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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 (UUV)

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Abstract

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 research 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 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).

Introduction

In summary, this study 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 research 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 hardwareintensive systems with the same effectiveness (Deshmukh et al., 2010; Hall, 2018). The systems engineering process enables identifying similarities among products 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.

Research Questions

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

Background And Literature Review

Throughout recent years, 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 (U.S. 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 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.

In parallel to this unmanned development effort, the DoD released its Digital Engineering Strategy (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 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.

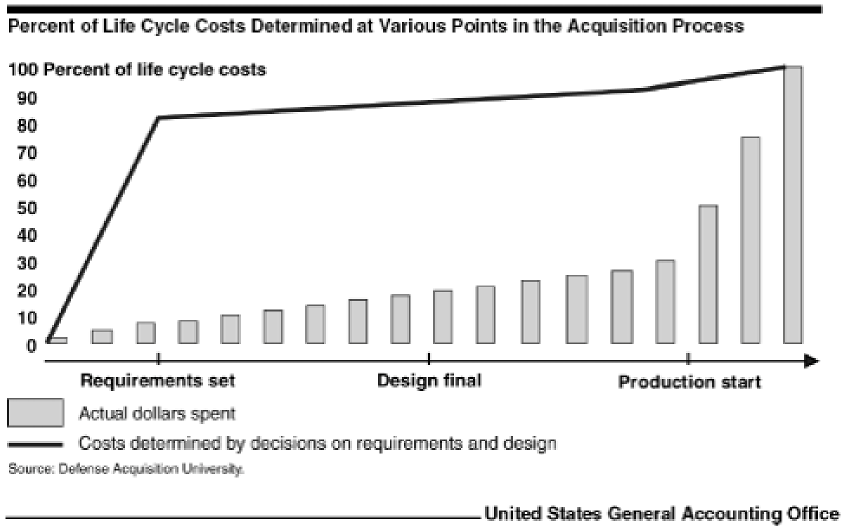

Figure 1. Cost Commitment Throughout the Life Cycle.
(Schinasi, 2003).

Recent research (Chance, 2019; Fraine et al., 2019; Hall, 2018) found that developing hardware and software components to be reused in different programs through a portfolio approach results 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 study 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, adding extra costs. From this perspective, Madachy and Green (2022) state the importance of applying PL approach during the earlier design phase when architecting and developing systems.

Product Line Approach—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 2). 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.

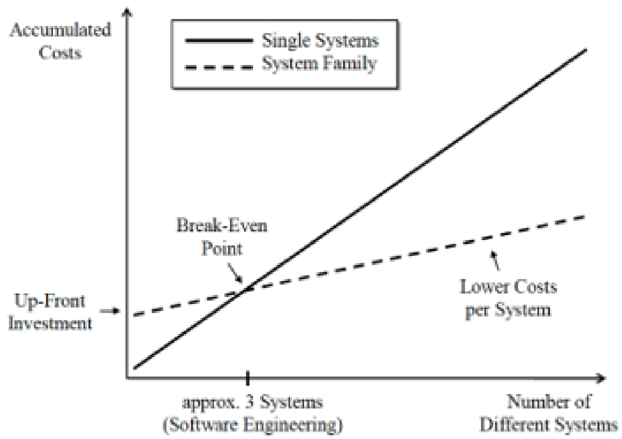

Figure 2. Costs For Developing Kinds of Systems as Single Systems Compared to Product Line Engineering.
(Pohl et al., 2005).

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.

Methodology

Using the systems engineering approach and the Orthogonal Variability Model (OVM; Pohl et al., 2005), this study capture variability and commonality obtained from six alternative functional architectures previously detailed by Camacho et al. (2017) through MBSE. This way, the baseline of this research’s methodology is considering those alternatives as system architecture for the analysis since the authors focused on their performance assessment and did not explore economic tradeoff analysis. Then, regarding the functional architecture decomposed by Camacho et al. (2017) is possible to identify components and/or set of components using the OVM 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 cost model based on 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 life cycle cost 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 3 summarizes the main steps of this study's methodology.

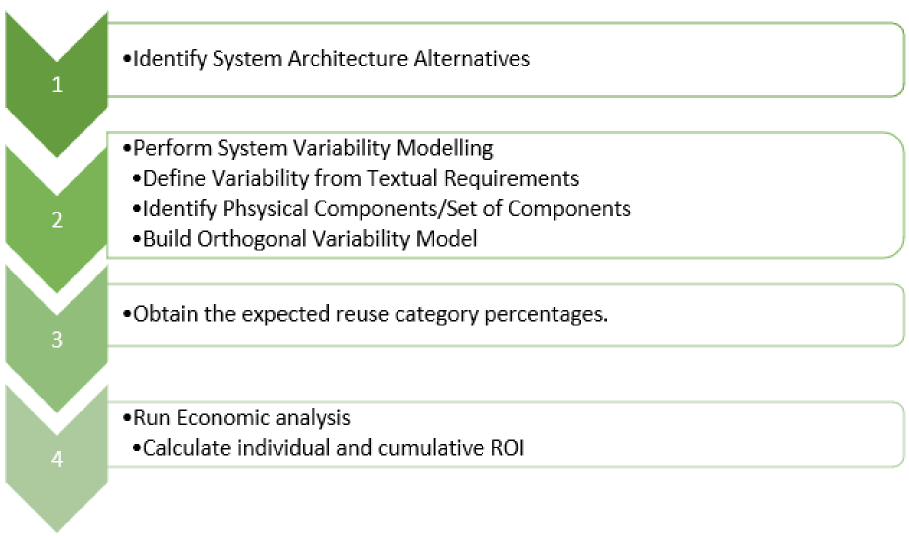

Figure 3. Process to Determining ROI Through a Product Line Approach

Identifying System Architecture Alternatives

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.

Figure 4 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.

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 5.

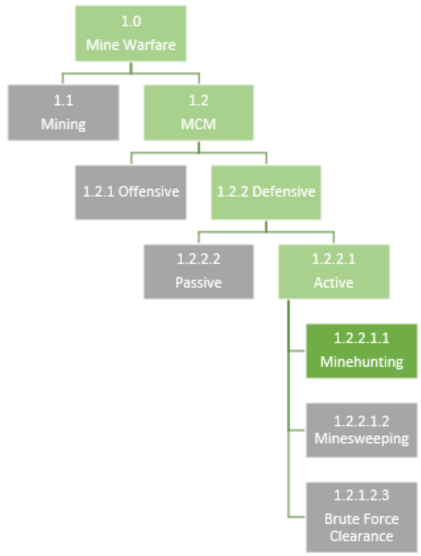

Figure 4. MIW Functional Decomposition Diagram.
(DoN, 1996).

Figure 5. Mine Hunting Functional Decomposition Diagram.
(DoN, 1996).

The PLE approach and open architecture guide this study to achieve a common system design (baseline) for the next-generation MCM UUVs to obtain potential savings in their total life cycle costs. 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 1.

Table 1. Alternative Functional Architectures.
(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 and 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 6). 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 7.

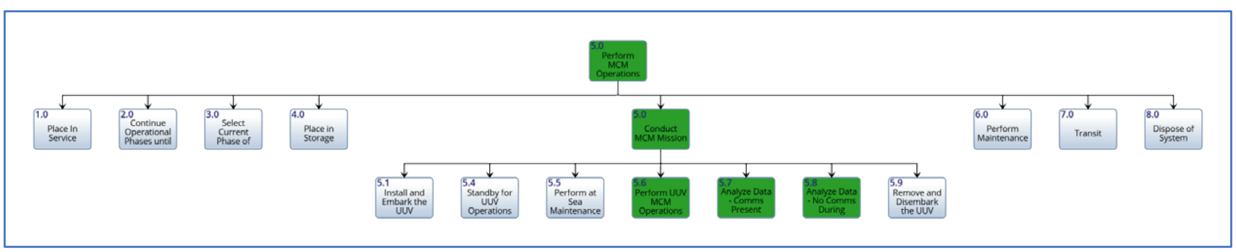

Figure 6. Functional Hierarchy.
(Camacho et al., 2017)

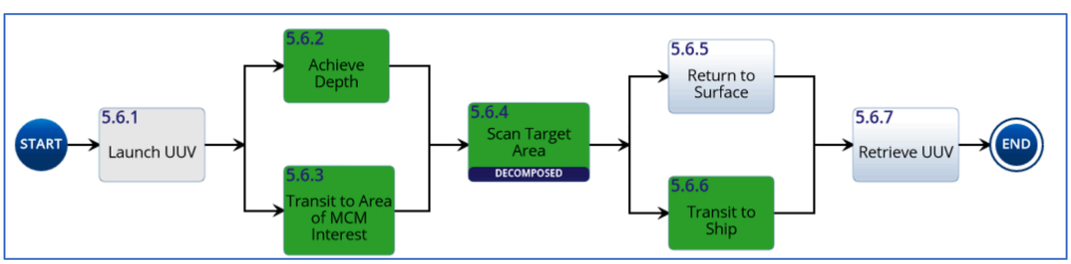

Figure 7. 5.6 Perform UUV MCM Operations.
(Camacho et al, 2017).

The execution steps of the UUV MCM operations considered for this research development were those previously determined by Camacho et al. (2017). 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

Figures 8 and 9 depict 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.

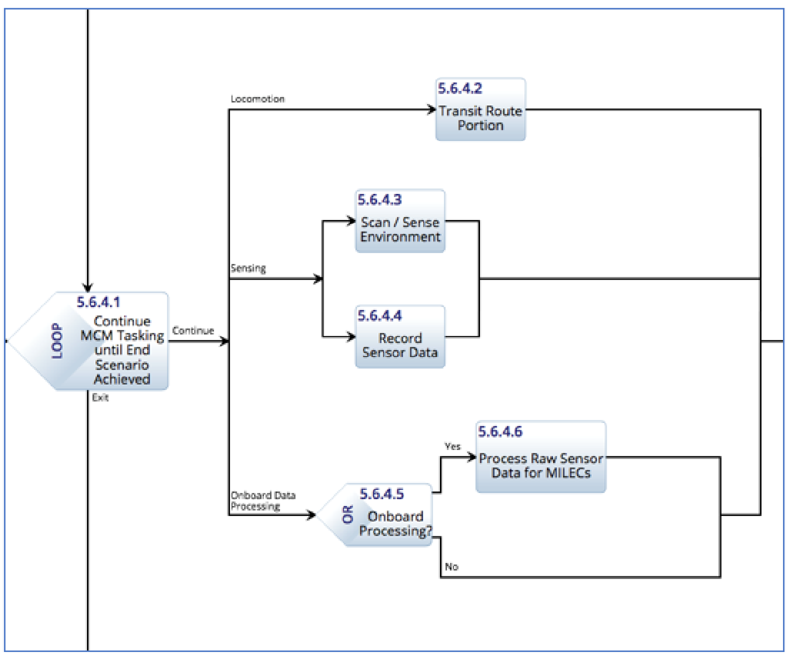

Figure 8. 5.6.4 Scan Target Area–Sensor Data Collection Portion. (Camacho et al., 2017).

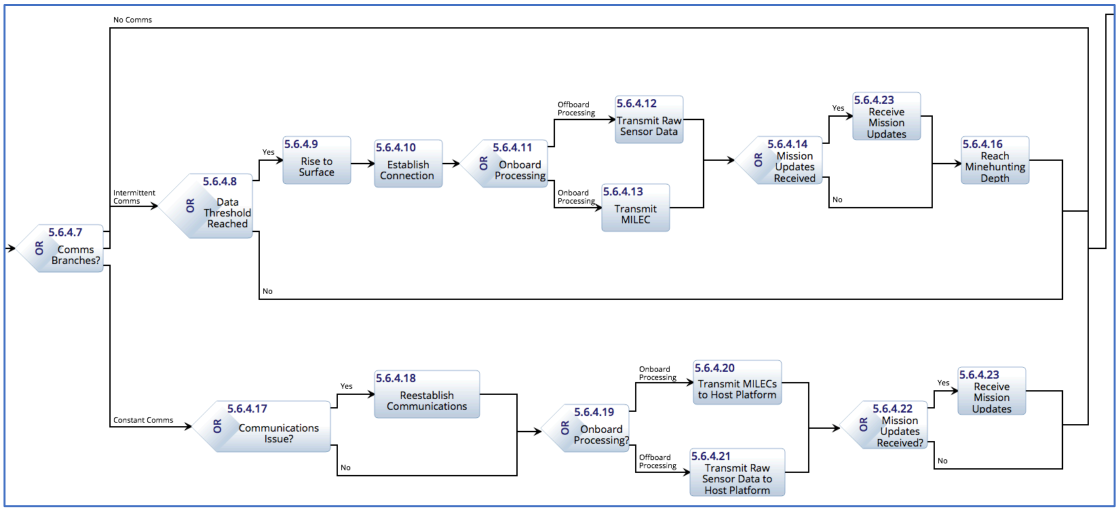

Figure 9. Scan Target Area–Communication of Data.
(Camacho et al., 2017).

System Variability Modeling

The next step of this research methodology is the system variability modeling, which comes from software PLE.

Defining Variability in Textual Requirements

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

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 remaining 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 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.

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.

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. 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.

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 makes it possible 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 associated with those two main system capabilities in terms of communication and data processing subsystems.

Expected Reuse Category Percentages

After identifying the components, this research 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.

Economic TRADEOFF Analysis

System Constructive Product Line Investment Model

Using a detailed reuse model based on COPLIMO focusing on hardware components, this study 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%. The percentages obtained in the previous step were used to feed the model.

Detailed Reuse Model Based on COPLIMO

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 below 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 = μ * Uniq % + μ *Adap% * RCR(Adap) + μ * Ruse% * RCR(Reuse)

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.

Sensitivity Analysis

As the reuse model initially used the COPLIMO standard up-front investment value, 1.7 (70%), this research 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%).

Results

The association of the variants related to each VP with their respective requirements and the components or set of components related to it were carefully demonstrated. 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 2 shows the demand for components for each of the alternatives.

Table 2. 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

Figure 10 exposes the entire next-generation MCM UUV Product Line OVM and the constraint dependencies across variants and variation points. The information previously depicted in Table 2 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.

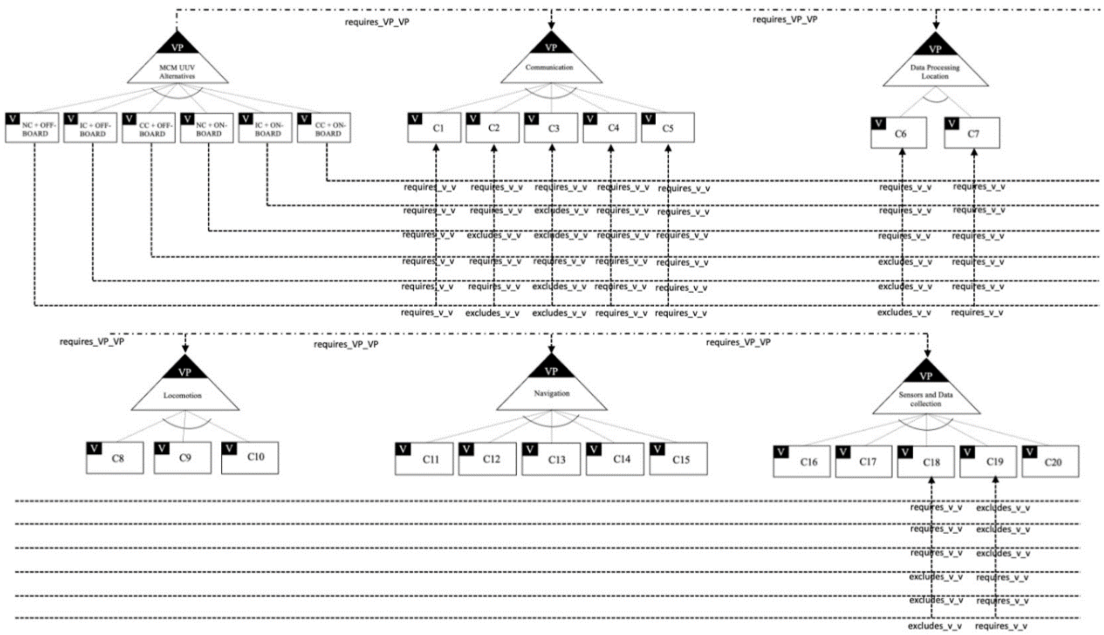

Figure 10. Next-Ceneration Mine Countermeasure UUV Product Line Orthogonal Variability Model

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 3). 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 six 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 used to calculate the product equivalent size (PES), it 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 3. 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 3. 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 11 presents the reuse effort savings through the alternatives and Figure 12 focuses on the cumulative ROI.

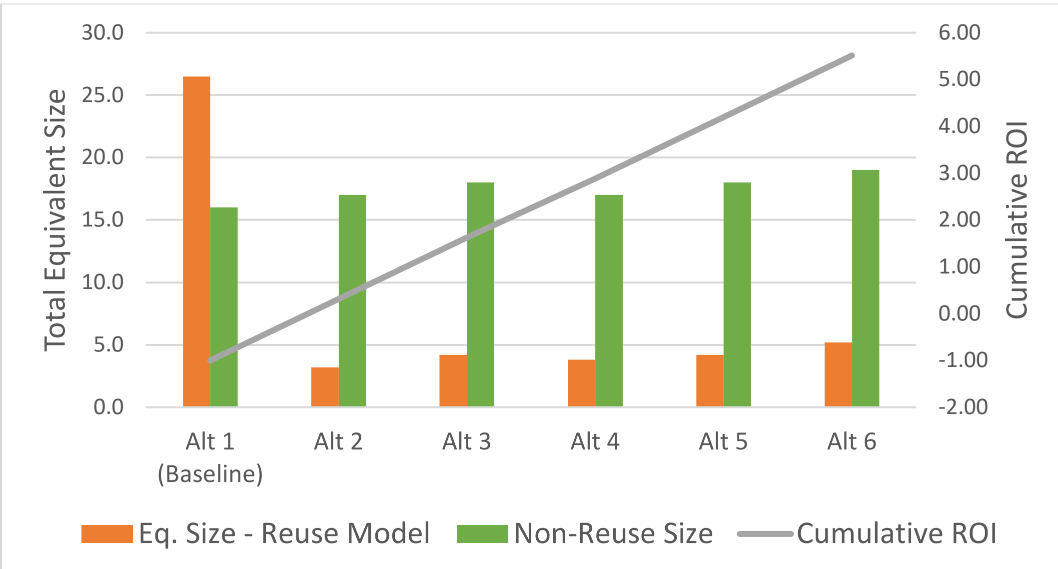

Figure 11. MCM UUV Reuse Effort Savings Through the Alternatives

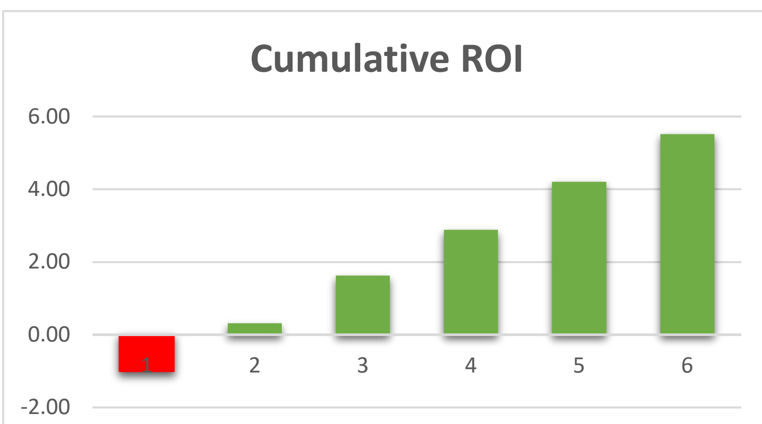

Figure 12. Cumulative ROI for RCDR 1.7

Then, performing a sensitivity analysis which proposes 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% when the RCDR is 1.5 (50% PL investment). Applying RCDR of 1.6 (60% PL investment) and 1.8 (80% PL investment) results in ROIs of 600% and 470%, respectively.

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.

Conclusion

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:

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, the product line architecture approach can benefit the development of the next generation MCM UUVs.

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%.

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