**20TH ANNUAL ACQUISITION RESEARCH SYMPOSIUM**

**MAY 10, 2023**

# 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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# INTRODUCTION

- Creating **reusable components** requires a certain degree of up-front investment.

- Although the reuse-driven investments approach was initially more used for **SW intensive systems**, some authors have demonstrated that it can be used for **HW intensive systems** with the same effectiveness.

- The **SE** process enables identifying **similarities** among products to develop reusable infrastructure and components.

- **The U.S. Navy has conducted studies to highlight that UMS are crucial to face contemporary threats.** Unmanned Campaign Framework (US Navy, 2021) - the DON established priorities in developing and deploying diverse unmanned systems.

# OVERVIEW

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 possible **benefits of reusing components in a family of systems** compared to the investments needed to develop individual stovepipe systems.

- The **importance of unmanned systems for mine countermeasures (MCM) operations**, especially unmanned underwater vehicles (UUV).

# RESEARCH QUESTIONS

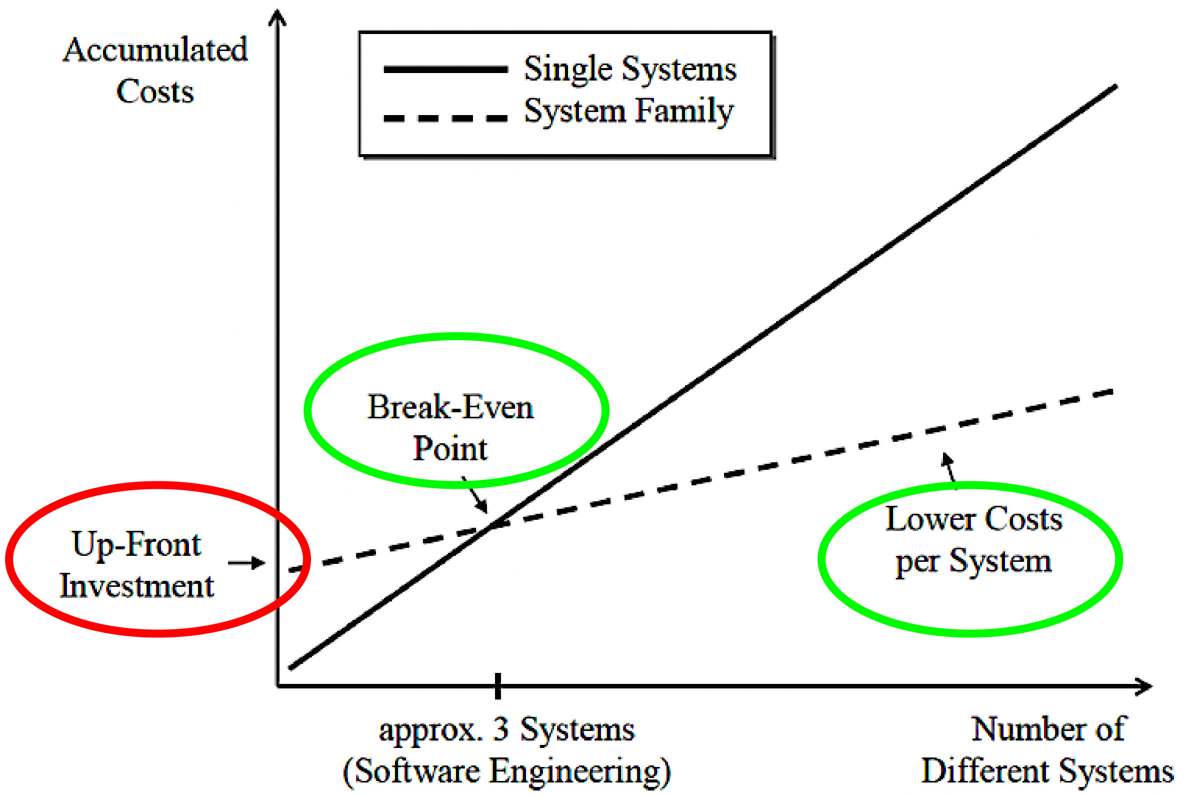
- Can the product line architecture approach benefit the development of the next generation MCM UUVs designs instead of using non-reusable systems/components?
- Can potential technological changes/solutions be used as performance drivers in the analysis of MCM UUVs product line architecture?
- How can 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?

# PRODUCT LINE APPROACH

- Pohl et al. (2005) suggest the existence of a **break-even point in terms of ROI**, which in SW engineering can be reached around the third system developed under a PLE approach.

- An individualized cost drop is achieved when SW/HW components are reused across different systems.

- Up-front investment is necessary to generate a common platform that will further reduce cost through the successively produced systems.



# METHODOLOGY

1

- Identify System Architecture Alternatives

2

- Perform System Variability Modelling
  - Define Variability from Textual Requirements
  - Identify Phsysical Components/Set of Components
  - Build Orthogonal Variability Model

3

- Obtain the expected reuse category percentages.

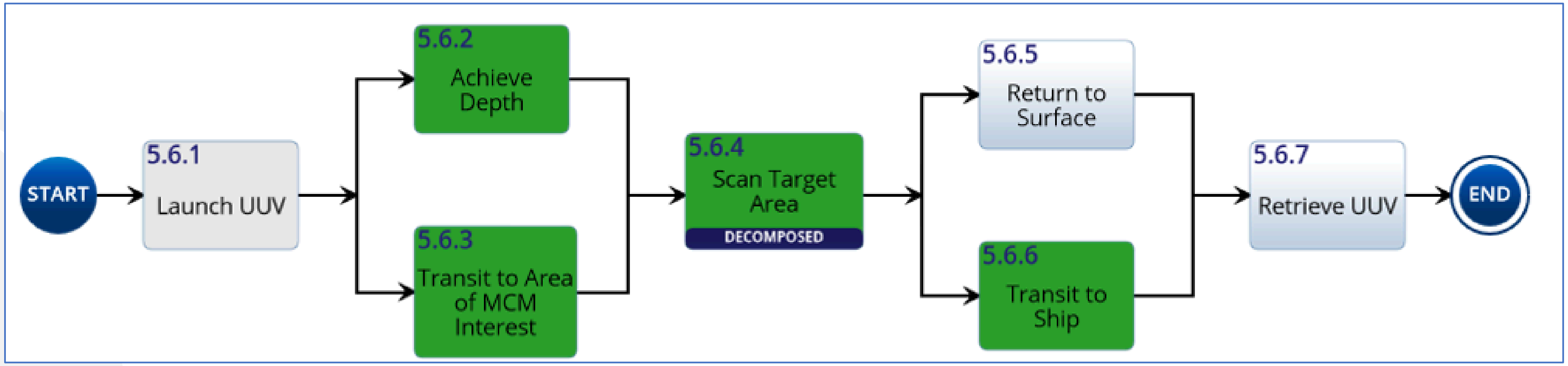
4

- Run Economic analysis
  - Calculate individual and cumulative ROI

# SYSTEM ARCHITECTURE ALTERNATIVES

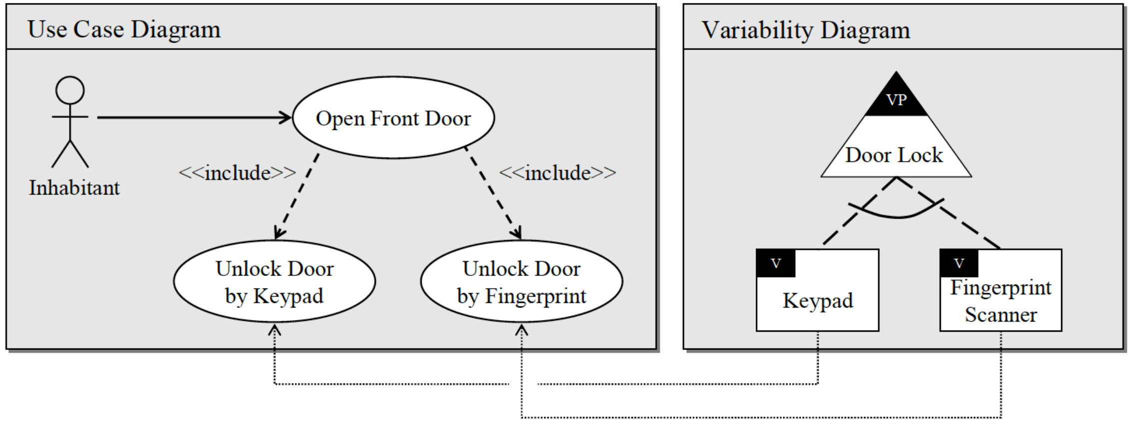
| | | Communications Cadence | | |
| --- | --- | --- | --- | --- |
| | | **No Communication** (NC) | **Intermittent Communication** (IC) | **Constant Communication** (CC) |
| Data Processing Location | Off-board UUV | Alternative 1. Post-Mission Analysis [Status Quo] | Alternative 2. IC with Off-board 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 |

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




Source: Camacho et al. (2017)

# SYSTEM VARIABILITY MODEL




Source: Pohl et al. (2005)

- Through a graphical notation, the OVM exposes the variability in the product line

- The components/set of components were associated with the six potential architectures, the baseline, and five alternatives developed under the PL approach.

- The objective was to identify the demand for those components across them.

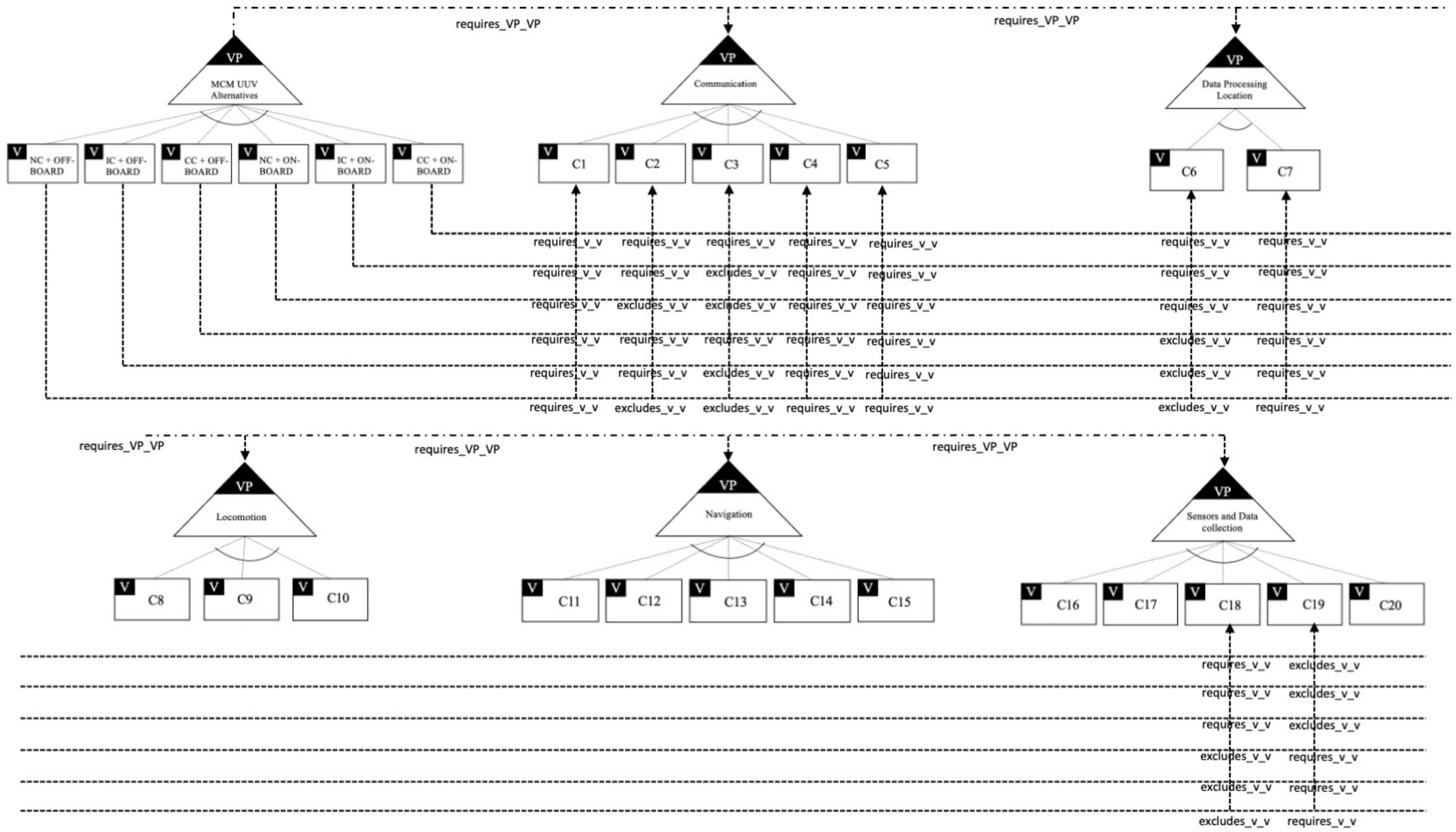
# TEXTUAL REQUIREMENTS AND COMPONENTS IDENTIFICATION

| 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 |

# 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 |

# MCM UUV PRODUCT LINE ORTHOGONAL VARIABILITY MODEL



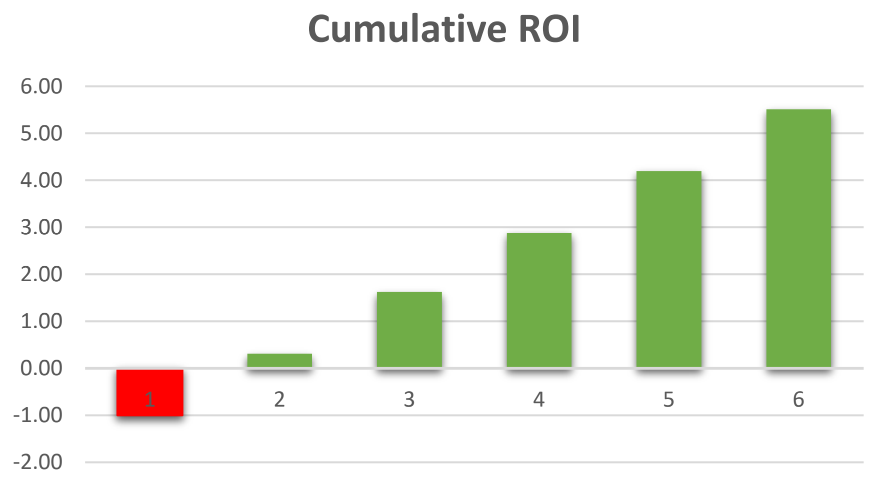
# EXPECTED REUSE CATEGORY

| | 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. |

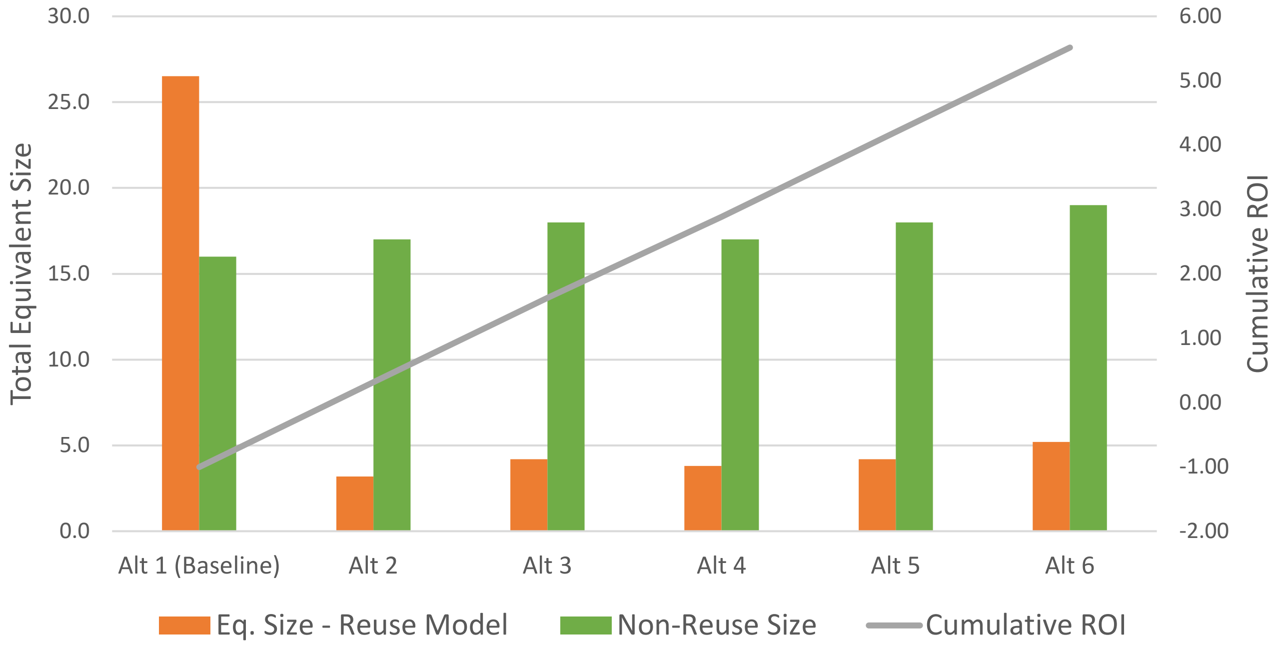
# ECONOMIC ANALYSIS

| | 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 | | | | | |

- reuse effort savings through the alternatives




MCM UUV Reuse Effort Savings through the Alternatives - cumulative ROI



# 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.

- 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.

# CONCLUSION

- From the analysis of hypothetical data regarding the next generation of MCM UUV, the PL architecture approach appears as a **great tool** in comparison to non-reusable approach;
- Regarding the two main subsystems, the data processing (on-board or off-board) and communication, the **technological variants did not have a relevant impact on the PL approach analysis**. Great decisions should fall on the performance data as main drivers;
- The OVM tool **allows an essential analysis** of the **relationships** between many variants particularly when **complex systems** are being projected and modeling is highly recommended;
- Integrating PL approach and *parametric cost modeling* can be very useful specially **in cost analyses (LCC)**. Further, ROI analysis can be expanded to the O&S phase, extending the study to logistics of spare parts, maintenance, testing and training;
- It was possible to obtain a **wide range of ROI** through the variation of the parameter of up-front investment in product line/reusability;