estimates (ICE) are LCC estimates conducted by an external organization, independently of the Program Management Office (PMO) or defense agency. LCC estimation is important to support decisions taken during the earlier architecture and design phases, which hardly impact further O&S cost of the system. Figure 21 shows O&S costs (blue slices), representing about 58% of the total LCC of UAVs and reaching 67% of surface ships, on average.

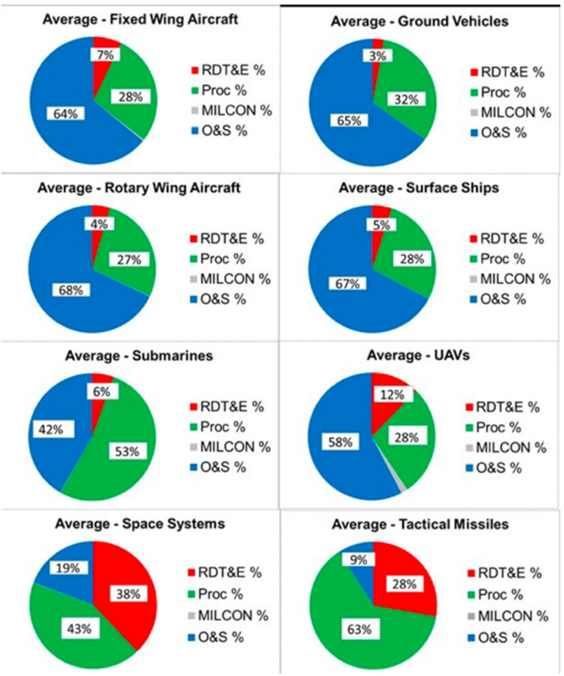


Figure 21. DOD Systems Life Cycle Costs. Source: Office of the Secretary of Defense [OSD] (2020).

Throughout the LCC perspective, the systems engineering approach and architecture and design tradeoffs impact the measurement of cost commitment versus the incursion of costs across the system life cycle phases. Figure 22 exposes the cumulative percentage LCC against time, exposing the cost commitment through the systems life cycle. It looks clear that about 85% of the system's cost is often committed through the concept and design phases. At the end of the design phase, the system usually consumed only 23% of the total LCC (INCOSE, 2015).

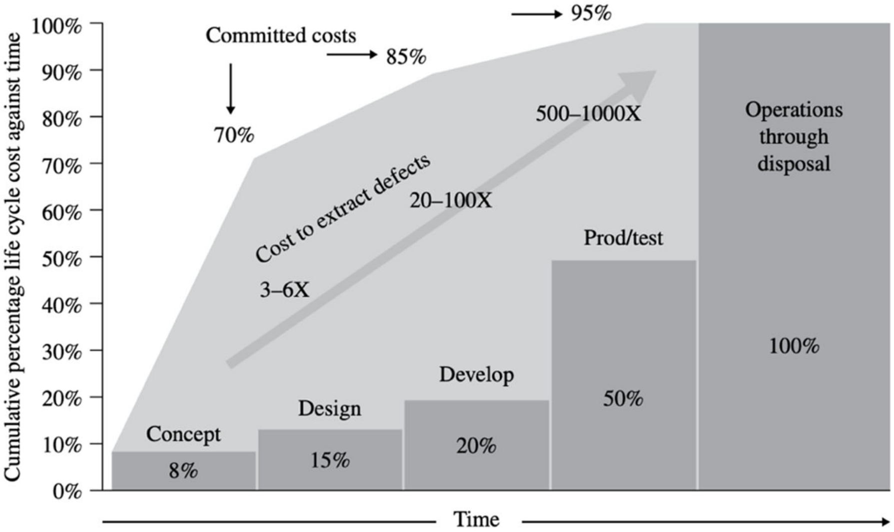


Figure 22. Commitment Life Cycle Costs through the System Life Cycle. Source: INCOSE (2015).

G. DIGITAL ENGINEERING (DE) AND MODEL-BASED SYSTEMS ENGINEERING (MBSE)

The OUSD(R&E) recently emitted the Digital Engineering (DE) Strategy in order to guide the DOD through the Digital environment direction when developing new defense systems. The document is structured in five core goals that drive "the use of digital representations of systems and components and the use of digital artifacts as a technical means of communication across a diverse set of stakeholders.," declared Michael D. Griffin, Under Secretary of Defense for Research and Engineering (DOD, 2018). It marks the DOD systems acquisition transition to the digital era. Instead, the traditional document-based approach has poor traceability and confusing cross-referencing when system engineers and program managers work simultaneously through the same project. It becomes even more complicated when government and contractors need to work together in a constant exchange of information, generating cost overruns, delayed schedules, and performance drops. Figure 23 depicts a MBSE tool generated in a DE environment which begins from the high-level requirements through many kinds of integrated diagrams, providing a high level of traceability during the entire process.

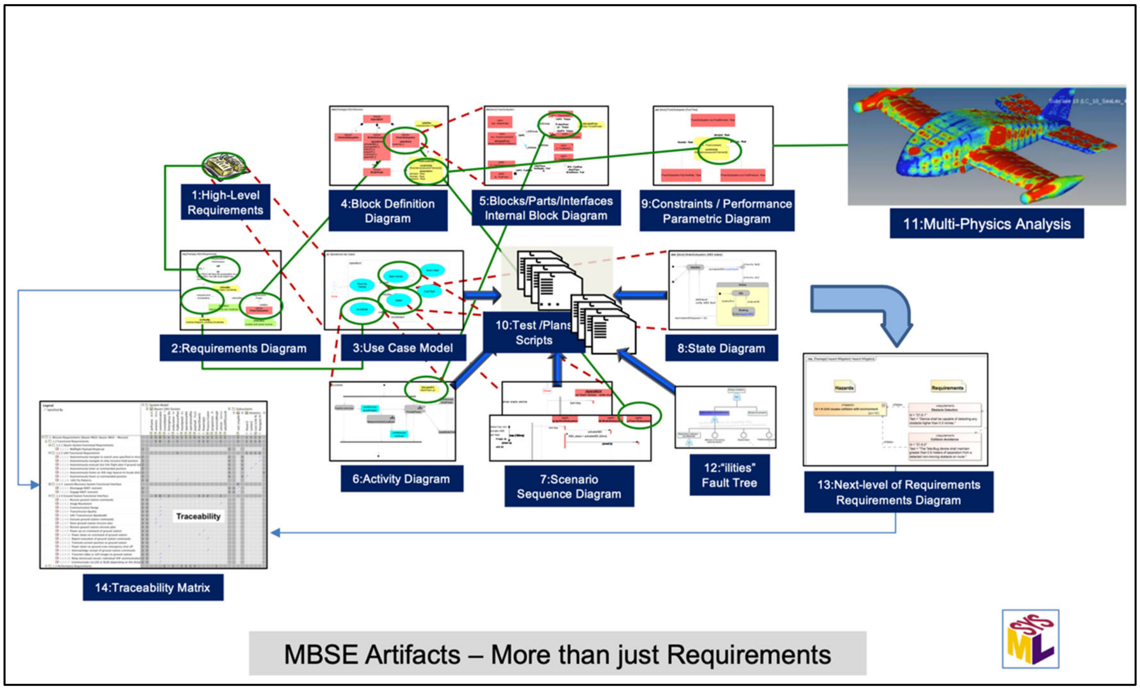


Figure 23. How MBSE Strengthens SE by Characterizing the Analysis of Structure, Behavior and Interfaces. Source: Blackburn & Verma (2020).

Hutchison (2022) argues that DE impacts the form engineers and the acquisition community accomplish their tasks, interaction, and information sharing. A holistic DE approach incorporates multiple disciplines into a rich model-based environment. Modeling and simulation generate artifacts; some focus on the system, some at the program level or higher. Many disciplines come together since DE is becoming the way the DOD does business by the DOD Digital Engineering Strategy.

MBSE uses modeling languages and representation frameworks to support the systems engineering process through a “model-based or model-driven context.” (*SysML Forum*, n.d.). That approach represents the standardized employment of modeling to support the systems engineering process from the requirements throughout the entire system life cycle. Figure 24 shows the difference between the traditional SE and MBSE approach, in which all digital models are integrated in order to provide real-time access to all program stakeholders. On the other hand, the traditional approach depends on many different tools without integration and traceability capability.

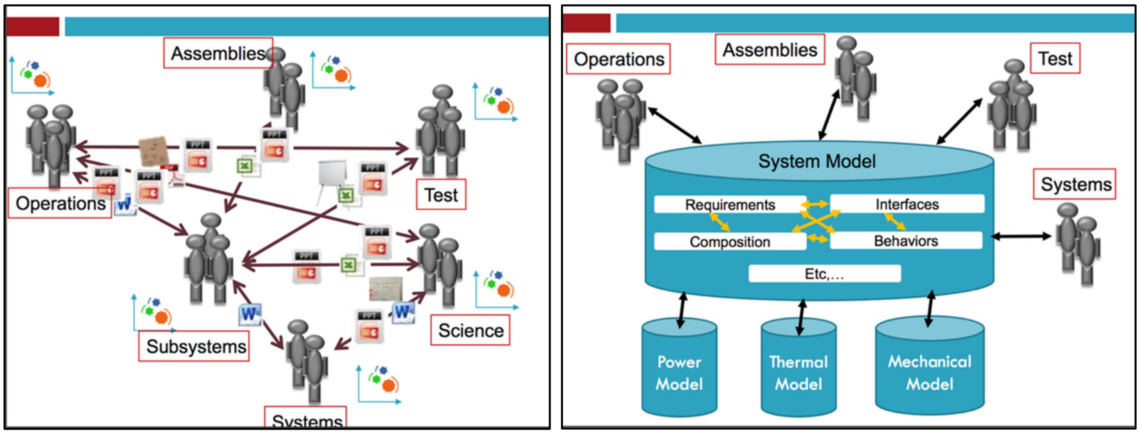
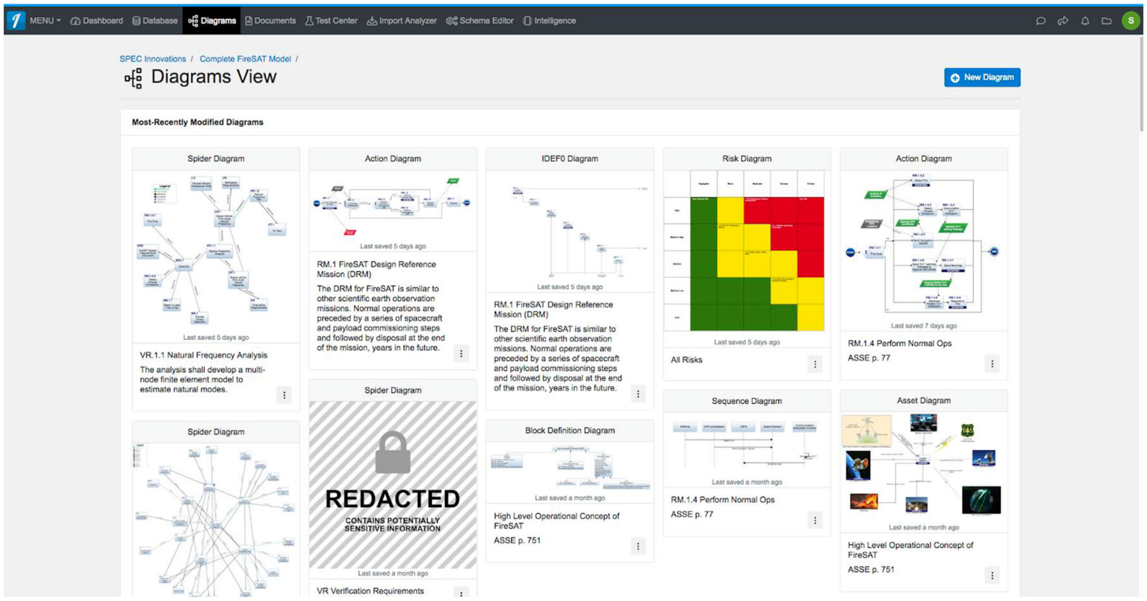


Figure 24. Traditional SE approach (left) vs. MBSE SE approach (right). Source: INCOSE IW cited in White SE3050 class (Spring, 2022).

SPEC Innovations developed a good approach to digital engineering, creating the Innoslate MBSE tool, which integrates aspects of systems engineering and program management (SPEC Innovations, 2022). They call that “horizontal integration.” This approach has provided a domain-independent way to optimize cost, schedule, and performance while mitigating risk throughout the product life cycle for SoS. The tool also provides interoperability from the systems engineering domain to the design engineering domains throughout the life cycle, which they call this “vertical integration.” Haller et al. (2022) and Camacho et al. (2022) used the Innoslate tool to conduct the systems engineering process to develop their analysis and models. Haller et al. argue that the digital capacity provided by MBSE within Innoslate “provides advanced insight on system relations and requirements and permits the ability to update changes in real-time models to assist with prompt decision making." Innoslate provides modeling capabilities across many languages/frameworks, including SysML, LML, UML, and IDEF. It also provides the capability to create documents with diagrams from the tool embedded in the document and update as those diagrams are updated.



VR.1.1 Natural Frequency Analysis

The analysis shall develop a multi-node finite element model to estimate natural modes.

RM.1 FireSAT Design Reference Mission (DRM)

The DRM for FireSAT is similar to other scientific earth observation missions. Normal operations are preceded by a series of spacecraft and payload commissioning steps and followed by disposal at the end of the mission, years in the future.

VR Verification Requirements

RM.1 FireSAT Design Reference Mission (DRM)

The DRM for FireSAT is similar to other scientific earth observation missions. Normal operations are preceded by a series of spacecraft and payload commissioning steps and followed by disposal at the end of the mission, years in the future.

High Level Operational Concept of FireSAT

ASSE p. 751

All Risks

RM.1.4 Perform Normal Ops

ASSE p. 77

RM.1.4 Perform Normal Ops

ASSE p. 77

High Level Operational Concept of FireSAT

ASSE p. 751

Figure 25. Innoslate Diagram View. Source: SPEC Innovations (2022).

H. SYSTEM ARCHITECTURE

Blanchard and Fabrycky (2011) defines system architecture as the step of the conceptual design phase in which the system's initial configuration is defined. The authors state that "the architecture deals with the top-level system structure, its operational interfaces, anticipated utilization profiles (mission scenarios), and the environment within which it will operate." Then, two important steps are performed, functional and physical architecture (Figure 26). Both are further explored through the methodology of unmanned underwater systems.

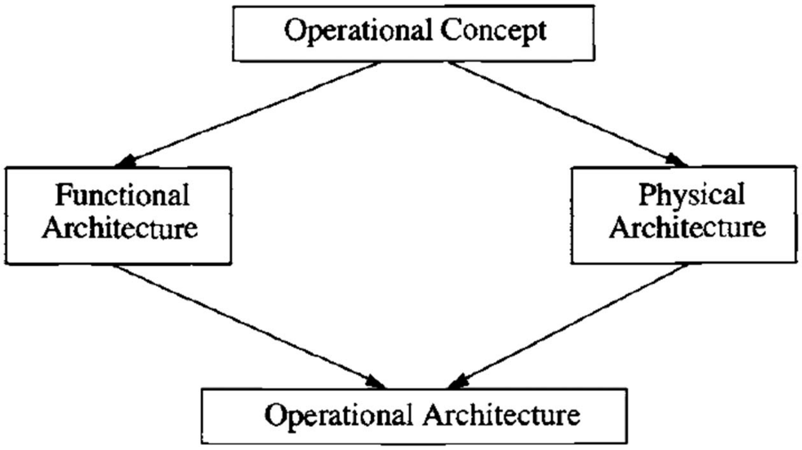
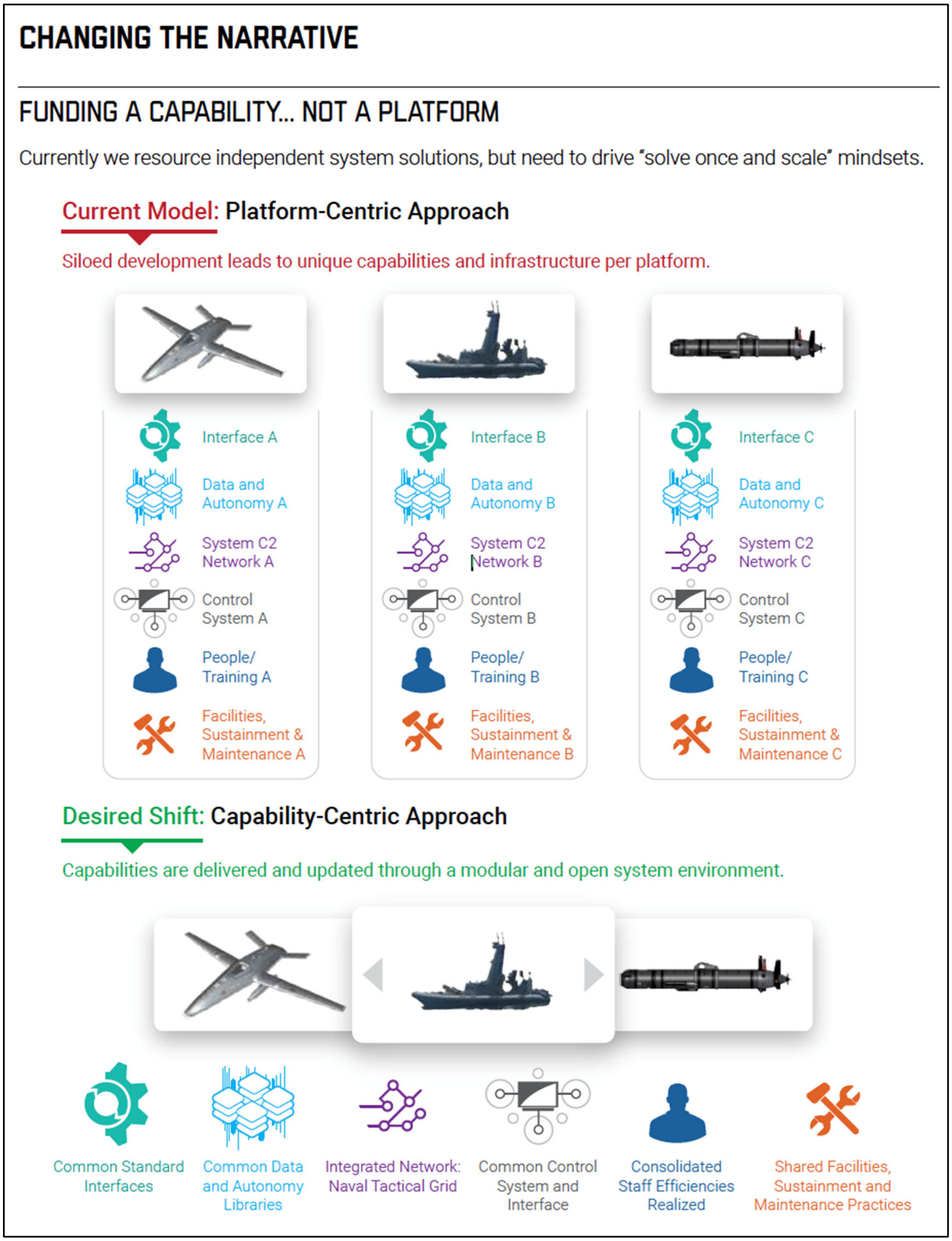


Figure 26. System Architecture Model. Source: Buede (2000).

1. Open architecture initiatives

Open architecture is a valuable feature of system architecture. Buede (2009) states that open architecture is established whether "the hardware and software interfaces are sufficiently well defined so that additional resources can be added to the system with little or no adjustment." This characteristic makes PLE feasible since common core attributes of an engineering product line require open architecture to build, deploy, and evolve the system across its life cycle. The Unmanned Campaign Framework (U.S. Navy, 2021) suggests that unmanned systems be developed under a new narrative. Instead of a "platform-centric approach," it should switch to a "capability-centric approach," in which "capabilities are delivered and updated through a modular and open system environment" (p. 24), corroborating the open architecture approach, not only across the same type of system but across a range of unmanned systems (Figure 27). This wider approach is not the scope of this study since it limits the UUVs that perform MCM missions, though it is very relevant for future research.



CHANGING THE NARRATIVE

FUNDING A CAPABILITY… NOT A PLATFORM

Currently we resource independent system solutions, but need to drive "solve once and scale" mindsets.

Current Model: Platform-Centric Approach

Siloed development leads to unique capabilities and infrastructure per platform.

Interface A
Data and Autonomy A
System C2 Network A
Control System A
People/ Training A
Facilities, Sustainment & Maintenance A

Interface B
Data and Autonomy B
System C2 Network B
Control System B
People/ Training B
Facilities, Sustainment & Maintenance B

Interface C
Data and Autonomy C
System C2 Network C
Control System C
People/ Training C
Facilities, Sustainment & Maintenance C

Desired Shift: Capability-Centric Approach

Capabilities are delivered and updated through a modular and open system environment.

Common Standard Interfaces
Common Data and Autonomy Libraries
Integrated Network: Naval Tactical Grid
Common Control System and Interface
Consolidated Staff Efficiencies Realized
Shared Facilities, Sustainment and Maintenance Practices

Figure 27. Funding a Capability…not a Platform. Source: U.S. Navy (2021).

System Engineering aspects are usually related to sensors, power sources, payloads, and logistics considerations. The UUV Master Plan (DON, 2004) recommended investing in critical technologies, such as autonomy, energy, propulsion, sensors, data processing, and communications-networks. The Master Plan also highlights how interoperability of systems impacts the open architecture and guides the coordination among different unmanned vehicle programs since there are numerous commonalities. As a recent example of this trend demonstration, the U.S. Navy Program Executive Office Unmanned and Small Combatants (PEO USC) Unmanned Maritime Systems Program (PMS 406) is coordinating the development of an Unmanned Maritime Architecture (UMAA), which means a common, modular, scalable, software for unmanned maritime vehicles, using standard interfaces (Figure 28).

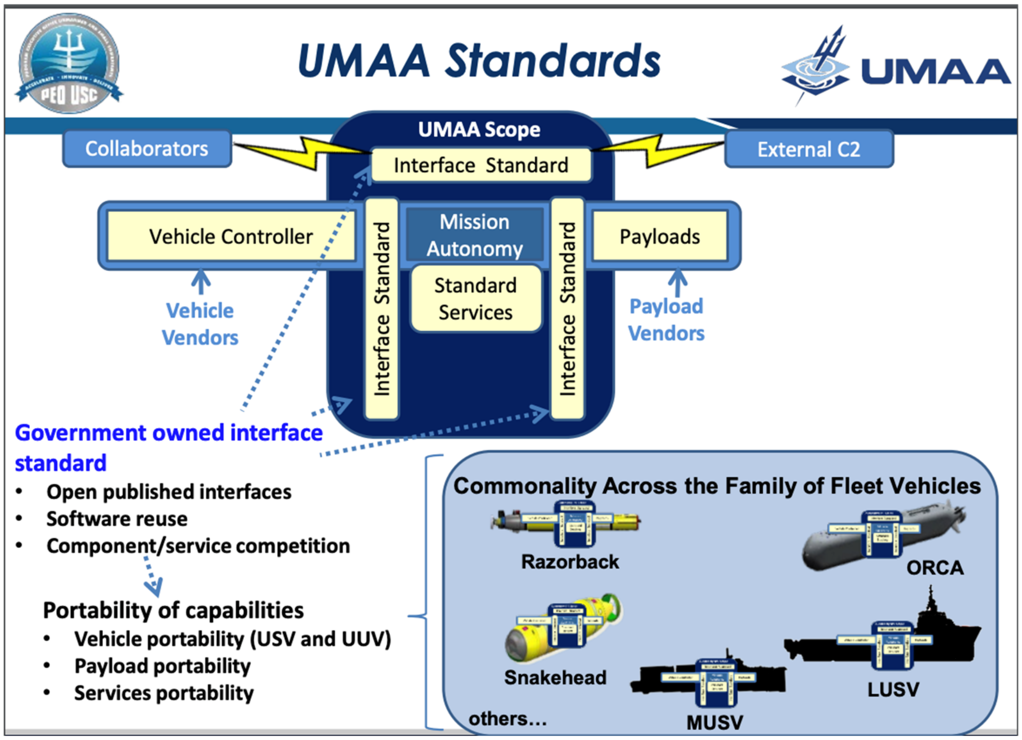


Figure 28. Scope of UMAA Standards. Source: PEO USC PMS 406 (2022).

I. PRODUCT LINE APPROACH

1. Product Line Engineering (PLE)

Pohl et al. (2005) remember that the earlier concept of the production line came from the automotive industry, specifically by Henry Ford, enabling mass production for a great demand cheaper than unique system production. In spite of that, it lowered the chances of diversity across the products, meaning that all consumers used to purchase rigidly the same item.

As people developed different car demands after the Model T (Ford Co.) boom, the automobile industry faced high demand for personalized products. From that period, the "mass customi [z]ation" concept surged. According to Pohl et al. (2005, p. 4), the term means "taking into account the customers' requirements and giving them what they wanted." Further, the industry developed the platform concept, seen as a technology baseline for other advances or processes that have been built. Through this process, the automotive industry developed common platforms for different car models, decreasing the production cost for a specific model.

Pohl et al. (2005) also highlight many motivations for the PLE approach. They suggest the existence of a break-even point in terms of ROI, which in software engineering can be reached around the third system developed under a PLE approach (Figure 25). An individualized cost drop is achieved when software or hardware components are reused across different systems. Up-front investment is necessary to generate a common platform (Pohl et al. (2005) that will further cause cost reduction through the successively produced systems.

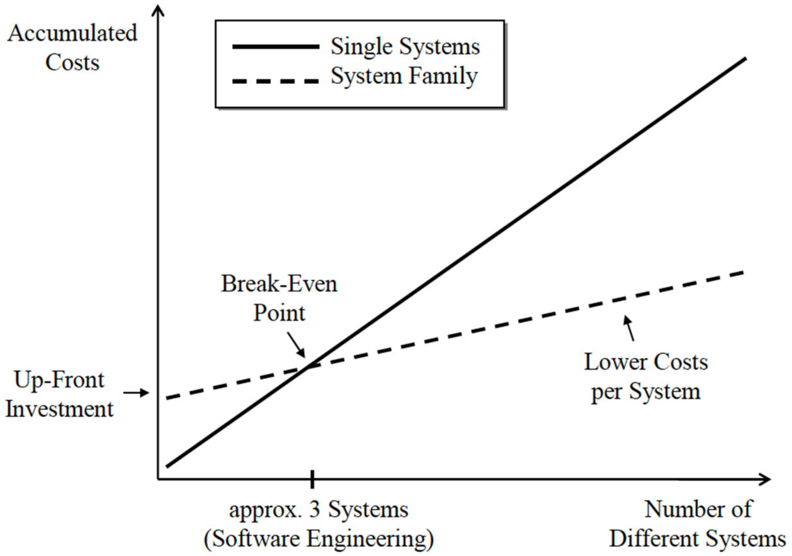


Figure 29. Costs for Developing *n* Kinds of Systems as Single Systems Compared to Product Line Engineering. Source: Pohl et al. (2005).

The core objective is to generate customized systems at reasonable costs under a portfolio approach, by which relative cost savings are even higher (Haller et al., 2022). Applying PLE to the architecture and design of the next-generation MCM UUV systems can form a system baseline. Further, it can reduce the individualized costs by reuse and consequently enhance the decision-making through a portfolio approach. From that perspective, the government and contractors should invest in developing a certain amount of components for reuse when dealing with defense systems acquisition; in opposite to developing systems independently in silos, which would also mean more cost in future maintenance efforts (Pohl et al. (2005) and consequently through the O&S phase.

Pohl et al. (2005) contrast the idea of the PL approach with the single system engineering approach, in which the components are developed individually and isolated. According to them, the core strategy to develop a product line is thinking about commonality first and variabilities further. It is possible creating a common platform by developing reusable components followed by identification of the elements that have to be unique.

2. Parametric Cost Modeling – Constructive Product Line Model (COPLIMO)

The cost estimation community often argues that the most important thing during an estimation process is the strategy to be used (International Society of Parametric Analysts [ISPA], 2008). Choosing the appropriate approach can generate cost modeling with a high potential to generate more accurate results, reducing the probability of exceeding the budgeted costs for the project, in addition to preparing proposals and subsidizing more improved information for decision-makers (ISPA, 2008).

The ISPA handbook (2008) demonstrates that a cost model generates a cost forecast for the future based on historical data. Usually, the company/government accounting system is the primary data source for the parametric cost model. The manual indicates that technical and physical information of systems and the performance of subsystems and components can also be significant generators of relevant data. For example, weight data is a standard physical feature in cost estimating relationships (CERs) and parametric models. Horsepower, watts, and source lines of code are also types of cost driver variables. The core point lies in finding the best cost predictors (ISPA, 2008).

The Cost Estimation Handbook version 4.0 (NASA, 2020) depicts that during the earlier concept and design phases, analogy and parametric are considered the most useful cost prediction methodologies (Figure 30). The NASA handbook also exposes that the analogy method "uses the cost of a similar system, adjusts for differences, and estimates the cost of the new system." The costs parameterization through models usually results from a statistical relationship between past costs and physical or performance variables of the analyzed system/program (NASA, 2020). As shown in Figure 30, the NASA's handbook (2020) recommends this method when a tiny volume of system data is known, usually in the conception and design phases. The basic premise of this methodology is that aspects that affected the cost in the past will produce a similar effect in the future, statistically.

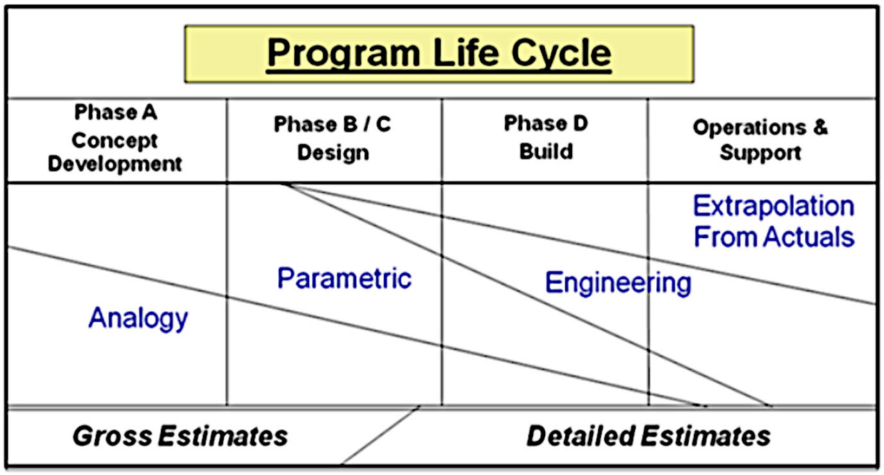


Figure 30. Cost Estimating Methodologies by Phase. Source: NASA Cost Estimating Handbook (2020).

COPLIMO is an extension made upon the Constructive Cost Model (COCOMO) II, adjusted for strategic software product line from industry data (Boehm et al., 2000). It originally models sets of software embracing product-specific. Boehm et al. (2004) claim that most cost estimation models available in 2004 to estimate software product line costs underestimated the return on investment of that approach, regarding just development versus life cycle savings and resulting in extra reuse charges across the entire system instead components. Faced with this demand, The authors developed COPLIMO, a parametric cost model that addresses such deficiencies. Briefly, the model uses the following classification as input parameters to obtain the ROI across several systems developed in a product line: the unique, specific parts of the system, totally reused components, and reused components with adaptation. The Constructive Product Line Investment Model webpage (*COPLIMO Product Line Investment Model*, n.d.) provides the following model's description:

> The Constructive Product Line Investment Model (COPLIMO) helps one estimate the costs and return-on-investment (ROI) of developing product lines. Initially, it was oriented for software product line development (Boehm, 2004). It has subsequently been expanded into a general framework for system product lines consisting of software, hardware, or combined elements. Cost model portions can be adapted for different product types, processes, and estimation relationships.

Hall (2018) highlights that the basic COPLIMO was primarily developed for the analysis of costs as well as return on up-front investment in software engineering domain. From that basic version, other models adapted for the entire systems were developed, expanding the product line and ROI analysis to hardware as well as to the systems engineering process (Boehm et al., 2004; Deshmukh et al., 2010; Madachy & Green, 2019).

As previously demonstrated in section F, defense systems acquisition demands actions and practices strongly related to the systems engineering approach. Given that and the necessity for cost estimates that better support the decision-making process, the product line surges as a promising approach when the defense sector faces a range of alternative solutions in terms of systems architecture's commonalities and variabilities. In the next chapter, this thesis will address a methodology based on the components' reusability model implicit in COPLIMO (*COPLIMO*, n.d.).

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III. METHODOLOGY AND APPROACH

A. OVERVIEW

Using the systems engineering approach and the OVM (Pohl et al., 2005), this study capture variability and commonality obtained from six alternative functional architectures detailed by Camacho et al. (2017) through MBSE. This way, the first step of this thesis's methodology is considering those alternatives as system architecture for the analysis since the authors focused on their performance assessment and did not explore cost or economic aspects. Then, regarding the functional architecture decomposed by Camacho et al. (2005) is possible to identify components/set of components using a system variability model described by Pohl et al. (2005). After that, this study estimates the expected reuse category (reused, adapted, and mission unique) percentages of the MCM UUVs' components/set of components across the identification of variations and variation points from the product line OVM.

Further, those expected reuse category percentages represent parametric inputs to the COPLIMO to support the approach's ROI analysis and consequently enhance the decision-making process during the earlier architecture and design phases when adopting a portfolio approach to manage the next-generation MCM UUVs programs. This economic analysis of the product line architecture approach through the integration of MBSE approach and a parametric cost modeling enables the assessment of potential cost savings across the system life cycle, even investing about 70% (basic COPLIMO standard) more during the development of the system baseline. This way, the LLC of the portfolio (family of systems) can be reduced by integrating different systems that, although they demand distinct capabilities, share similar operations objectives and capabilities. Figure 31 summarizes the main steps of this thesis's methodology.

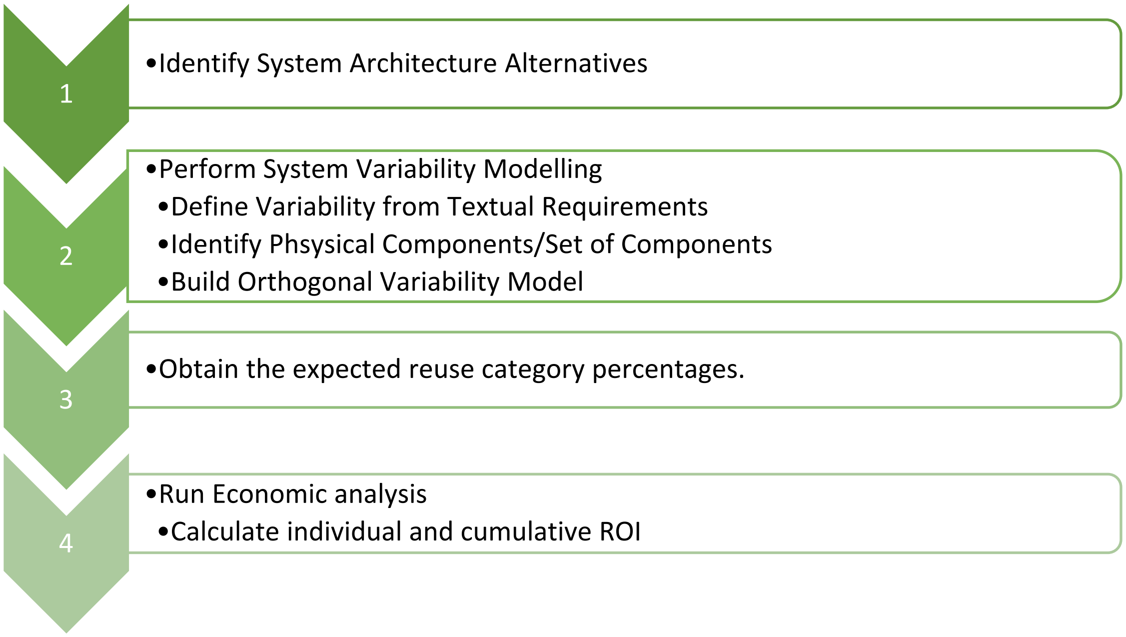


Figure 31. Process to Determining ROI through a Product Line Approach

B. SYSTEM ARCHITECTURE

1. Functional Analysis

The NWP 3-15 Mine Warfare Doctrine (DON, 1996) primarily classifies MCM into two broad groups: offensive (proactive) and defensive (enabling). The offensive MCM has a preventive characteristic as opposed to the defensive MCM, which has the characteristic of cleaning an already mined site. According to the NWP 3-15 (DON, 1996), offensive actions seek to mitigate or even eliminate the risk of damage to the fleet of ships, submarines, merchant ships, and other maritime systems that need to cross a given region. This research focuses on the second group of MCM, the defensive, which the NWP 3-15 (DON, 1996) subdivides into passive or active. This thesis analysis does not consider the first subgroup. On the other hand, the active subgroup requires a reactive movement by the naval force specialized in this type of operation by using assets that will interface with the mines.

Figure 32 depicts the MIW functional decomposition from the DON mine warfare doctrine. This diagram demonstrates a progressive perspective of the MCM (1.2) process as a subdivision of the MIW (1.0). Then, the MCM is divided into offensive and defensive, decomposed into passive and active. The active MCM currently employs UUVs predominantly in mine hunting operations.

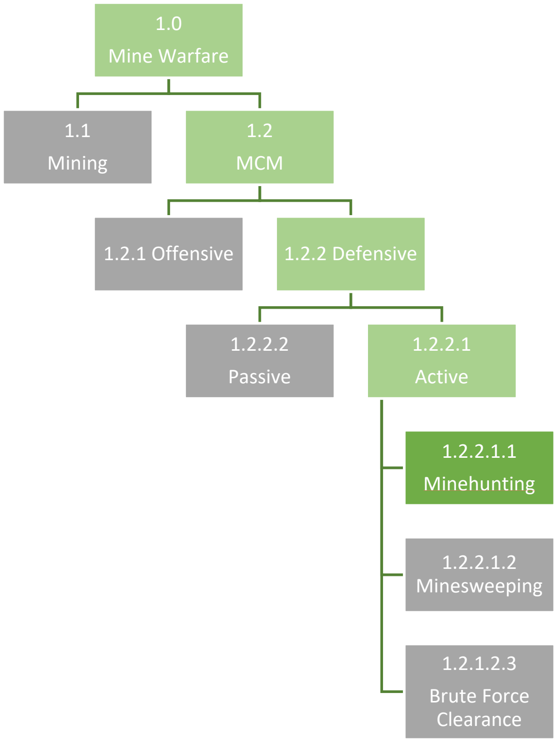


Figure 32. MIW Functional Decomposition Diagram. Adapted from DON (1996).

Camacho et al. (2017) demonstrates that the first step of a common mine hunting CONOPS is the decision to perform that. The sequence of events considered begins with the MCM mission planning. After the planning is ready, the mission effectively starts with the unmanned vehicle launch from a host vessel, which navigates to the MDA. Then, it runs sorties until it is picked up by the launch/recovery platform. Finally, the post mission analysis (PMA) is conducted. The detailed mine hunting functional decomposition can be observed in Figure 33.

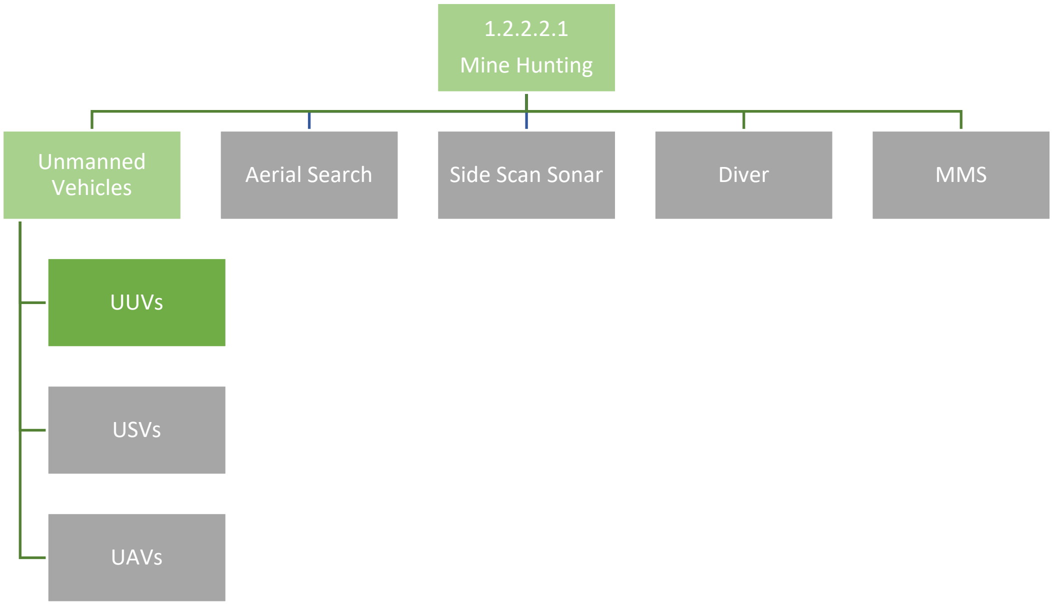


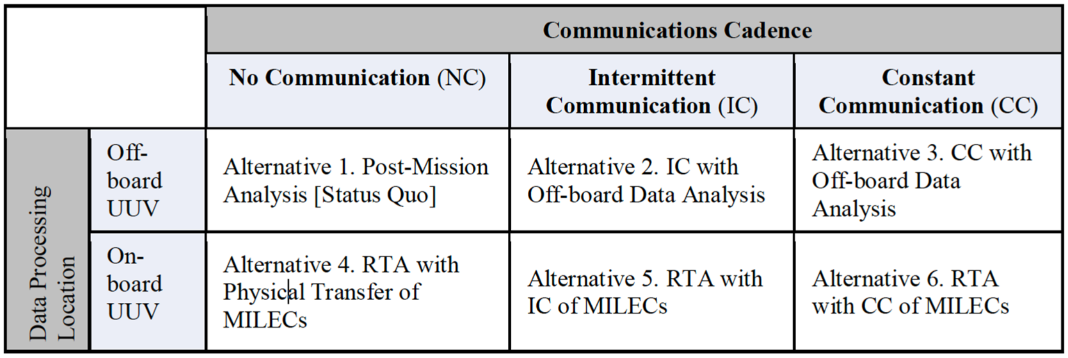
Figure 33. Mine Hunting Functional Decomposition Diagram. Adapted from DON (1996).

Research by Camacho et al. (2017) supports that the current set of U.S. MCM UUVs involved in “detect and classify” portions of the defensive-active MCM missions count on a physical transfer of not-processed data for processing through resources not available in the UUVs available in the year of the survey. (Status quo at the time of their research). Hence, they examined the UUV technology and technological capacities with expected availability until 2027, focusing on the performance assessment of proposed architectures.

In this sense, Camacho et al. (2017) recognized a group of operating concepts the system could execute. By examining the minehunting mission goals, they found the MCM mission heart: convert an unidentified battlespace into a known battlespace through collecting and transforming environmental data collected by the UUV sensors.

The PLE approach and open architecture guide this thesis to achieve a common system design (baseline) for the next-generation MCM UUVs to obtain potential savings in their total LCC. Two potential technological changes/solutions identified by Camacho et al. (2017) are used as core performance drivers to the MCM UUVs’ concept of operations, “data processing location” and “communications cadence,” which were combined by the authors using MBSE tools, generating six potential architecture alternatives described in Table 2.

Table 2. Alternative Functional Architectures. Source: Camacho et al. (2017).



		Communications Cadence		
		No Communication (NC)	**Intermittent Communication** (IC)	**Constant Communication** (CC)
Data Processing Location	Off-board UUV	Alternative 1. Post-Mission Analysis [Status Quo]	Alternative 2. IC with Off-board Data Analysis	Alternative 3. CC with Off-board Data Analysis
	On-board UUV	Alternative 4. RTA with Physical Transfer of MILECs	Alternative 5. RTA with IC of MILECs	Alternative 6. RTA with CC of MILECs

Alternative 1 (NC & Off-board data processing) was chosen as the baseline architecture for the next-generation MCM UUV. It is characterized by the absence of remote communication capability and the absence of on-board data processing capacity. This architecture was the *status quo* technology when Camacho et al. (2017) conducted their performance-focused research. The other alternatives comprise the proposed product line combining two main subsystems’ capabilities, communications cadence and data processing location. Each alternative will guide the identification and assessment of components in the OVM from the requirements analysis.

Further, the authors developed a functional hierarchy using the Innoslate (SPEC Innovations, n.d.), a MBSE tool that catches the core aspects and behavior needed for the systems. The functional decomposition starts at the highest level (Figure 33). It then goes to the most detailed level that captures the variations among the proposed communication alternatives and the different data processing methods. The processes required throughout the system life cycle are represented in Figure 34.

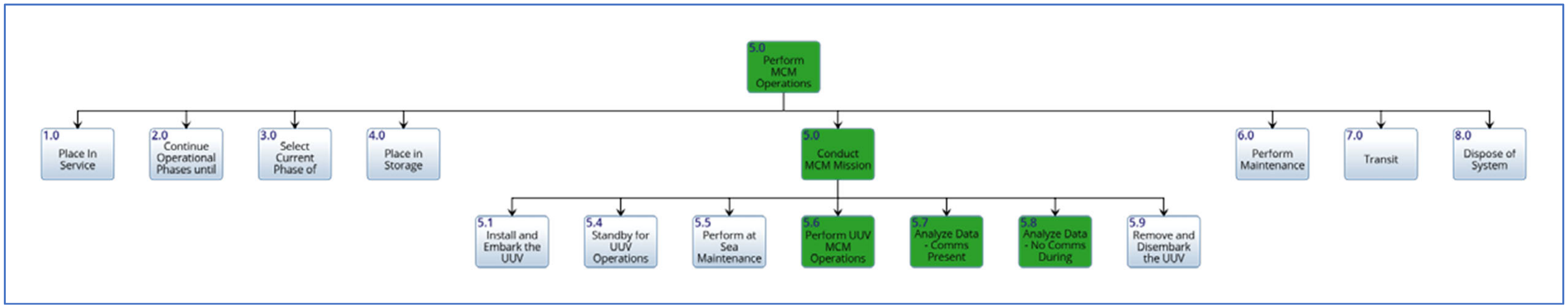


Figure 34. Functional Hierarchy. Source: Camacho et al. (2017).

This study follows Camacho et al.'s (2017) scope in terms of the proposed alternatives, assuming the next-generation MCM UUV will conduct the "detect and classify" tasks.

By decomposing the MCM UUV functions, the authors of the study abovementioned detail Function 5.0 (Figure 35), which consists of activities executed from the moment the UUV embarks on minehunting operations until the time the system is disembarked. All the MCM mission tasks can be seen from Function 5.1 to Function 5.10. From these functions they architected using the Innoslate, this research spotlights Functions 5.6, which relates directly to MCM UUV minehunting operations, and Functions 5.7 and 5.9, related to the presence or not of communications capability. Those functions will further guide the system components analysis in order to assess the expected reuse category percentages.

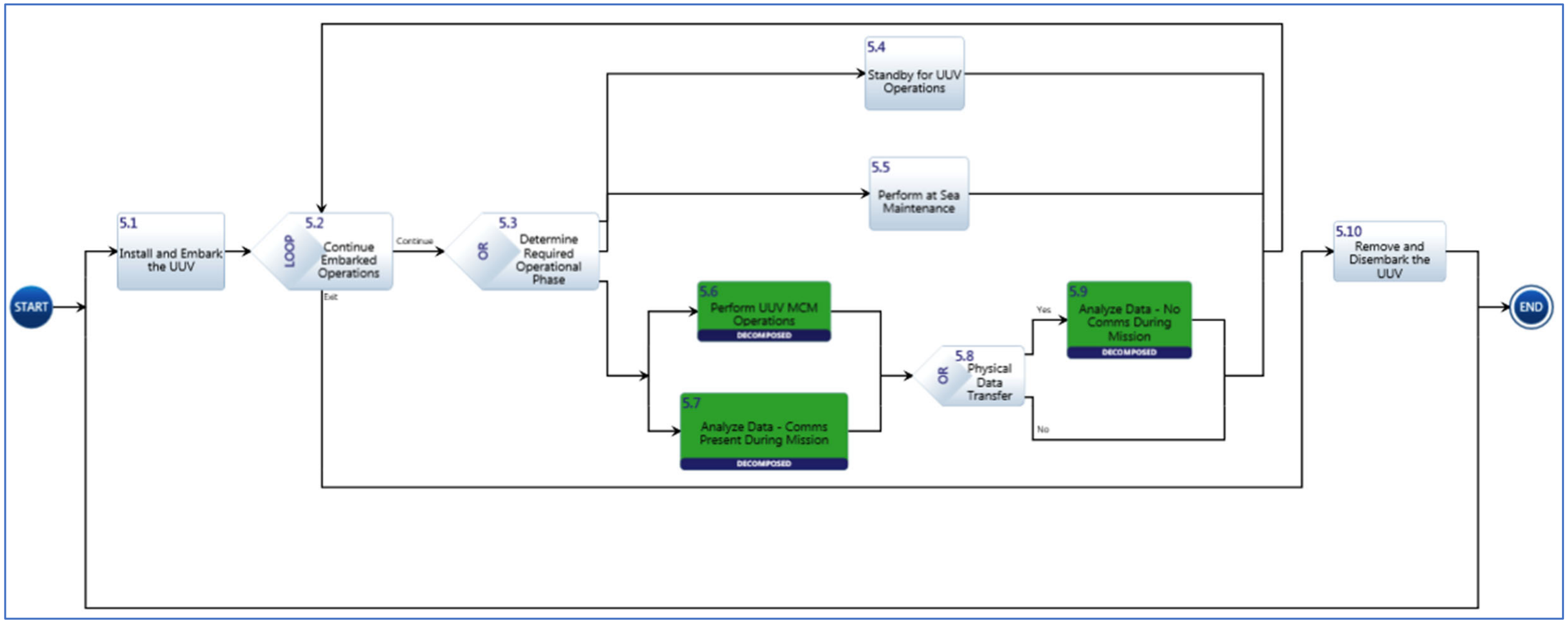


Figure 35. 5.0 Conduct MCM Mission. Source: Camacho et al. (2017).

The execution steps of the UUV MCM operations considered for this research development were those previously determined by Camacho et al. (2017), which are exposed by function 5.6, decomposed in Figure 36. The UUV hypothetically operates far from a host ship when performing them. In this way, UUV launch and retrieve would occur from this. For the efficient execution of the function, it is also essential to consider the transit to and from the minefield and the reach of the desired depth for hunting the mines and their return. As well as Camacho et al. (2017), this study focuses on the functions performed in the minefield. Thus, five central subsystems directly related to the 5.6 functions are considered: communication cadence, data processing location, locomotion, navigation, and sensors – data collection. Along this, it is possible to evaluate internal and external data processing architectures and three communication cadences, as previously described in Table 2. The key factor in classifying these communication functions is related to the data. When processed on board, they are considered mine echo (MILEC), being called raw data when this processing does not occur onboard.

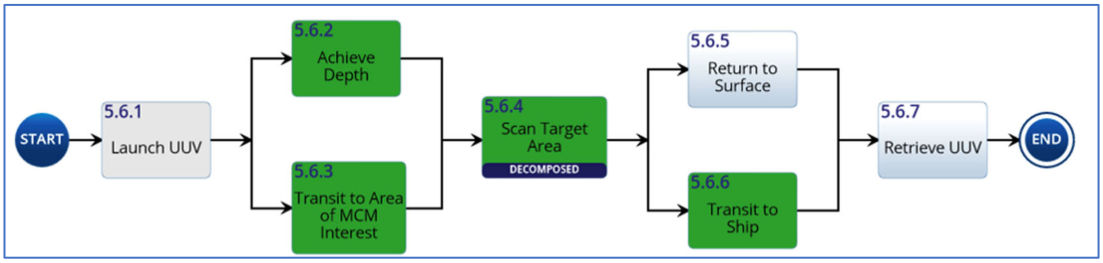


Figure 36. 5.6 Perform UUV MCM Operations. Source: Camacho et al. (2017).

The “scan target area (5.6.4)” function represents a defining point among the possible proposed system architectures given the aforementioned data processing and communication capabilities (Camacho et al., 2017). It is possible to follow in figures 37 and 38, respectively, the functional progress considering the availability or not of the technologies proposed as the game changer for the shape of alternatives proposed by the authors. They suggest that the IC is performed when the UUV reaches the surface to communicate. On the other hand, CC is constantly performed underwater through acoustic communication methods. The reader can find more details about this dedicated function in Chapter III of Camacho et al. (2017) capstone.

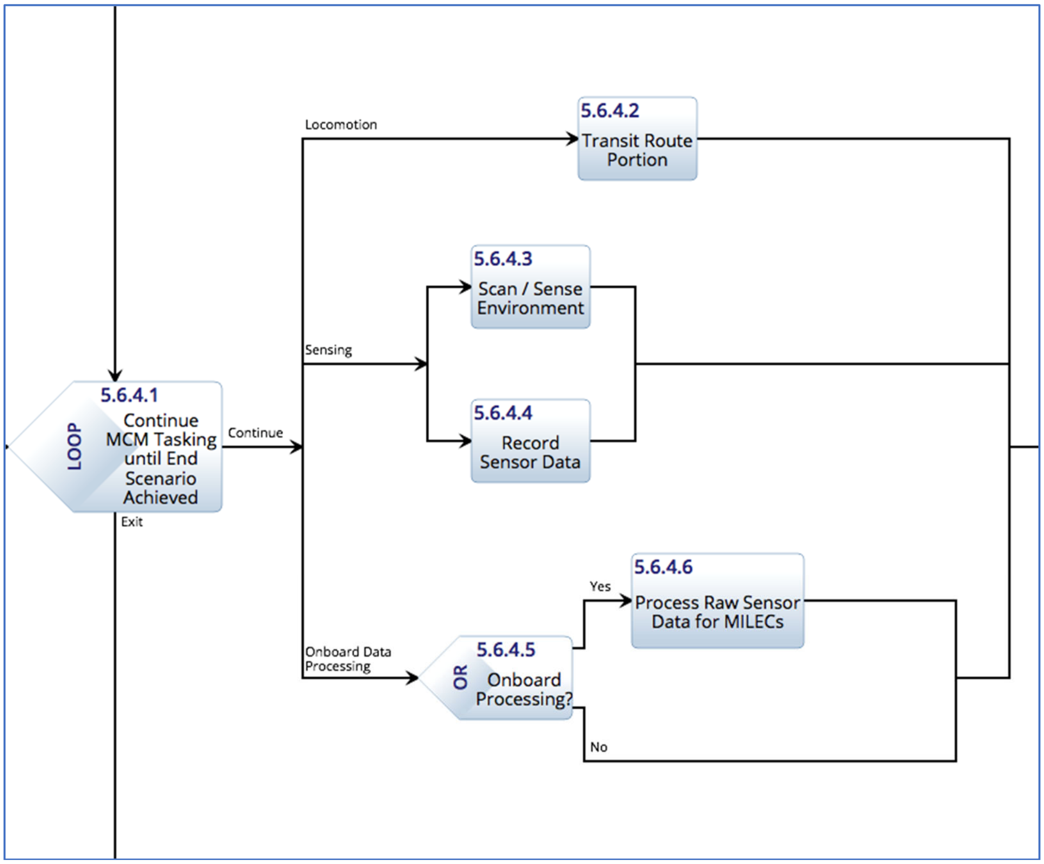


Figure 37. 5.6.4 Scan Target Area – Sensor Data Collection Portion. Source: Camacho et al. (2017).

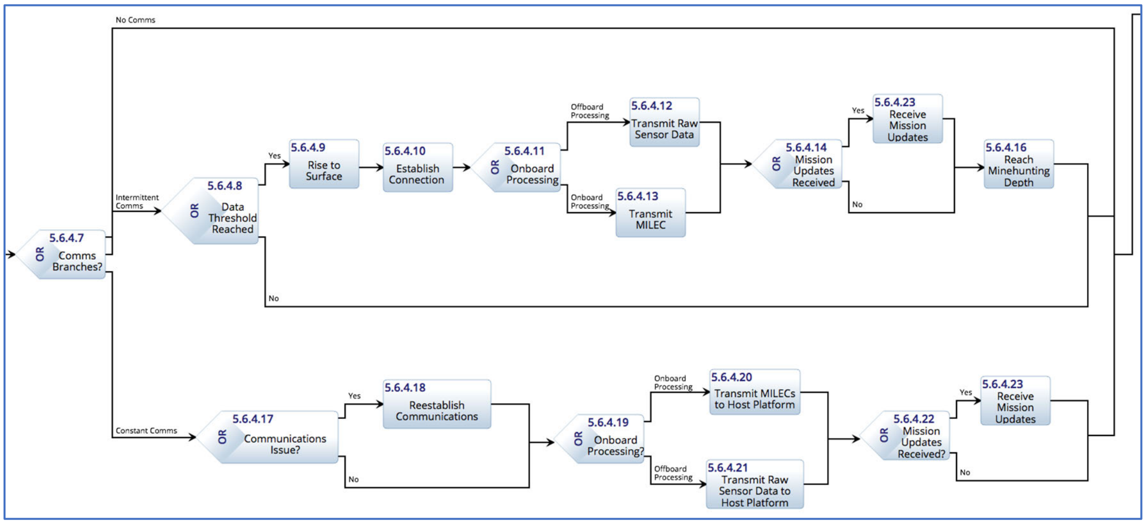


Figure 38. 5.6.4 Scan Target Area – Communication of Data. Source: Camacho et al. (2017).

C. SYSTEM VARIABILITY MODELING

The next step of this thesis methodology is the system variability modeling, which comes from software PLE. According to Pohl et al. (2005), that model captures the variability of domain requirements, architecture, components, and tests. In common language, variability refers to the ability or the tendency to change. As example they cite the electric bulb case, which can be turned on off. To characterize product line variability, the authors define two important concepts: “variability subject and object.” (p. 60). A variability subject is defined as “a variable item of the real world or a variable property of such an item.” (p. 60) That corresponds to the variation points (VP) within the product line. Instead, a variability object “is a particular instance of a variability subject” (p. 60) corresponding to variants for the product line.

As a simple example, a variability subject “color” (VP) has several variability objects (variants in the model), such as ‘red,’ ‘blue,’ ‘green,’ etc., as demonstrated in Figure 39. Pohl et al. (2005) systematically identify variation points and variants through three basic actions. The first step is identifying the elements of the real world that vary; then outlining the VP based on the real-world variability from the system architecture. Finally, the last stage is defining the set of variants associated with the VPs supplementing their information.

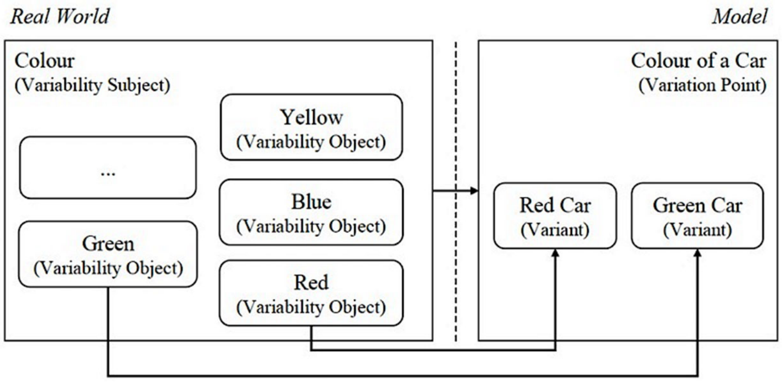


Figure 39. Variability in the Real World vs. Model. Source: Pohl et al. (2005).

1. Defining Variability in Textual Requirements

Through the analysis of the six next-generation MCM UVVs architectures studied by Camacho et al. (2017), this thesis identified five variation points for further decomposition and component allocation.

Pohl et al. (2005, p. 91) specify that "a model defines an abstraction of a system at a chosen level of detail from a particular viewpoint." In this way, the variability of requirements is systematically recorded, supporting the important feature of traceability among different types of artifacts. In this section, the textual requirements that enable greater accuracy in developing OVMs were defined. These requirements were based on those developed by Camacho et al. (2017) and Haller et al. (2022) for MCM UUVs. The criterion used to identify the requirements was based on the works mentioned. Two of them, the communications and the data processing subsystems, play a key role, as they work as drivers to variations among the alternatives in this research. The remain subsystems (Navigation, Locomotion, Localization) were selected because they are crucial for the operation of the UUVs for the execution of the studied mission.

Variation points provide the top-level components, while variants provide the second-level components in the physical hierarchy. The tables from this step requirements relating each VP with the textual and its related variants will be presented in the next chapter of this thesis.

2. Variation Points Decomposition and Components Identification

After obtaining a set of data from incorporating the textual variability requirements allocated to each variation point, components or a set of potential components were identified. The identification of these components was carried out with the contribution of LT Casares, an engineer at the Brazilian Navy, Master's student in Naval Architecture and Marine Engineering at the University of Michigan.

Subsequently, the components/set of components were associated with the six potential architectures, the baseline, and five alternatives developed under the product line approach. The objective is to identify the demand for those components across the alternatives and provide the baseline knowledge for the next step of the analysis.

3. Orthogonal Variability Model (OVM)

The concept of orthogonal variability model comes from the software engineering. Pohl et al. (2005, p. 75) as "a model that defines the variability of a software/system product line." Through a graphical notation, the OVM exposes the variability in the product line (Figure 40). This notation makes it possible to define the dependencies in terms of variability, an important feature of the relationship between VP and variants. Pohl et al. (2005) argue that this relationship obeys some conditions. This way, a VP can be associated with a single variant or offer several. Similarly, a variant can be associated with only one VP or different ones. It is also important to note that all VPs must always be associated with at least one variant. In the same way, all variants must be related to at least one VP.

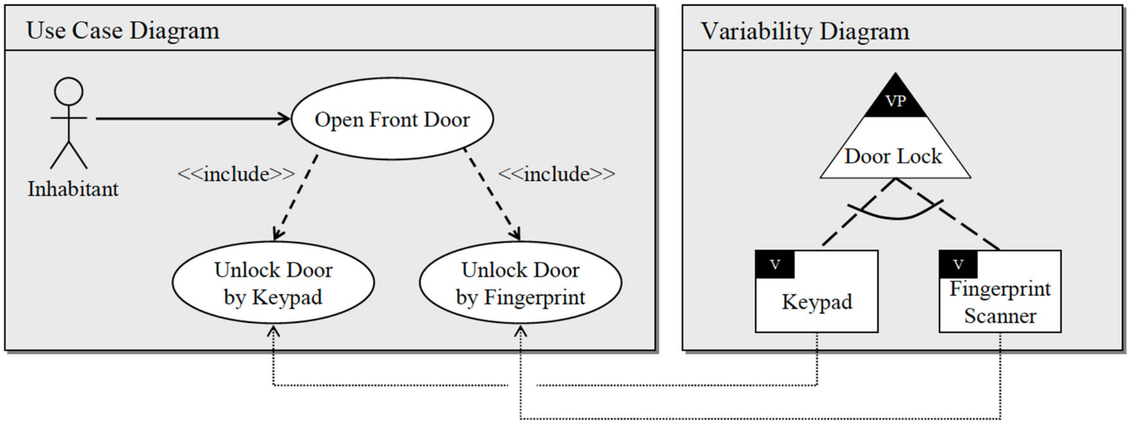


Figure 40. Example of Orthogonal Variability Modeling. Source: Pohl et al. (2005).

The relationship between variants and their VPs may be either mandatory or optional variability dependence. The first one occurs when a variant can only be selected if the VP to which it is associated is part of the application. On the other hand, the second is associated with those cases in which a variant may or may not be part of a PL application, that is, optionally (Pohl et al., 2005). The OVM notation is presented in Figure 41.

Pohl et al. (2005) also present two types of constraint dependence relationships when two variants are analyzed. The first, called "variant requires variant" (requires_V_V), occurs when the selection of a variant (V1) makes the selection of another variant (V2) mandatory. The second occurs when the selection of one variant (V1) automatically excludes the selection of another variant (V2); this is known as "variant excludes variant" (excludes_V_V). It should be noted that these dependency relationships are established independently of the variation points to which the variants are associated. Figure 41 shows the dashed lines between the sensors' variation point and each variant represent the "optional" variability dependency. Here, these variants are relevant to the alternatives proposed by Camacho et al. (2017).

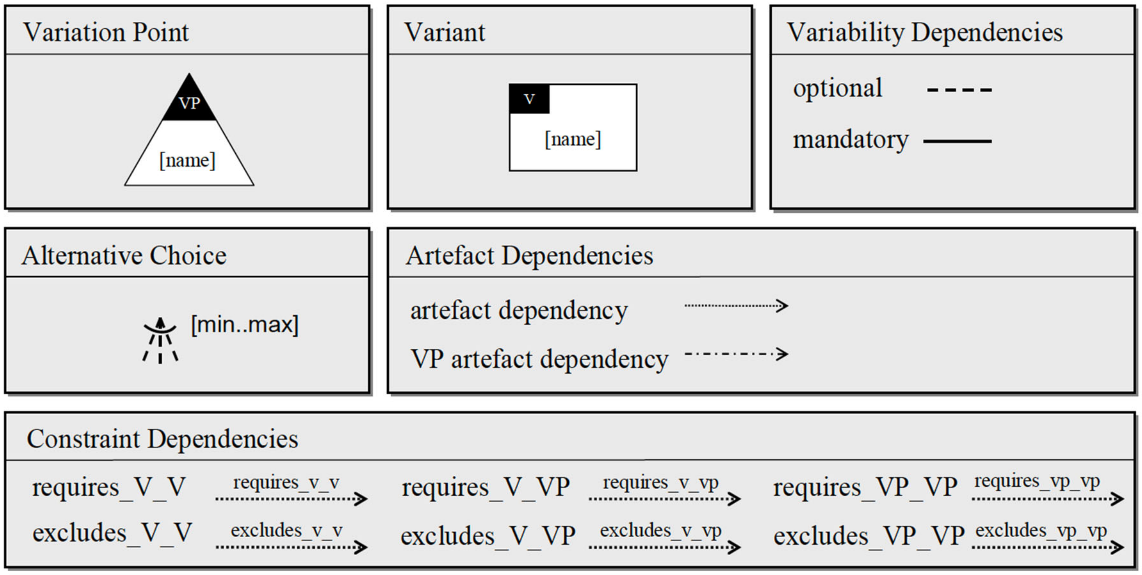


Figure 41. Graphical Notation for Variability Models. Source: Pohl et al. (2005).

OVMs for variation points highlight alternative variant choices as well as variability dependencies. In this step, each of the five points of variation and the proposed alternatives were combined to produce the OVM product line. This OVM product line allows to drill down into constraint dependencies for variants and VPs. In this way, it provides a common model to determine which variation points and variants would be needed for each alternative that constitutes the MCM UUV product line.

Then the six possible architectures for next-generation MCM UUVs were exposed in OVM diagrams, presenting optional variants associated with five subsystems UUVs, described as variation points.

The proposed baseline architecture chosen in this study to the next-generation MCM UUVs (alternative 1), is characterized by the absence of remote communication capability and the absence of on-board data processing capacity. This architecture was the *status quo* technology when Camacho et al. (2017) conducted their research. This alternative includes constraint dependencies (see Figure 41 – graphical notation) associated with those two main system capabilities in terms of communication and data processing subsystems

D. EXPECTED REUSE CATEGORY PERCENTAGES

After identifying the components, this thesis performed an individual analysis in order to obtain their classification regarding their reusability throughout the six MCM UUV architecture alternatives. Concomitantly, rationales were defined to clarify their categorization as reused, adapted, or mission unique.

After that, it was possible to identify which components were present in each alternative. In this route, this study determined how many components were present through alternatives, and finally, the number of components reused, adapted, and mission unique. These numbers were then transformed into percentages that later served as input parameters to calculate the system equivalent sizes in the economic analysis.

E. ECONOMIC ANALYSIS

1. System Constructive Product Line Investment Model

The basic COPLIMO uses the average product size (AVSIZE) as the first input parameter, when assessing a software. This is an estimate of the number of source lines of code (SLOC) produced by a software project. The basic model assumes that all systems are of the same average size or cost and are also homogeneous with reference to the reuse portions. Thus, every successive product contributes equivalent ROI and is the same size (Madachy, email to author, July 25, 2022).

When assessing software, the basic COPLIMO uses the average product size (AVSIZE) as the first input parameter. The size parameter estimates the number of source lines of code (SLOC) produced by a software project. The basic model assumes that all systems are the same average size or cost and are also homogeneous concerning the reuse portions. Hence, every successive product contributes equivalent ROI and is the same size (Madachy, email to author, July 25, 2022).

Using a detailed reuse model based on COPLIMO focusing on hardware components, this thesis overlaps that limitation since it assessed the variations among each of the six alternatives via COPLIMO reused parameters. This study accounted for their differences providing much more information for systems acquisition decision-making.

The COPLIMO manual (n.d.) exposes the core input parameters (percentages) considered for the system ROI analysis: Uniq%, Adap% and Ruse%. Respectively they mean the system portion unique components to each application, the system portion adapted components from product line, and the system portion designed for reuse, that is, as an intact black box. The percentages obtained in the previous step were used to feed the model.

2. Detailed Reuse Model based on COPLIMO

This detailed reuse model provided the capacity to explore each of the six alternatives (the baseline system and five additional products) in the product line since it was possible to obtain the reuse classification of the system's components.

Product line percentages for the six MCM UUVs architecture alternatives were determined using countable system components (variants). Then, the variants were organized by variation points with rationale for their classification as mission unique, adapted, or reused across alternatives. The alternatives were used as the parametric inputs for the detailed reuse model.

Another essential input parameter is the expected relative percentages of costs to reuse (RCR), which reflect the initial investment in the product line model, responsible for 100% of a mission's unique component. Those percentages represent the cost to reuse the system component in a new product line family application relative to developing a newly built component. The basic COPLIMO tool uses 40% as a typical value of RCR-Adap and 5% for RCR-Ruse.

The last and an important input parameter considered in the basic COPLIMO model is the relative cost of writing for reuse, RCWR, renamed in this study as the relative cost of development for reuse, RCDR. In software engineering, that parameter represents the multiplicative factor determining the total cost of writing software to achieve better cost-effectiveness through a product line family of applications compared to single application development. Across the systems engineering perspective it denotes the additional effort/ cost required to generalize the architecture and design, validating the reused components will work across the product line. Before exploring a sensitivity analysis, this thesis considered a hypothetical RCDR of 1.70, representing 70% additional effort/cost in comparison to a non-product line system.

To calculate the economic benefit of using a product line approach, the basic COPLIMO uses the product equivalent size measure to compare the effort/cost of the components developed for reuse vs. components developed as a stovepipe approach. While that model uses the average size (μ) in Equation 1 to find the product equivalent size (PES), this detailed model employs the number of components estimated through five subsystems (communication, data processing, locomotion, navigation, sensors, and data collection) explored across six architecture alternatives proposed for the future MCM UUVs.

$$PES = \mu * Uniq\,\% + \mu * Adap\% * RCR(Adap) + \mu * Ruse\% * RCR(Reuse) \qquad (1)$$

where μ = Average Size.

In this way, it was possible to determine the net savings in effort/cost and the accumulated savings in effort/cost. Then, the ROI index was determined as well as the accumulated ROI through these six alternatives.

3. Sensitivity Analysis

As the reuse model initially used the COPLIMO standard up-front investment value, 1,7 (70%), this thesis also explores a sensitive analysis comparing the effects of the RCDR variation in order to expand the analysis regarding the differences in ROI results. This analysis was conducted by entering different RCDR, 1.5 (50%), 1.6 (60%), and 1.8 (80%).

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IV. RESULTS AND DISCUSSION

A. SYSTEM VARIABILITY MODELING

1. Variability in Textual Requirements

As described in section C of the previous chapter, from the VPs and the textual requirements associated with each of them, the variations of each VP were determined, which are listed below in Table 3 to Table 7.

Table 3. Communication Variation Point Textual Requirements

Variation Point A (VPA)	The UUV's communication components shall have the ability to...
Variation A1 (VA1)	1.0.1 upload mission requirements
Variation A2 (VA2)	1.0.2 allow remote communications on surface
Variation A3 (VA3)	1.0.3 allow remote communications underwater
Variation A4 (VA4)	1.0.4 start the mission when commanded
Variation A5 (VA5)	1.0.5 allow manual download (All versions can have this capability)
Variation A6 (VA6)	1.0.6 allow surface data transfer (IC)
Variation A7 (VA7)	1.0.7 or allow sub-surface data transfer (CC)

Table 4. Data Processing System Variation Point Textual Requirements

Variation Point B (VPB)	The data processing system shall have the ability to...
Variation B1 (VB1)	1.1.1 process the data on-board (RTA)
Variation B2 (VB2)	1.1.2 process the data off-board

Table 5. Locomotion Variation Point Textual Requirements

Variation Point C (VPC)	The UUV locomotion shall be capable to...
Variation C1 (VC1)	1.2.1 complete a mission of *xx* duration
Variation C2 (VC2)	1.2.2 develop a top speed of *xx* knots
Variation C3 (VC3)	1.2.3 rise to surface from mine hunting depth in a *xx* time
Variation C4 (VC4)	1.2.4 dive to mine hunting depth from surface in a *xx* time

Table 6. Navigation System Variation Point Textual Requirements

Variation Point D (VPD)	The UUV’s navigation system shall be capable to…
Variation D1 (VD1)	1.3.1 know its geographic location when navigating on surface
Variation D2 (VD2)	1.3.2 know its geographic location when navigating underwater
Variation D3 (VD3)	1.3.3 open ocean navigation
Variation D4 (VD4)	1.3.4 store waypoints
Variation D5 (VD5)	1.3.5 contain obstacle avoidance software capable of avoiding obstacles of xx size within yy distance
Variation D6 (VD6)	1.3.6 perform returning to its point of deployment at mission conclusion
Variation D7 (VD7)	1.3.7 conduct to a specific location when commanded

Table 7. Data Collection’s Sensors Variation Points Textual Requirements

Variation Point E (VPE)	The data collection’s sensors shall be capable to…
Variation E1 (VE1)	1.4.1 discern between an emission and background noise
Variation E2 (VE2)	1.4.2 track contacts
Variation E3 (VE3)	1.4.3 detecting mines of xx size from yy distance (on board)
Variation E4 (VE4)	1.4.4 detecting mines of xx size from yy distance (off board)
Variation E5 (VE5)	1.4.5 cover a search area of xx dimension
Variation E6 (VE6)	1.4.6 collect data while searching
Variation E7 (VE7)	1.4.7 search for targets at a UUV's top speed xx

2. Variation Points Decomposition and Components Identification

Table 8 shows the data set resulting from the association of the variants related to each VP with their respective requirements and the components or set of components related to it. When more than one component (set) was associated with a variation, it was only considered a new identification/classification if at least one new component was added. On the other hand, when a requirement/variant was met by a component/set that was previously indicated (it meets more than one variation), there was no insertion of a new one. Table 9 shows the demand for components for each of the alternatives. As explained above, the N/A (not applicable) classification was attributed to some components not considered new.

Table 8. Textual Requirements and Components Identification

Variations	Requirements to Conduct MCM UUV Mission	Components or set of components	Component/Set of Components Description
Variation Point A (VPA)	Communication (1.0)		
VA1	1.0.1 upload mission requirements	C1	[Vehicle Interface Program (VIP) + Embbeded Computer]
VA2	1.0.2 allow remote communications on surface	C2	[Wifi Antenna + SatCom]
VA3	1.0.3 allow remote communications underwater	C3	Acoustic modem
VA4	1.0.4 start the mission when commanded	C4	RF
VA5	1.0.5 allow manual download (All versions can have this capability)	C5	Interface (USB)
VA6	1.0.6 allow surface data transfer (IC)	C2	[Wifi Antenna + SatCom]
VA7	1.0.7 or allow sub-surface data transfer (CC)	C3	Acoustic modem
Variation Point B (VPB)	Data Processing Location (1.1)		
VB1	1.1.1 process the data on-board (RTA)	C6	[Dedicated Embbeded Computer + VIP]
VB2	1.1.2 process the data off-board	C7	[Embbeded Hard Disk + VIP]
Variation Point C (VPC)	Locomotion (1.2)		
VC1	1.2.1 complete a mission of xx duration	C8	[Lithium ion batteries + energy distribution system (bus/wire system)]
VC2	1.2.2 develop a top speed of xx knots	C9	[C8 + Hull + Motor + Thruster + Embbeded Computer]
VC3	1.2.3 rise to surface from mine hunting depth in a xx time	C10	[C9 + Ballast management/Control Planes]
VC4	1.2.4 dive to mine hunting depth from surface in a xx time		
Variation Point D (VPD)	Navigation (1.3)		
VD1	1.3.1 know its geographic location when navigating on surface	C11	GPS
VD2	1.3.2 know its geographic location when navigating underwater	C12	Inertial Navigation System (INS) + Doppler Velocity Log (DVL) + USBL
VD3	1.3.3 open ocean navigation	C13	C1 + C12 + (C8/C9/C10) + CTD (conductivity, temperature & depth)
VD4	1.3.4 store waypoints	C14	C1 + Positioning Storage Program
VD5	1.3.5 contain obstacle avoidance software capable of avoiding obstacles of xx size within yy distance	C15	[Forward looking sonar + altimeter + preprogrammed maneuver in software]
VD6	1.3.6 perform returning to its point of deployment at mission conclusion		C1 + (C8/C9/C10) + C12
VD7	1.3.7 conduct to a specific location when commanded		C1 + C2 + (C8/C9/C10) + C12
Variation Point E (VPE)	Sensors and Data collection (1.4)		
VE1	1.4.1 discern between an emission and background noise	C16	Multibeam Sonar
VE2	1.4.2 track contacts	C17	Multibeam Sonar + Side Scan Sonar + software tool
VE3	1.4.3 detecting mines of xx size from yy distance (on board)	C18	Multibeam Sonar + Side Scan Sonar/Synthetic Aperture Sonar (SAS) + software tools
VE4	1.4.4 detecting mines of xx size from yy distance (off board)	C19	Multibeam Sonar + Side Scan Sonar/Synthetic Aperture Sonar (SAS)
VE5	1.4.5 cover a search area of xx dimension	C20	Multibeam Sonar + Side Scan Sonar
VE6	1.4.6 collect data while searching		Multibeam Sonar + Side Scan Sonar
VE7	1.4.7 search for targets at a UUV's top speed xx		Multibeam Sonar + Side Scan Sonar

Table 9. Components vs. Architecture Alternatives

Components or set of components	Requirements to Conduct MCM UUV Mission	Alternative 1/Baseline (NC + Off-board)	Alternative 2 (IC + Off-board)	Alternative 3 (CC + Off-board)	Alternative 4 (NC + On-board)	Alternative 5 (IC + On-board)	Alternative 6 (CC + On-board)
Communication (1.0)							
C1	1.0.1 upload mission requirements	X	X	X	X	X	X
C2	1.0.2 allow remote communications on surface		X	X		X	X
C3	1.0.3 allow remote communications underwater			X			X
C4	1.0.4 start the mission when commanded	X	X	X	X	X	X
C5	1.0.5 allow manual download (All versions can have this capability)	X	X	X	X	X	X
C2	1.0.6 allow surface data transfer (IC)	N/A	N/A	N/A	N/A	N/A	N/A
C3	1.0.7 or allow sub-surface data transfer (CC)	N/A	N/A	N/A	N/A	N/A	N/A
Data Processing Location (1.1)							
C6	1.1.1 process the data on-board (RTA)				X	X	X
C7	1.1.2 process the data off-board	X	X	X	X	X	X
Locomotion (1.2)							
C8	1.2.1 complete a mission of xx duration	X	X	X	X	X	X
C9	1.2.2 develop a top speed of xx knots	X	X	X	X	X	X
C10	1.2.3 rise to surface from mine hunting depth in a xx time	X	X	X	X	X	X
	1.2.4 dive to mine hunting depth from surface in a xx time		X	X	X	X	X
Navigation (1.3)							
C11	1.3.1 know its geographic location when navigating on surface	X	X	X	X	X	X
C12	1.3.2 know its geographic location when navigating underwater	X	X	X	X	X	X
C13	1.3.3 open ocean navigation	X	X	X	X	X	X
C14	1.3.4 store waypoints	X	X	X	X	X	X
C15	1.3.5 contain obstacle avoidance software capable of avoiding obstacles of xx size within yy distance	X	X	X	X	X	X
	1.3.6 perform returning to its point of deployment at mission conclusion	N/A	N/A	N/A	N/A	N/A	N/A
	1.3.7 conduct to a specific location when commanded	N/A	N/A	N/A	N/A	N/A	N/A
Sensors and Data collection (1.4)							
C16	1.4.1 discern between an emission and background noise	X	X	X	X	X	X
C17	1.4.2 track contacts	X	X	X	X	X	X
C18	1.4.3 detecting mines of xx size from yy distance (on board)				X	X	X
C19	1.4.4 detecting mines of xx size from yy distance (off board)	X	X	X			
C20	1.4.5 cover a search area of xx dimension	X	X	X	X	X	X
	1.4.6 collect data while searching	N/A	N/A	N/A	N/A	N/A	N/A
	1.4.7 search for targets at a UUV's top speed xx	N/A	N/A	N/A	N/A	N/A	N/A

3. Orthogonal Variability Modeling

The first OVM diagram depicts the baseline MCM UUV plus five alternative choices that constitute the proposed product line (Figure 42).

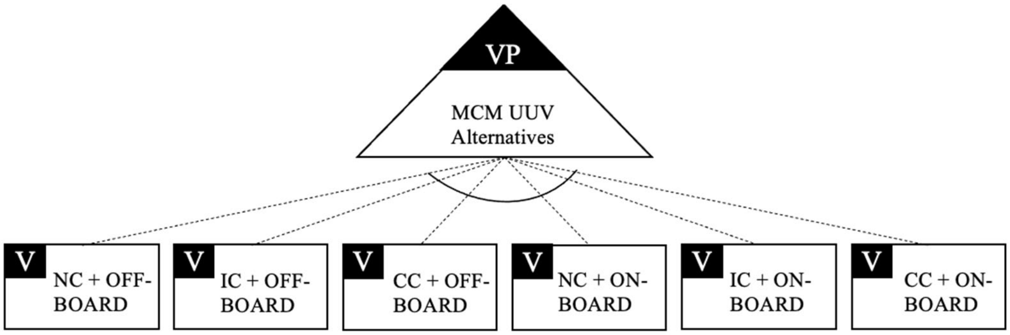


Figure 42. Systems Alternatives as Variants of MCM UUVs

After exposing the six possible architectures to next-generation MCM UUVs in OVM diagrams, this study presented optional variants (components previously identified in Table 9) associated with five UUVs subsystems, described as variations points, resulting in another five OVM diagrams which are shown from Figure 43 to Figure 47.

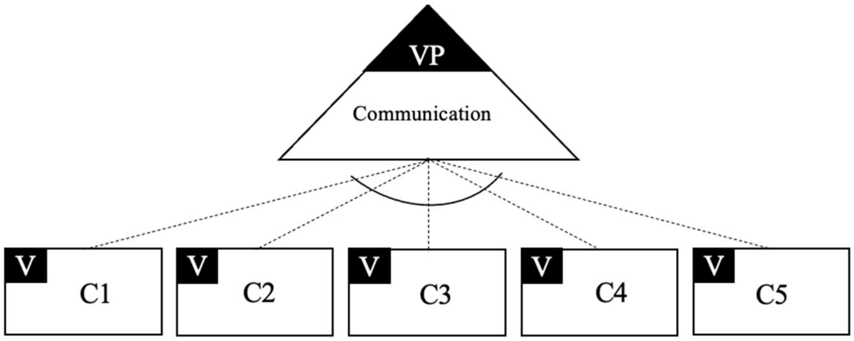


Figure 43. Communication Variation Point OVM

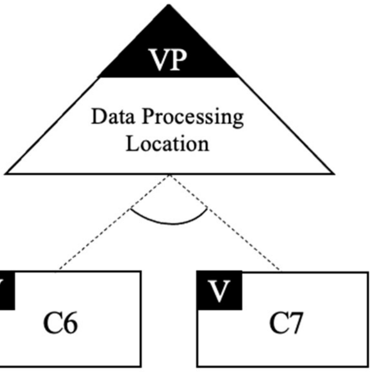


Figure 44. Data Processing Location Variation Point OVM

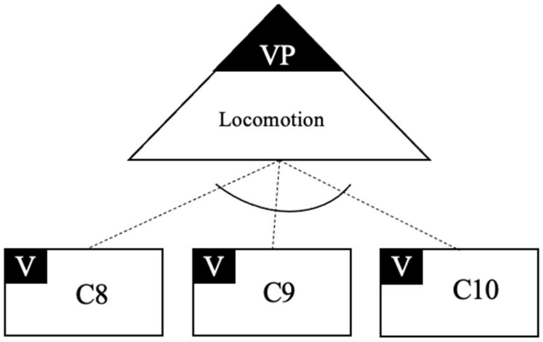


Figure 45. Locomotion Variation Point OVM

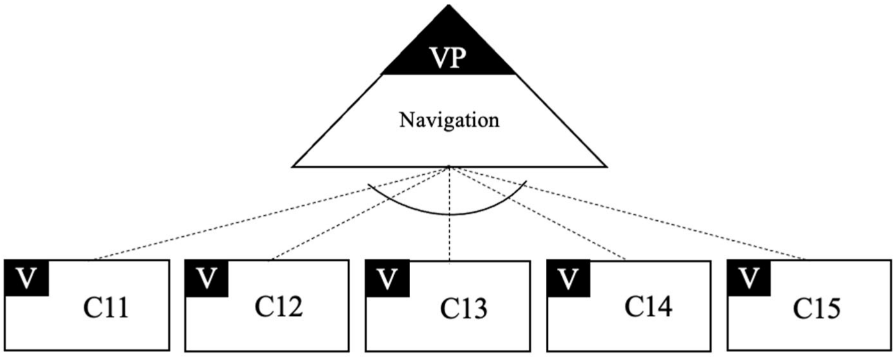


Figure 46. Navigation Variation Point OVM

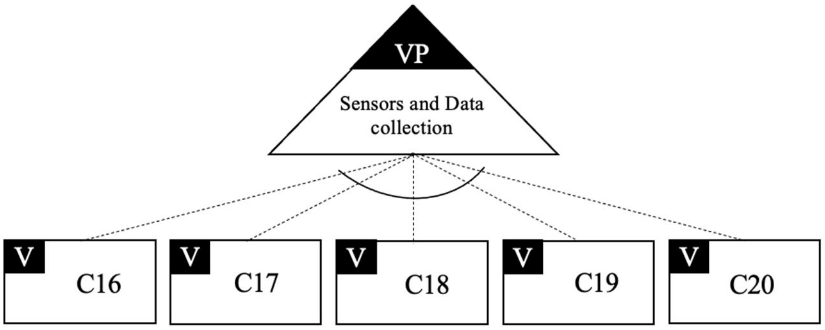


Figure 47. Sensors and Data Collection Variation Point OVM

Figure 48 exposes the entire next-generation MCM UUV Product Line OVM and the constraint dependencies across variants and variation points explained in Chapter III, section C, item 3. The information previously depicted in Table 9 is so organized under the OVM structure, demonstrating the constraint dependencies among them through the interconnection among the components and driven by the alternatives, defined here as VPs.

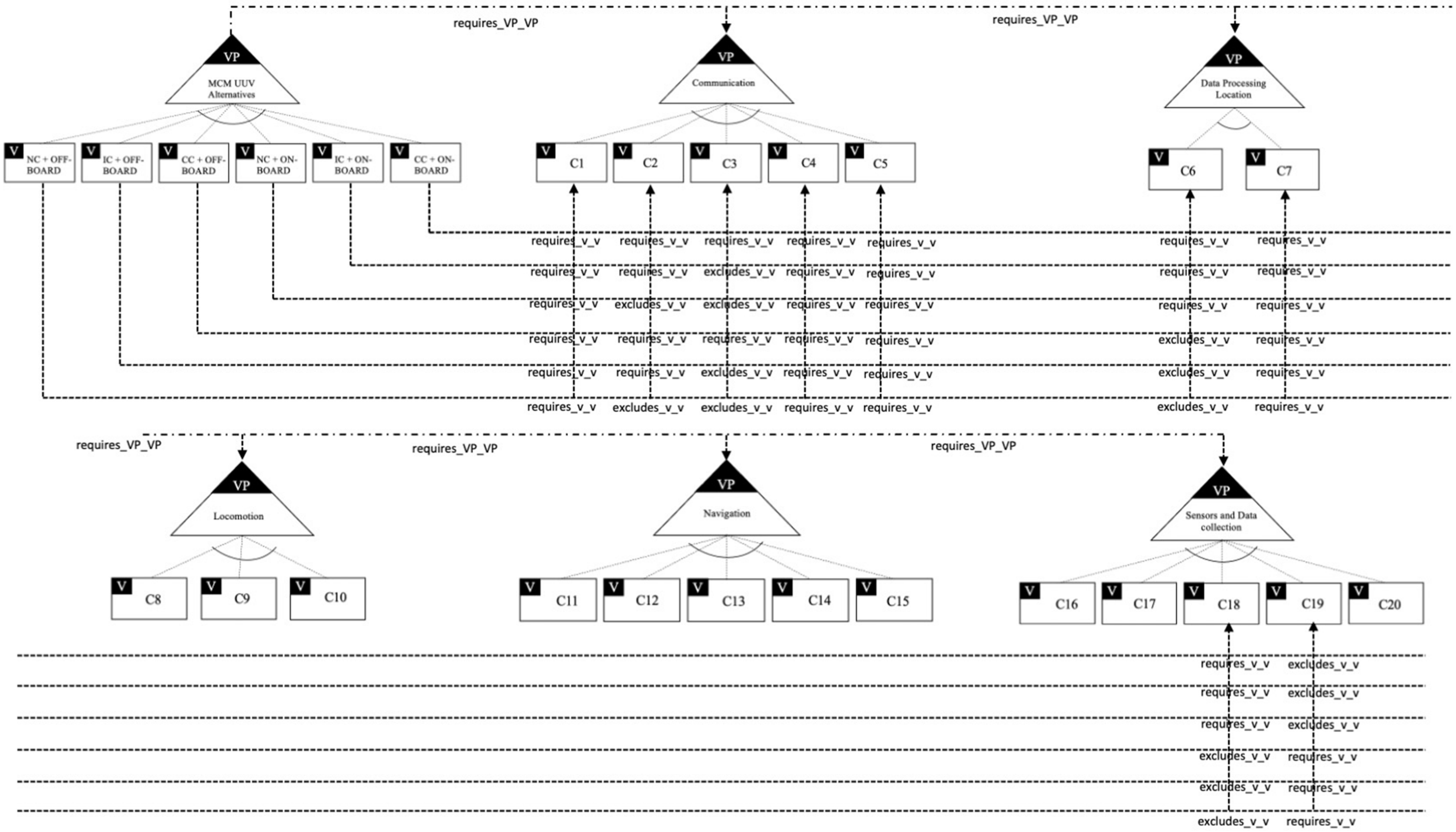


Figure 48. Next-generation Mine Countermeasure UUV Product Line Orthogonal Variability Model

B. EXPECTED REUSE CATEGORY PERCENTAGES

From the data extracted from previously Tables 8 and 9, and Figure 48, the twenty variants were organized by variation point listed in Table 10 with rationale for their classification as mission unique, adapted, or reused across alternatives.

The classification follows the definition of the basic COPLIMO, as detailed in Chapter III, and then will serve as a basis for calculating the percentages that will serve as input for the reuse model to determine the ROI of this approach for MCM UUVs. Each component or set of components was meticulously detailed in order to clarify commonalities and variabilities by a justified classification.

Table 10. Product Line Classification

	Component	Product Line Classification	Rationale
VPA: Communication			
C1	[Vehicle Interface Program (VIP) + Embbeded Computer]	Reused	Hardware and Software common to all alternatives.
C2	[Wifi Antenna + SatCom]	Adapted	The set of communication components is present in the alternatives with IC and CC but the capacity can be specified by the different demands of each system.
C3	Acoustic modem	Mission Unique	Underwater remote communication is only present in CC alternatives.
C4	RF	Reused	As the most basic comm resource, all alternatives must have the ability to start the mission when commanded by RF
C5	Interface (USB)	Reused	All alternatives must allow manual download even if they have remote data transfer.
VPB: Processing Location			
C6	[Dedicated Embbeded Computer + VIP]	Mission Unique	It is necessary to add this set of components [Dedicated Embbeded Computer + VIP] only when there is on-board data processing
C7	[Embbeded Hard Disk + VIP]	Reused	All alternatives must be able to store data in case of need for off-board processing even though they have on-board processing capability.
VPC: Locomotion			
C8	[Lithium ion batteries + energy distribution system (bus/wire system)]	Adapted	This set of communication components is present in all alternatives, but the characteristics of each of the analyzed combinations generate different demands that require adaptation.
C9	[C8 + Hull + Motor + Thruster + Embbeded Computer]	Adapted	See C8 justification.
C10	[C9 + Ballast management/Control Planes]	Adapted	See C8 justification.
VPD: Navigation			
C11	GPS	Reused	All alternatives must have a GPS to know its geographic location when navigating on surface.
C12	Inertial Navigation System (INS) + Doppler Velocity Log (DVL) + USBL	Reused	All alternatives must have a these components added to know its geographic location when navigating underwater.
C13	C1 + C12 + (C8/C9/C10) + CTD (conductivity, temperature & depth)	Reused	All alternatives must have CTD associated with the other set of components mentioned to allow open ocean navigation.
C14	C1 + Positioning Storage Program	Reused	All alternatives must have a Positioning Storage Program to store their waypoints.
C15	[Forward looking sonar + altimeter + preprogrammed maneuver in software]	Reused	This set of components [Forward looking sonar + altimeter + preprogrammed maneuver in software] must be present in all alternatives so that obstacles can be avoided.
VPE: Sensors and Data collection			
C16	Multibeam Sonar	Reused	All alternatives must have the ability to discern between an emission and background noise through this sonar.
C17	Multibeam Sonar + Side Scan Sonar + software tool	Reused	The association of these two types of sonar and the use of software suitable for the operation of both must be present in all alternatives so that they can track contacts.
C18	Multibeam Sonar + Side Scan Sonar/Synthetic Aperture Sonar (SAS) + software tools	Mission Unique	For mines to be detected and identified on-board, in addition to the association of the three types of sonar, the related software must be added. These software will only be present in alternatives with on-board processing.
C19	Multibeam Sonar + Side Scan Sonar/Synthetic Aperture Sonar (SAS)	Mission Unique	For mines to be detected and identified off-board, a Synthetic Aperture Sonar (SAS) type sonar must be associated with the two mentioned above. This association is specific to alternatives with off-board data processing.
C20	Multibeam Sonar + Side Scan Sonar	Reused	The association of these two types of sonar and the use of software suitable for the operation of both must be present in all alternatives for the search in a certain area.

The detailed reuse model provided the capacity to explore each of the six alternatives through the reuse classification of the system's components, obtaining their total amounts and respective percentages. Tables 11 through 16 summarize the results in percentage terms, which were found across the six alternatives analyzed.

Table 11. Alternative 1 (Baseline) Product Line Percentages

Alternative 1 (System Baseline): Post-Mission Analysis [Status Quo] (16 Total Components or set of components)		
System Component Type	Count	Product Line Percentage
Reused	12	75.00%
Adapted	3	18.75%
Mission Unique	1	6.25%
Total	16	100.00%

Table 12. Alternative 2 Product Line Percentages

Alternative 2: IC with Off-board Data Analysis (17 Total Components or set of components)		
System Component Type	Count	Product Line Percentage
Reused	12	70.59%
Adapted	4	23.53%
Mission Unique	1	5.88%
Total	17	100.00%

Table 13. Alternative 3 Product Line Percentages

Alternative 3: CC with Off-board Data Analysis (18 Total Components or set of components)		
System Component Type	Count	Product Line Percentage
Reused	12	66.67%
Adapted	4	22.22%
Mission Unique	2	11.11%
Total	18	100.00%

Table 14. Alternative 4 Product Line Percentages

Alternative 4: RTA with Physical Transfer of MILECs (17 Total Components or set of components)		
System Component Type	Count	Product Line Percentage
Reused	12	70.59%
Adapted	3	17.65%
Mission Unique	2	11.76%
Total	17	100.00%

Table 15. Alternative 5 Product Line Percentages

Alternative 5: RTA with IC of MILECs (18 Total Components or set of components)		
System Component Type	Count	Product Line Percentage
Reused	12	66.67%
Adapted	4	22.22%
Mission Unique	2	11.11%
Total	18	100.00%

Table 16. Alternative 6 Product Line Percentages

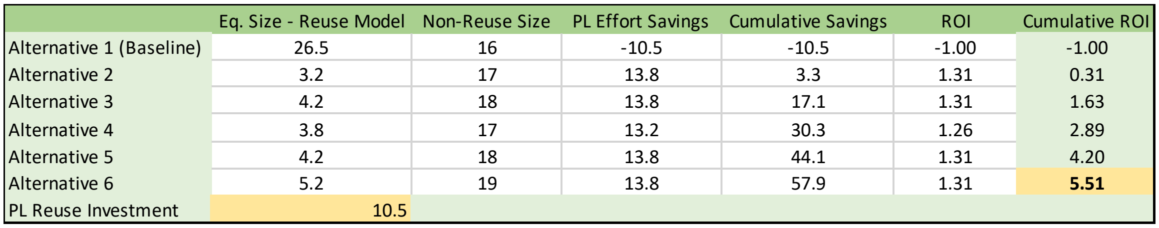
Alternative 6: RTA with CC of MILECs (19 Total Components or set of components)		
System Component Type	Count	Product Line Percentage
Reused	12	63.16%
Adapted	4	21.05%
Mission Unique	3	15.79%
Total	19	100.00%

C. ECONOMIC ANALYSIS

The PL investment in the baseline product reflects subsequent PL effort/costs across the five subsequent alternatives of approximately 14 in each product., representing an individual ROI of around 130% (Table 17). The break-even-point falls at the alternative 2, the second product in the proposed family of systems, culminating in a ROI of 551% across those 6 products through a PL approach. It demonstrates how relevant, from an effort/cost point of view, this approach can be impactful and reach savings during the life cycle of a family of systems, considering that it can generate future savings throughout the entire system's life cycle.

From the result of Equation 1 (chapter III), the product equivalent size was found for the six architecture alternatives proposed for the future MCM UUVs. The result of this calculation is shown in column 1 of Table 17. The second column represents the difference between the equivalent size vs. the non-reuse size, resulting in net effort/cost savings depicted in the third column. From that, it was possible to calculate the cumulative effort/cost savings (column 4). Then, the ROI index was obtained by dividing the net effort/cost saving by the PL reuse investment (column 5), and the sixth column depicts the cumulative ROI through those six alternatives.

Table 17. ROI Analysis for RCDR 1.7 through Six Architecture Alternatives



	Eq. Size - Reuse Model	Non-Reuse Size	PL Effort Savings	Cumulative Savings	ROI	Cumulative ROI
Alternative 1 (Baseline)	26.5	16	-10.5	-10.5	-1.00	-1.00
Alternative 2	3.2	17	13.8	3.3	1.31	0.31
Alternative 3	4.2	18	13.8	17.1	1.31	1.63
Alternative 4	3.8	17	13.2	30.3	1.26	2.89
Alternative 5	4.2	18	13.8	44.1	1.31	4.20
Alternative 6	5.2	19	13.8	57.9	1.31	**5.51**
PL Reuse Investment	10.5					

Figure 49 presents the reuse effort savings through the alternatives and Figure 50 focuses on the cumulative ROI.

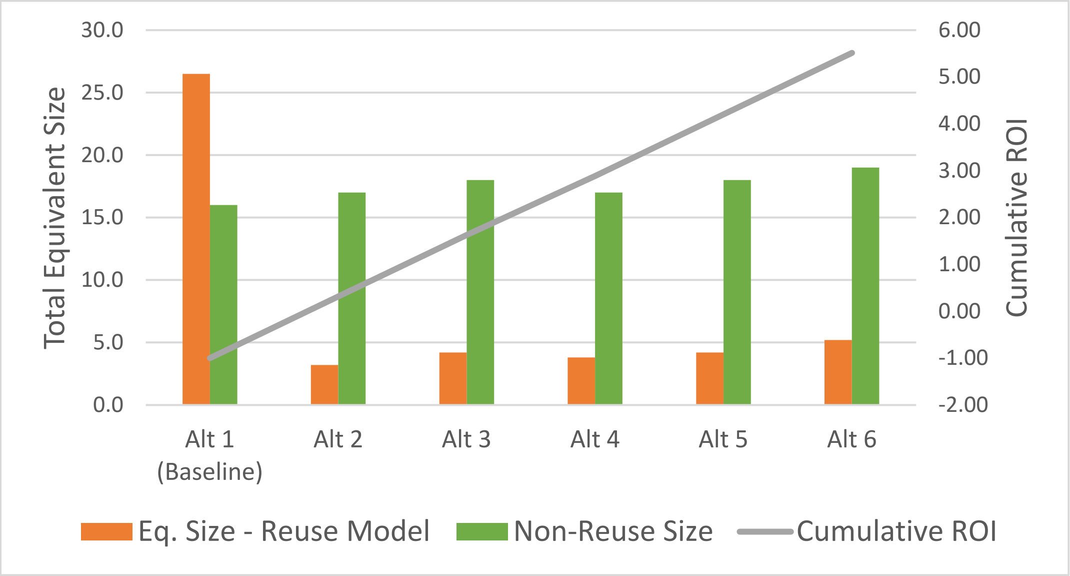


Figure 49. MCM UUV Reuse Effort Savings through the Alternatives

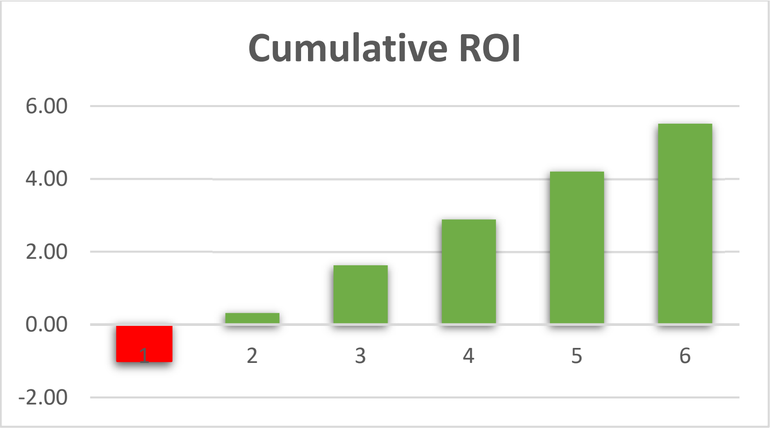


Figure 50. Cumulative ROI for RCDR 1.7

D. SENSITIVITY ANALYSIS

This section performs a sensitivity analysis proposing the variation of the RCDR and verifies how the outcomes of the detailed reuse model behaviors throughout the alternatives. It is possible to notice that the ROI index achieves nearly 800% (Table 18) when the RCDR is 1.5 (50% PL investment). Then, applying RCDR of 1.6 (60% PL investment) and 1.8 (80% PL investment) results in ROIs of 600% and 470%, respectively (Tables 19 and 20). The graphics shown in Figures 51, 52, and 53 represent the evolution of the cumulative ROI regarding the RCDR variations.

Table 18. ROI Analysis for RCDR 1.5 through Six Architecture Alternatives

	Eq. Size - Reuse Model	Non-Reuse Size	PL Effort Savings	Cumulative Savings	ROI	Cumulative ROI
Alternative 1 (Baseline)	23.50	16	-7.50	-7.50	-1.00	-1.00
Alternative 2	3.20	17	13.80	6.30	1.84	0.84
Alternative 3	4.20	18	13.80	20.10	1.84	2.68
Alternative 4	3.80	17	13.20	33.30	1.76	4.44
Alternative 5	4.20	18	13.80	47.10	1.84	6.28
Alternative 6	5.20	19	13.80	60.90	1.84	**8.12**
PL Reuse Investment	7.5					

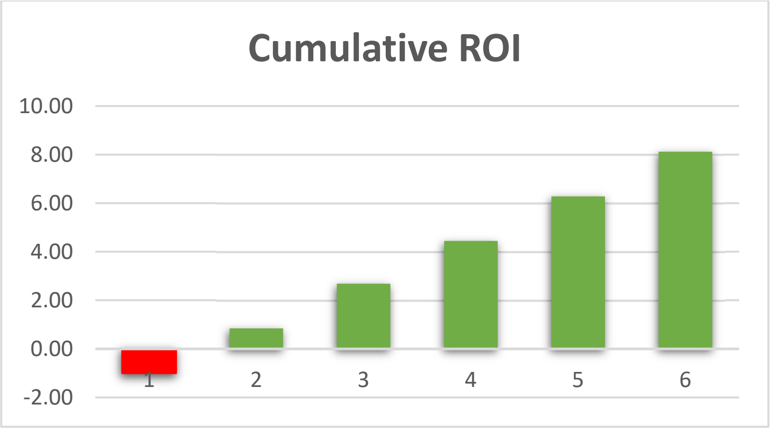
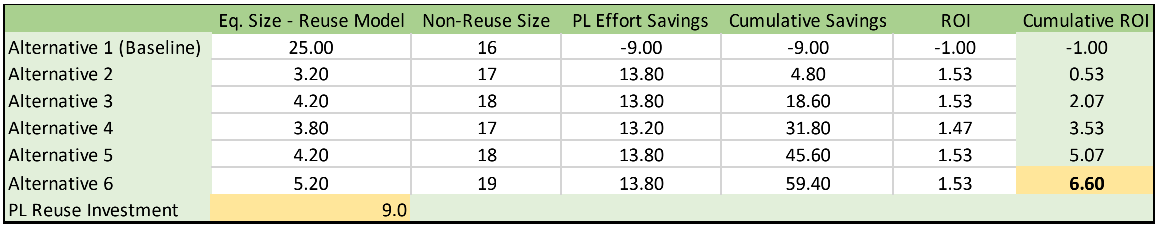


Figure 51. Cumulative ROI for RCDR 1.5

Table 19. ROI Analysis for RCDR 1.6 through Six Architecture Alternatives



	Eq. Size - Reuse Model	Non-Reuse Size	PL Effort Savings	Cumulative Savings	ROI	Cumulative ROI
Alternative 1 (Baseline)	25.00	16	-9.00	-9.00	-1.00	-1.00
Alternative 2	3.20	17	13.80	4.80	1.53	0.53
Alternative 3	4.20	18	13.80	18.60	1.53	2.07
Alternative 4	3.80	17	13.20	31.80	1.47	3.53
Alternative 5	4.20	18	13.80	45.60	1.53	5.07
Alternative 6	5.20	19	13.80	59.40	1.53	**6.60**
PL Reuse Investment	9.0					

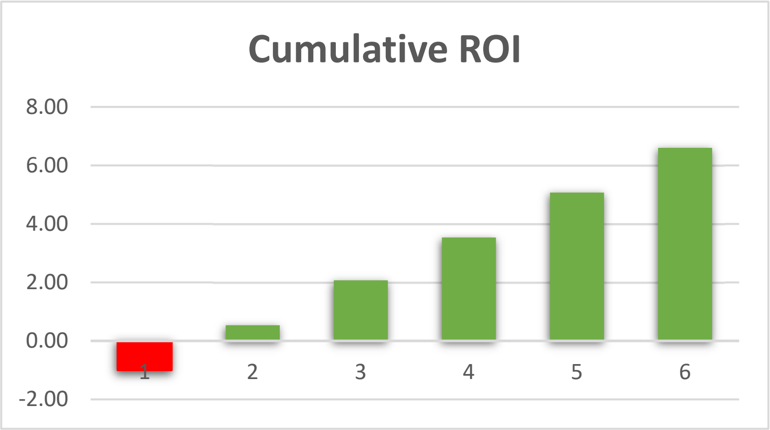
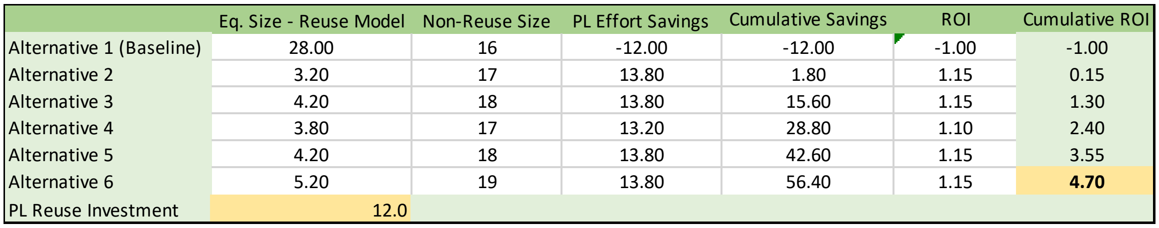


Figure 52. Cumulative ROI for RCDR 1.6

Table 20. ROI Analysis for RCDR 1.8 through Six Architecture Alternatives



	Eq. Size - Reuse Model	Non-Reuse Size	PL Effort Savings	Cumulative Savings	ROI	Cumulative ROI
Alternative 1 (Baseline)	28.00	16	-12.00	-12.00	-1.00	-1.00
Alternative 2	3.20	17	13.80	1.80	1.15	0.15
Alternative 3	4.20	18	13.80	15.60	1.15	1.30
Alternative 4	3.80	17	13.20	28.80	1.10	2.40
Alternative 5	4.20	18	13.80	42.60	1.15	3.55
Alternative 6	5.20	19	13.80	56.40	1.15	**4.70**
PL Reuse Investment	12.0					

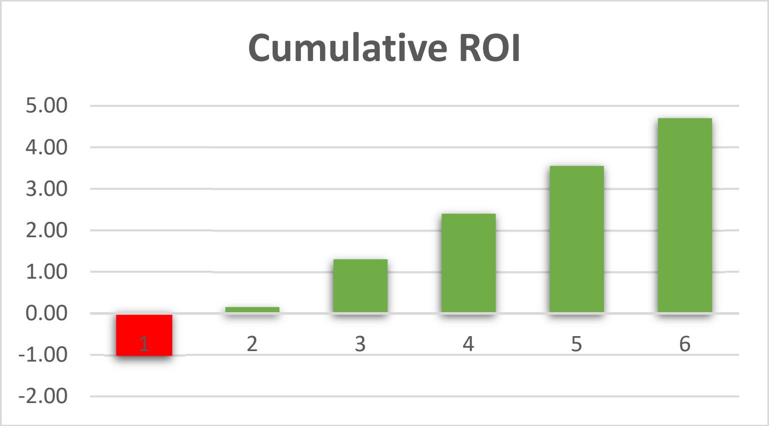


Figure 53. Cumulative ROI for RCDR 1.8

E. DISCUSSION

All alternatives presented positive and considerable ROI, most with equal values (alternatives 2, 3, 5, and 6), culminating in a break-even point in the second alternative developed in a proposed product line, regardless of the order chosen between the architectures. A slight exception appeared in alternative 4, which resulted in 5% lower than the others, in charge of the magnitude of 130%, making it a difference that can be considered negligible. Hence, the results support the idea that the cumulative ROI keeps a nearly linear behavior among the six alternatives, both in the primary and sensitive analyses. All alternatives proved to be viable to be part of a PL considering the different architectures of MCM UUVs studied.

Through the conduction of a sensitivity analyses, which tested an up-front investment variation between 1.5 (50%) and 1.8 (80%), the cumulative ROI result varies between 470% and 800%, proving valuable in this entire range of initial investment in the reusability approach. Even investing almost twice, what would be a hundred percent mission unique system's components, there is a relevant ROI in a family of products.

Although the concept of PL originally appeared in the private industry, the defense sector can benefit a lot during the process of engineering its systems, forming a mentality of commonality and reusability in order to promote, jointly with the contractors, the development of systems that meet that. Given the results obtained, the PL approach can provide the acquisition and development of defense systems, as the MCM UUV considered in this work, with great financial returns. Hence, there is great potential for savings over the system's life cycle, which in the defense environment can reach 50 years, since common components generate logistical and maintenance savings, in addition to being a team training facilitator. Particularly regarding the UUVs studied, such systems can be developed with a range of flexibility for use in different mission types, generating greater flexibility for the naval Force that operate them. From the earlier definition of the System requirements as well as the system architecture, the systems engineering team and the program manager can jointly enable the availability of more than one product, which can meet different kinds of concepts of operations with more than one configuration. However, what initially may seem like just a high investment to develop systems with a high level of commonality proves to be advantageous when the demand for different configurations rises, bringing even better results in cumulative ROI.

Although this study only explored the architectural alternatives of MCM UUV, that approach is not limited to those systems. Instead, it can be applied in distinct engineered systems such as aircraft, ships, submarines, etc. The defense sector often demands different configurations for a given system developed in order to meet needs in different concepts of operations. In this way, attributing this mentality to the formulation of the requirements and especially in the architecture phase of the defense systems can generate great savings in the total life cycle cost, in addition to great flexibility for the Service.

Integrating systems engineering and program management can provide several benefits to defense programs. The strategic association among PL approach, systems engineering, and program management approaches can benefit future defense programs, which demand a long development, then production and operation. A vision of flexibility still in the system's design phase will bring several future benefits, both in the economic sphere and in the effectiveness of operations since the defense sector may have available systems with similar and adaptable characteristics seeking to fulfill different missions. A reuse model falls between developing a fully standardized system without any flexibility and a system with a whole individualized shape. The approach allows planning the percentage of reuse and adaptability of components from the beginning.

V. CONCLUSION

A. SUMMARY

This research investigated the potential benefits of enlarging the product line architecture approach through the systems engineering process of the next-generation MCM UUVs. To achieve that, the study employed parametric cost modeling, some empirical data collected from recent research, and the demonstration of MBSE approach to verify potential economic savings through systems product line architecture. At the end, it is possible to answer the following questions proposed in the Introduction chapter:

Can the product line architecture approach benefit the development of the next generation MCM UUVs designs instead of using non-reusable systems/components?

From the analysis of hypothetical data about the next generation of MCM UUV, it was possible to conclude that yes.

Can potential technological changes/solutions be used as performance drivers in the analysis of MCM UUVs product line architecture?

Focusing on the two main subsystems previously proposed by Camacho et al., the data processing (on-board or off-board) and communication capabilities, it is possible to conclude that the technological variants did not have a relevant impact on the product line approach analysis. In this way, it suggests that the decisions of which order of alternatives must be prioritized should fall on the performance data achieved by the authors.

How can the OVM contribute to the product line strategy?

The tool allows an essential analysis of the relationships between the available/analyzed variants. Indeed, the OVM tool is even more relevant given the complexity of current systems since they have a very large number of possible variants. Thus, testing them through software that model in OVM is very useful for decision-making.

How can the product line approach be integrated into a parametric cost model in order to conduct a cost analysis and ROI assessment of MCM UUVs?

It was shown that integrating the two approaches can generate important benefits in cost analyses, especially in life cycle cost analyses. The ROI analysis can be expanded to the O&S phase, extending the study to logistics, maintenance, and training data.

What is the potential ROI for applying a product line architecture when developing MCM UUVs?

It was possible to obtain a wide range of ROI through the variation of the parameter of up-front investment in product line/reusability. The lowest individual ROI obtained was that of alternative 4, with an RCDR of 1.8, resulting in 110%. The highest ROI was achieved by alternatives 2, 3, 5, and 6 with an RCDR of 1.5, resulting in 185%.

B. RECOMMENDATIONS

Analyze the Impact of the PL Approach into MCM UUV’s Life Cycle Costs

Comparatively and on average, 68% of the total LCC of an unmanned aerial vehicle (UAV), as previously exposed in Chapter II, section F, occurred during the O&S phase of the system, and only 12% occurred during the RDT&E phase. It is widely known that maintenance, training, and sustainment expenses are the major costs during the system operations phase. All these factors are directly related to the components present in the system. This way, the savings evaluated by this research can be potentially enhanced during the O&S phase, maybe facilitated by the supply chain of common items to the entire family of systems in operation through most variable mission types. This way, future research can amplify this analysis to the other phases of the system life cycle in order to identify how big it can be.

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