NPS-SE-21-035

# ACQUISITION RESEARCH PROGRAM SPONSORED REPORT SERIES

## Naval Combat System Product Line Architecture Economics

February 26, 2021

**Raymond Madachy, Professor**

**John (Mike) Green, Senior Lecturer**

Graduate School of Engineering and Applied Sciences

**Naval Postgraduate School**

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Defense Management at the Naval Postgraduate School.

To request defense acquisition research, to become a research sponsor, or to print additional copies of reports, please contact the Acquisition Research Program (ARP) via email, arp@nps.edu or at 831-656-3793.

Acquisition Research Program
Graduate School of Defense Management
Naval Postgraduate School

# Abstract

A Model-Based Systems Engineering (MBSE) approach has been developed at the Naval Postgraduate School that integrates parametric cost and product modeling methods for economic trade-off analysis of system product lines. The research assesses the economic consequences of DoD product line options and has been refining a framework for others to use and adapt. This report provides details of the methodology and its application to several empirical case studies.

The modeling framework includes a reference architecture and cost model for a general combat system product line that is extensible to other DoD and government domains. It has been applied to assess the economics of Navy combat system product line architecture approaches in coordinated case studies.

The case studies were performed for a three-tier cruise missile system, the Aegis ship software product line, and an Anti-Submarine Warfare (ASW) cross-domain product line architecture for air, surface, and sub-surface applications. An overall business case analysis for DoD product line practices was performed synthesizing the case studies with recommendations generated.

THIS PAGE LEFT INTENTIONALLY BLANK

# About the Authors

**Dr. Raymond J. Madachy**—is a professor in the Systems Engineering Department at the Naval Postgraduate School. His research interests include system and software cost modeling for total ownership cost, affordability, and Tradespace analysis; modeling and simulation of systems and software engineering processes, and the DoD acquisition process; and integrating systems engineering and software engineering disciplines empirical-based research with process simulation.

Madachy's books include *Software Process Dynamics*, *Software Cost Estimation with COCOMO II* (co-author), *Software Cost Estimation Metrics Manual for Defense Systems*, and *What Every Engineer Should Know about Modeling and Simulation*. He is currently writing *Systems Engineering Principles for Software Engineers*.

**John M. (Mike) Green**—is a senior lecturer in the Systems Engineering Department at the Naval Postgraduate School. His research interests are naval combat system architectures, model-based systems engineering, and product line architectures.

Green's related experience includes employment as a senior principal systems engineer with Raytheon Naval and Maritime Integrated Systems in San Diego, where he researched interoperability issues related to network-centric warfare and worked on the architecture for common command and control. Before Raytheon, he was manager of Advanced Systems at ITT Gilfillan, Van Nuys, CA, where he led a team developing concepts for high-power, solid-state radars.

THIS PAGE LEFT INTENTIONALLY BLANK

NPS-SE-21-035

# ACQUISITION RESEARCH PROGRAM SPONSORED REPORT SERIES

## Naval Combat System Product Line Architecture Economics

February 26, 2021

**Raymond Madachy, Professor**

**John (Mike) Green, Senior Lecturer**

Graduate School of Engineering and Applied Sciences

**Naval Postgraduate School**

THIS PAGE LEFT INTENTIONALLY BLANK

# Table of Contents

THIS PAGE LEFT INTENTIONALLY BLANK

# Introduction and Background

Department of Defense (DoD) systems within and across domains exhibit much functional commonality but are largely acquired independently, leading to suboptimal designs and unnecessary costs. A product line approach can reduce costs, increase mission effectiveness, and accelerate deployment. An associated product line architecture and cost modeling framework will support related acquisition decisions. Thus this research is relevant to public procurement policy and management in terms of how DoD systems and associated acquisition processes can improve by focusing on product line efficiencies.

Product line investment returns accrue from reusing common pieces in different systems/products that share features. Furthermore, systems can be fielded faster, leading to increased overall mission effectiveness. Flexibility is enhanced, increasing the option space. These benefits occur because previously built components reduce the effort and enable more rapid development. Employing a product line engineering approach to future combat system design is beneficial for all stakeholders.

There are other significant product line benefits besides life-cycle cost savings, such as rapid development time and adaptability to mission changes. Cost models provide an easy-to-use framework for performing these broader "ility" and affordability analyses.

The models also demonstrate that not all attempts at product line reuse will generate considerable savings. A good deal of domain engineering needs to be done well to identify product line portions of the most likely to be product-specific, fully reusable, or reusable with adaptation. Product line architecting needs to be done well to encapsulate the sources of product line variation effectively. Cost models help evaluate the trade-offs of different architectural options and determine when product line approaches are justified.

### Product Line Cost Models

Product line models for Total Ownership Cost (TOC) provide strong capabilities for analyzing the economic consequences of alternative system acquisition approaches. They show that if total life-cycle costs are considered for development and maintenance, product lines can have a considerably larger payoff, as there is a smaller base to undergo corrective, adaptive, and perfective maintenance.

The Constructive Product Line Investment Model (COPLIMO) is used to assess the costs, savings, and return on investment (ROI) associated with developing and reusing software product line assets across families of similar applications [4]. Detailed COPLIMO for software [20] and System COPLIMO as a system-level extension were created during this research.

The original COPLIMO was co-developed by Madachy as a detailed model for software product lines [1] and extended for software quality. It was modified further for systems-level product lines for valuing flexibility research [4] [5] and demonstrated for DoD system types using empirical maintenance data with Monte Carlo simulation. Thus, life-cycle cost ratios for Operations and Support for hardware and software system types were derived from [6] and [7]. The software product line model was also enhanced and adopted for a NAVAIR avionics software product line.

We subsequently devised an integrated method, Orthogonal Variability Modeling (OVM), for representing architectural variants to enumerate as parametric inputs for System COPLIMO. At NPS, there has been active student research on combat system product line architectures and cost analysis using this MBSE foundation.

**Product Line Architecting**

Composable systems allow for selecting and assembling components in different ways to meet changing user requirements. For a system to be composable, its components must also be reusable, interoperable, extensible, and modular. A reusable artifact is one that provides a capability that can be used in multiple contexts. Reuse is not confined to a software or hardware component but any life-cycle artifact.

Efficient product line architecting requires modularization of the system's architecture around its most frequent sources of change [8] as a key principle for affordability. When changes are needed, their side effects are contained in a single systems element, rather than rippling across the entire system. For modularization, it is desirable to identify the commonalities and variability across the families of products or products and develop architectures for creating and evolving the common elements with plug-compatible interfaces to insert the variable elements.

Modeling product line architectures using OVM was the basis for cost modeling input for portions of mission-unique, adapted, and reused size. This modeling approach was applied to several combat system case studies.

THIS PAGE LEFT INTENTIONALLY BLANK

## Method

The approach employs parametric cost modeling, empirical data collection of DoD programs for model calibration, application of MBSE methods to product line architectures, and integration of the modeling methods. The product line options are assessed with economic measures of ROI and TOC.

This method integrates product line architecting best practices with an automatic cost analysis of hardware and software architectural options. Functional decomposition of the DoD systems provides the framework for product lines incorporating the commonalities needed for effective capabilities.

The overall technical approach integrating the OVM method and COPLIMO applied to combat systems is summarized as follows [22]:

1. Describe a general domain model of the given system with common elements. Generic kill chain architectures, including sensors, weapons, and hardware/software, are formally modeled to identify common functions and variations.
2. Develop a reference product architecture with variation points. Variation points are identified for sensors, HSI/consoles, weapons, and data links with choices for a combat system product line. These also serve as cost model inputs.
3. Map existing systems to the reference architecture.
4. Collect empirical costs and map them to system elements from above. Empirical cost data from DoD systems programs is allocated to the system functions in the architecture models to calibrate and populate cost models for specific system configurations. Alternatively, use detailed parametric cost models instead of empirical averages when data is available.
5. Tailor the system COPLIMO framework. Modify the reference architecture as appropriate or develop new cost models for each application, as necessary.
6. Use the cost model to assess product line economic trade-off decisions for the given system. The value of investing in product-line flexibility is quantified using ROI and TOC vs. traditional one-off designs for specific systems and their constituent elements.

Coordinated case studies were performed by student capstone teams, on individual theses, and by ourselves as primary researchers. An overall business case analysis as a synthesis of case studies for DoD product line practices was performed with recommendations.

Additionally, the following activities were conducted throughout the research:

- Engaging students from NPS curricula on individual theses and capstone projects
- Literature review and survey of current approaches to DoD system architecture
- Empirical data collection on the development and maintenance of DoD and other government systems
- Calibration and refinement of the product line investment cost model family
- Analysis and modeling of alternative methods and approaches for product line architecting across DoD and other government domains

**Parametric Cost Modeling**

The value of investing in product-line flexibility using ROI and TOC is assessed with parametric models adapted from COPLIMO [2]. The initial basic version of COPLIMO was designed to assess the costs, savings, and return on ROI associated with developing and reusing software product line assets across families of similar applications [2].

Most software product line cost estimation models are calibrated only to local product line data rather than to a broad range of product lines. They also underestimate the ROI for product lines by focusing only on development vs. life-cycle savings, and by applying writing-for-reuse surcharges to the entire product rather than to the portions of the product being reused.

COPLIMO addresses these shortfalls and consists of two components: a product line development cost model and an annualized post-development life-cycle extension. It models the portions of software that involve product-specific newly built software, fully reused black-box product line components, and product line components that are reused with adaptation. It is an extension built upon the well-calibrated and most widely used software cost model Constructive Cost Model (COCOMO) II [3], tailored for strategic software product line decision issues with available supporting industry data.

Product line investment models must address two sources of cost investment or savings:

- <u>The Relative Cost of Developing for Product Lines</u>: The added effort of developing flexible product line architectures to be most cost-effectively reused across a product line family of applications, relative to the cost of developing a single system

- The Relative Cost of Reuse: The cost of reusing system architecture in a new product line family application relative to developing new systems

The System COPLIMO framework is a model extension at the systems level, used to assess flexibility and ROI trade-offs [4] [5]. The same concepts and phenomena of software product lines also apply at the system level. It models up-front investment in creating reusable system architectures for product lines composed of software and hardware. It performs a TOC analysis for a family of systems. The TOC covers the full system lifespan and normalized to net present value at specified interest rates. Figure 1 shows the model inputs and outputs.

The ROI output provides a metric for determining the cost-benefit of a product line engineering approach. ROI is defined as the net effort savings (PL Effort Savings), divided by the product line (PL) flexibility investment. See example results in the case studies described next.

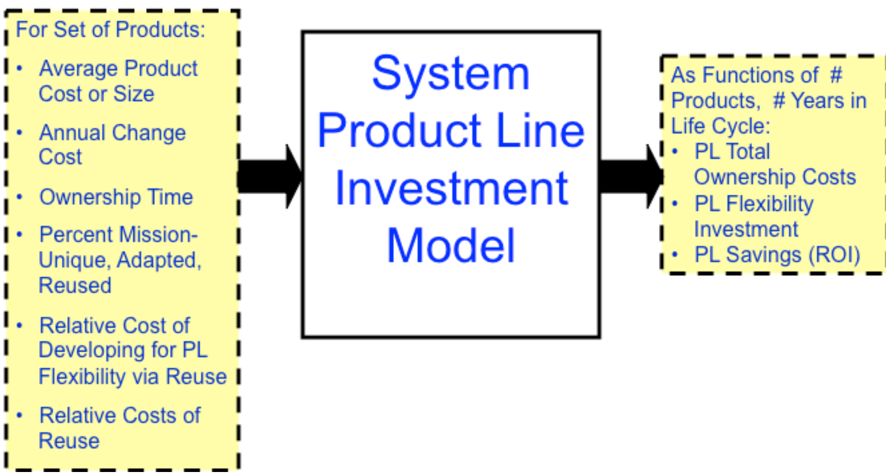



**Figure 1. System Product Line Investment Model**

## Product Line Architecture Modeling

In DoD systems, there are a variety of configurations that include sensors, weapons, and hardware/software integrations to accomplish similar goals. These common hardware and software elements with their interfaces can be modeled as flexible product lines, which are then enumerated for product line cost and investment analysis. This integrated method was the research basis for [19] [20] [21].

The system architecture starts with the Hatley-Pirbhai notation and associated architecture template. An enhanced data flow diagram and architectural flow diagram (AFD) describe the functional and physical behavior of the combat system. Each system architecture diagram utilizes the detect, control, engage paradigm as the central premise of the combat system architecture, both functional and physical.

The AFD provides the structure for variation point identification necessary for OVM modeling in the product line construct. Variation points are identified for sensors, HSI/consoles, weapons, and data links. The variation points and associated variants are presented as OVMs and consolidated into a product line OVM with packaged variants and constraint dependencies. The constraint dependencies demonstrate feasible combinations of packaged variants, variation points, and variants for the combat system product line. OVMs are then used to quantify variation points for COPLIMO product line percentages for mission-unique, reused, and adapted portions [19] [22]. The case studies next show example OVMs used to quantify variation points for COPLIMO product line allocations.

## DoD Empirical Cost Data Collection

To collect relevant data on systems development costs, the Defense Acquisition Management Information Retrieval (DAMIR) repository has been a primary source. All the weapons cost data required for three tiers of a cruise missile defense system in [2] were obtained in President's Budget Submission reports [9] and DOD Selected Acquisition Reports [10] for chosen programs in there. The DOD Selected Acquisition Reports also provide data on the system ownership times.

Data required for the investment model on inflation rates come from the Bureau of the Fiscal Service, U.S. Department of the Treasury. The Navy Visibility and Management of Operating and Support Costs (VAMOSC) management information system has also been used by students to obtain actual costs. It has data for different levels of system elements useful for the product line variation modeling and WBS cost mapping.

Software development cost data is analyzed from the DoD Cost Assessment Data Enterprise (CADE) Software Resources Data Report (SRDR) records [12]. This repository provides actual software development costs that can be tied to contractor product line components and practices. Additionally, it is a rich database containing essential data on software reuse and modification parameters that can be directly used to set defaults and tailor the COPLIMO model. The relative costs of reuse adapted and developing for product line flexibility can be inferred for given programs and application domains [11]. Software maintenance SRDRs can provide insight into annual system change costs and percentages.

THIS PAGE LEFT INTENTIONALLY BLANK

# DoD Product Line Architecture and Cost Modeling Case Studies

The case studies have driven model improvements and identified further refinements for actual DoD scenarios. Results of the case studies collectively demonstrated large economic returns of potential and actual (retrospective) product lines. They addressed single system types and meta-architectures for multiple domains. The cost model framework was also extended for more detailed and realistic DoD acquisition scenarios. Further details of these case studies are described next. The initial cruise missile case study is elaborated with more details to illustrate steps in the general method.

## Cruise Missile System Product Line

The integrated method of representing architectural variants to enumerate as parametric inputs for the System COPLIMO cost model was first demonstrated in a master's thesis [2]. It was applied to successive tiers of a cruise missile combat system product line using rigorously collected actual system costs from DoD databases. The tiers were modeled as product line architectures suitable for further system development activities and automatic cost estimation. Domain-specific defaults were replaced with actual system costs and maintenance parameters.

The modeling process for the case study is detailed here and in Figure 2.

1. Conduct an architectural analysis of current combat systems (scoped to surface combatant applications).
2. Determine necessary architectural functions and commonalities.
3. Model a case study three-tier product line with increasing capability in each tier while still utilizing architectural component commonalities.
4. Use identified commonalities to determine the percentage of unique, reused, and adapted components.
5. Apply percentages to System COPLIMO to determine the ROI of a product line approach.

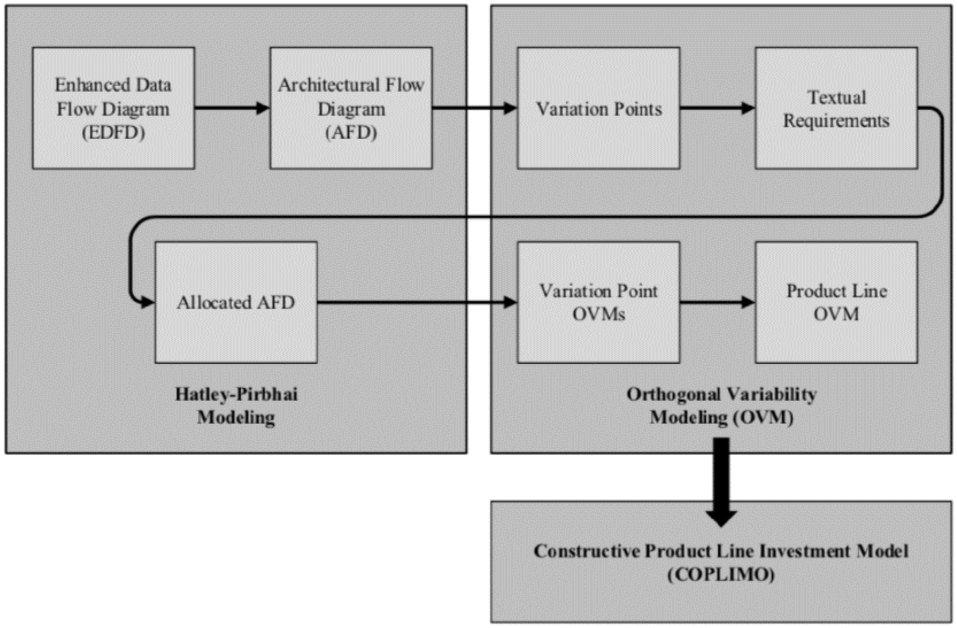



**Figure 2. Modeling Process for Tiered Combat System Product Line**

The System COPLIMO tool used in [2] was an adaption of the system-level product line flexibility tool described in [3]. The pre-sets for domain-specific defaults were replaced with provisions for actual system costs and maintenance parameters. This was done by accessing and consolidating empirical weapons cost data from DoD repositories to populate the model.

The first tier includes surface warfare (SUW) capability designed for a small surface combatant. The second tier is designed around a cruise missile defense capability that could be employed on a future frigate (FFGX), amphibious assault ship, and aircraft carrier (CVN) platforms. The third tier includes theater ballistic missile defense (TBMD) and cruise missile defense capabilities, designed to facilitate the needs of a future guided-missile destroyer (DDGX) and guided-missile cruiser (CGX). See Figure 3.

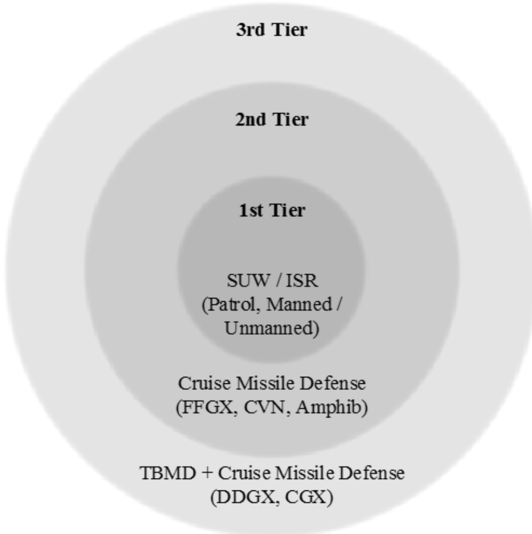



**Figure 3. Combat System Product Line Tiers**

The combat system's functional and physical architectures provided the construct for identifying variability subjects within the combat system. For orthogonal variability modeling after analyzing the functional and physical constructs of the EDFD and AFD, four variation points were identified for further decomposition and component allocation:

1. Sensors
2. HSI/Console
3. Weapons
4. Data Links

Each variant textual requirement is associated with a variation point. Textual requirements do not specify what the variant is. Textual requirements were generated for all variation points based on a review of current combat system mission capabilities. An example is shown in Figure 4.

| Variation Point | The sensors shall have the ability to... |
| --- | --- |
| Variant | ...conduct volume air search and tracking... |
| Variant | ...and conduct surface search and tracking... |
| Variant | ...and search / track in the electro-optical (EO) / infrared (IR) spectrum... |
| Variant | ...and provide high resolution imagery for identification and targeting... |
| Variant | ...and query manned / unmanned aerial systems... |
| Variant | ...and provide passive electromagnetic (EM) wave detection. |

**Figure 4. Example Textual Requirements for Sensors Variation Point**

Physical components identified from textual requirements were then assigned to the AFD. Components are variants that will be used for orthogonal variability modeling. These components are general, for example, without specifying specific types of sensors. Figure 5 shows the allocated AFD.

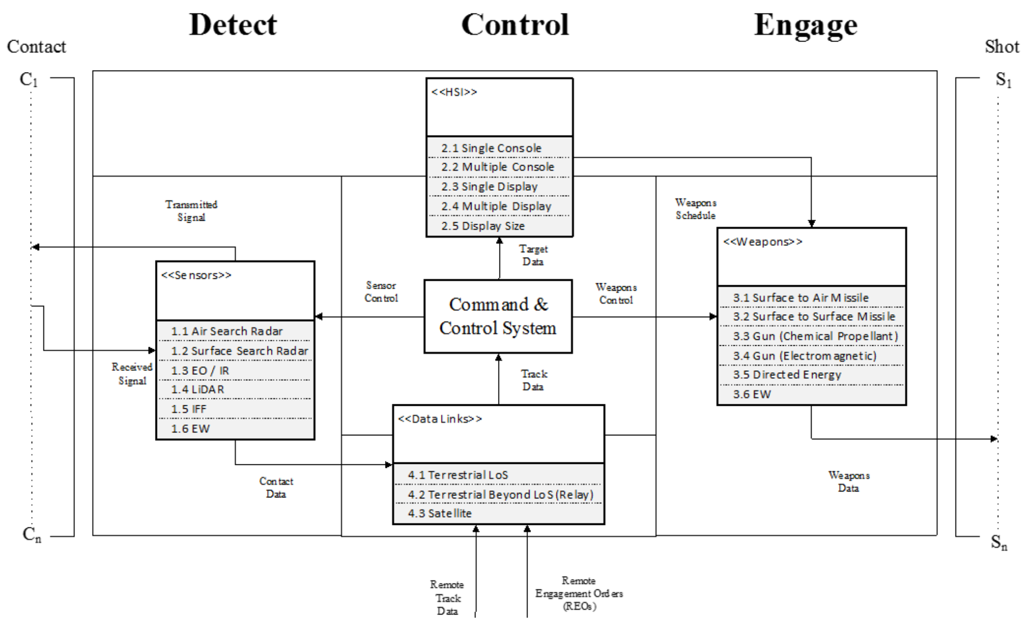



**Figure 5. Allocated Architectural Flow Diagram**

OVMs were then generated for the variation points. See Figure 6 for the sensors OVM. The product line OVM in Figure 7 shows constraint dependencies between variation points and variants at a product-line level. The packaged variants require or exclude different variants depending on the capabilities of the combat system tier. These variant requirements and exclusions parallel the detect, control, engage paradigm.

The Product Line OVM helps identify reused, adapted, and mission unique components within the product line, necessary for COPLIMO. The OVM used to quantify variation points for COPLIMO product line percentage inputs for the tiers is in Figure 7.

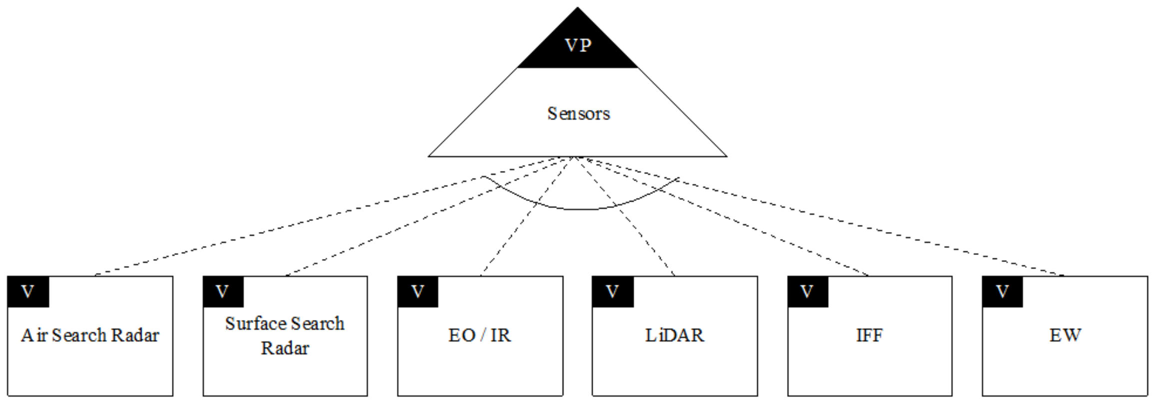



**Figure 6. Sensor Variation Point Orthogonal Variability Model**

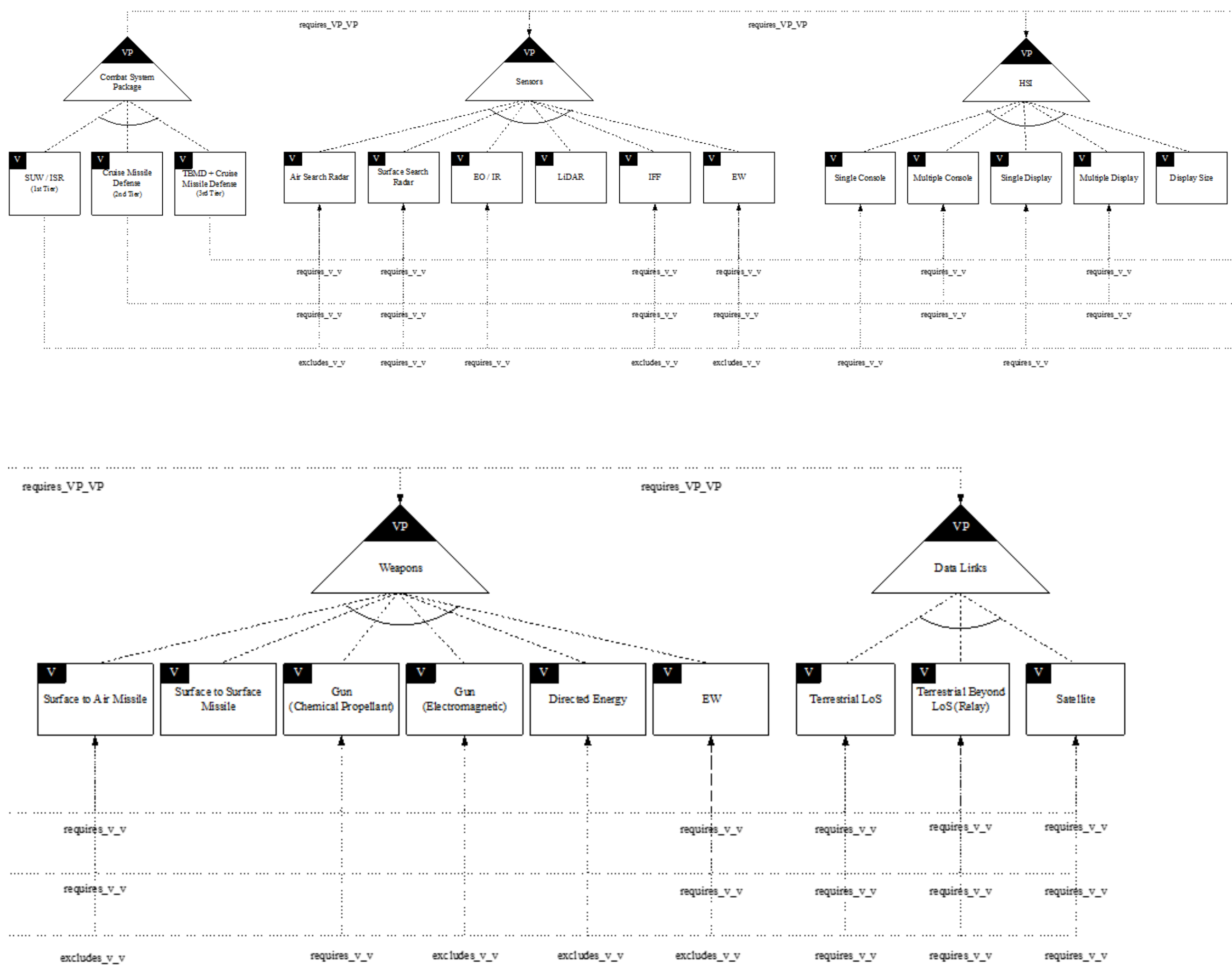



**Figure 7. Combat System Product Line Orthogonal Variability Model (Portion)**

The product line orthogonal variability model describes the three tiers of combat systems that are proposed for the product line. This OVM introduces the concept of packaged variants to reduce the complexity of the model when representing each of the tiers. The variation point of "Combat System Package" includes three variants, SUW (1st tier), cruise missile defense (2nd tier), and TBMD + cruise missile defense (3rd tier). These variants are all optional, packaged variants that can be chosen based on the customer's needs. Such variation points are shown textually in Figure 8.

| Variation Point | The console / HSI shall be equipped with... |
|---|---|
| Variant | ...either single... |
| Variant | ...or multiple consoles... |
| Variant | ...and single... |
| Variant | ...or multiple displays... |
| Variant | ...and allow for various display sizes. |

| Variation Point | The weapons shall have the ability to... |
|---|---|
| Variant | ...target and engage air targets at long range... |
| Variant | ...and target and engage surface targets at long range... |
| Variant | ...and target and engage air / surface targets a short range... |
| Variant | ...and provide long range naval surface fire support... |
| Variant | ...and provide supportability for future weapons technology... |
| Variant | ...and provide offensive capability in the EM spectrum. |

| Variation Point | The data links shall have the ability to... |
|---|---|
| Variant | ...transfer data with assets within line of sight (LoS)... |
| Variant | ...and transfer data with assets beyond LoS... |
| Variant | ...and transfer data via satellite... |

**Figure 8. Variation Points**

The product line components are enumerated in Table 1. They are classified as adapted, reused, or mission-unique to specify for COPLIMO. The COPLIMO model inputs and their rationales are shown in Table 2. These inputs model the Tier 3 Capability for Theater Ballistic Missile Defense and Cruise Missile Defense Capable.

**Table 1. Product Line Components**

| Product Line Classification | Variant | Justification |
|---|---|---|
| **Variation Point: Sensors** | | |
| Adapted | Air Search Radar | Power, beam forming, and search / track functions different for 2nd and 3rd tier packaged variants. |
| Adapted | EW | Power and physical size requirements may be different for 2nd and 3rd tier packaged variants. |
| Reused | Surface Search Radar | Physical size and capabilities of sensor can be used for 1st, 2nd, and 3rd tier packaged variants. |
| Reused | EO / IR Sensor | See Surface Search Radar justification. |
| Reused | LiDAR | See Surface Search Radar justification. |
| Reused | IFF | Hardware and interfaces are the same for 2nd and 3rd tier packaged variants. |
| **Variation Point: HSI** | | |
| **Product Line Classification** | **Variant** | **Justification** |
| Reused | Single Console | Consoles common across 1st, 2nd, and 3rd tier packaged variants. |
| Reused | Multiple Console | See Single Console justification. |
| Reused | Single Display | Displays common across 1st, 2nd, and 3rd tier packaged variants. |
| Reused | Multiple Display | See Single Display justification. |
| Adapted | Display Size | Displays are common but size can be specified by customer. |
| **Variation Point: Data Links** | | |
| **Product Line Classification** | **Variant** | **Justification** |
| Reused | Terrestrial LoS | Data links standardized across US and NATO platforms, therefore they will also be common across 1st, 2nd, and 3rd tier packaged variants. |
| Reused | Terrestrial Beyond LoS | See Terrestrial LoS justification. |
| Reused | Satellite | See Terrestrial LoS justification. |
| **Variation Point: Weapons** | | |
| **Product Line Classification** | **Variant** | **Justification** |
| Mission Unique | Surface to Air Missile | Ranges and kill mechanisms are different for 2nd and 3rd tiers. |
| Mission Unique | Surface to Surface Missile | Ranges and size of missile different for 1st, 2nd and 3rd tiers based on mission and ship size. |
| Mission Unique | Gun Electro-Magnetic | Power and size constraints dependent on ship size and cost for 2nd and 3rd tiers. |

**Table 2. Product Line Components**

| System COPLIMO Input Summary (3rd Tier Packaged Variant) | | |
|---|---|---|
| **Input** | **Value** | **Rationale** |
| **System Costs** | | |
| Average Product Development Cost | $322M | Department of Defense Fiscal Year (FY) 2017 President's Budget Submission 2016, 127-138 |
| Annual Change Cost | 10 % | Estimate |
| Ownership Time | 40 years | DoD Selected Acquisition Report 2015, 48 |
| Interest Rate | 2.625 % | Bureau of the Fiscal Service, US Department of the Treasury 2018 |
| **Product Line Percentages** | | |
| Mission Unique | 20 % | From system architecture analysis |
| Adapted | 25 % | From system architecture analysis |
| Reused | 55 % | From system architecture analysis |
| **Relative Cost of Reuse** | | |
| Relative Cost of Reuse for Adapted | 40 % | COPLIMO default |
| Relative Cost of Reuse for Reused | 5 % | COPLIMO default |
| **Investment Cost** | | |
| Relative Cost of Developing for PL Flexibility via Reuse | 1.7 | COPLIMO default |

An example product line investment analysis for the tiered product line using System COPLIMO is shown in Figure 9. Inputs were based on rigorous data collection for cruise missile programs from the DoD databases.

The ROI output provides a metric for determining the cost-benefit of a product line engineering approach. ROI is defined as the net effort savings (PL Effort Savings), divided by the product line (PL) flexibility investment. The results suggest a very strong ROI as the number of cruise missiles in the product line increases. For simplification, in this case, each successive product was modeled with the same change percentage parameters. With these assumptions, the results indicate an ROI greater than 20 after the seventh built system.

**System Costs**

Average Product Development Cost (Burdened $M) 322 | Ownership Time (Years) 30

Annual Change Cost (% of Development Cost) 10 | Interest Rate (Annual %) 2.6

**Product Line Percentages**

Unique % 20

Adapted % 25

Reused % 55

**Relative Costs of Reuse (%)**

Relative Cost of Reuse for Adapted 40

Relative Cost of Reuse for Reused 5

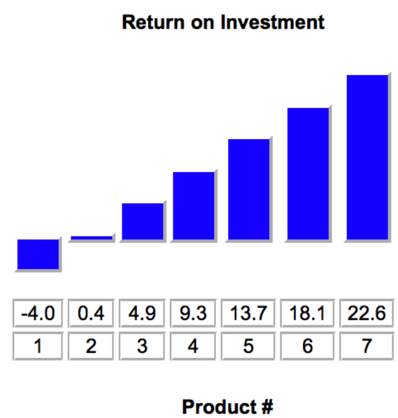
**Investment Cost**

Relative Cost of Developing for PL Flexibility via Reuse 1.7

Calculate | Monte Carlo Off

**Results**

| # of Products | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|---|
| Development Cost ($M) | $457.2 | $172.3 | $172.3 | $172.3 | $172.3 | $172.3 | $172.3 |
| Ownership Cost ($M) | $1,371.7 | $516.8 | $516.8 | $516.8 | $516.8 | $516.8 | $516.8 |
| Cum. PL Cost ($M) | $1,829.0 | $2,518.0 | $3,207.1 | $3,896.2 | $4,585.3 | $5,274.4 | $5,963.4 |
| PL Flexibility Investment ($M) | $135.2 | $0 | $0 | $0 | $0 | $0 | $0 |
| PL Effort Savings | ($541.0) | $58.0 | $656.9 | $1,255.8 | $1,854.7 | $2,453.6 | $3,052.6 |
| Return on Investment | -4.00 | 0.43 | 4.86 | 9.29 | 13.71 | 18.14 | 22.57 |




Created by Ray Madachy at the Naval Postgraduate School. For more information contact him at rjmadach@nps.edu

**Figure 9. System COPLIMO Results for Tier 3 Cruise Missile Defense Product Line Investment**

## AEGIS Ship Combat System Product Line Affordability Analysis

A thesis research case study leveraged COPLIMO to analyze product line savings and ROI for the AEGIS combat system software [9]. The AEGIS common source library is a proven standard for an evolving product line architecture to meet Navy requirements and has proven cost savings since its inception.

The case study required an extension to COPLIMO to compensate for limitations in the default Basic COPLIMO. The extension allows for varying sized products vs. an assumed homogeneous size, and it models different relative portions for each individual baseline for unique, adapted, and reused code.

The new model accounts for varying sized products with different compositions for unique, adapted, reused code. It provides per product cost savings versus a product line average using more granular data for individual programs. The analysis also used software productivity for the ship domain based on empirical cost metrics in [13].

The added granularity of Detailed COPLIMO yielded higher returns on investment than in the basic cost model. The resulting cost avoidance numbers were verified against contractor data from Lockheed Martin for the Aegis product line. Detailed COPLIMO provided comparable results.

Five consecutive Aegis baselines were modeled retrospectively and one future baseline to estimate product line effort, savings, per product cost savings, per product cost avoidance, and cumulative ROI. For the Aegis baseline of 1.8 million software lines of code, the model indicates a potential ROI of 3.88 after the seventh product is delivered.

The Detailed COPLIMO results compared favorably to the cost avoidance metrics from 2011 through 2014. Detailed COPLIMO provided similar cost avoidance varying from 21% to 31% after the delivery of the first product, and estimated ROI of 3.54 for the fifth delivered Aegis baseline in the product line and 5.40 for a future Aegis baseline.

**ASW Combat System Product Line Architecture Affordability Analysis**

This team capstone research study addressed the cross-domain applicability of an ASW combat system product line for air, surface, and subsurface applications (LAMPS MK III (SH-60 Helicopters), AN/BYG-1 (Virginia Class), SQQ-89 (FFG 7, DDG 51, and CG 47 class). By defining the ASW domain in product models, the commonality was assessed of cross-domain systems to determine if an overarching product line approach can help reduce cost, increase mission effectiveness, and enable rapid deployment.

Reference architectures were developed to identify variation points for applicability across the operational domains for product line development. The COPLIMO framework was utilized in conjunction with the variations for economic consequences of alternative system acquisition approaches for both system-level and software development costs. Both system and software cost models generated high ROI across the worst case, most likely, and best-case economic scenarios.

The domain model subsystems include Signal Processing, Fire Control, Weapon Control, SONAR, and weapons. The reference architecture is derived from the domain model, and it consists of a block diagram of components utilized in a "kill-chain" and a functional block diagram for the functions detect, plan, launch, and communicate. Each individual system fulfills the functions but uses varying components to perform the kill-chain.

The architecture models provide structure for defining variation points for the orthogonal variability modeling. Five variation points were identified as Sensors/Arrays, Weapons, Tactical Control, Data Link, and HSI. The OVM variabilities for LAMPS MK III, AN/BYG-1, and SQQ-89 were mapped to portions of unique, adapted, and reused for product line costing.

The COPLIMO framework was used with the combat system variations for both system and software. Actual DoD system costs were mapped to the architecture subsystems. Both models show an initial increase in development cost with a decline in subsequent product line cost, which yields a high ROI.

High ROI was yielded for both system and software COPLIMO using a triangular distribution for pessimistic, most likely, and best-case scenarios for the relative cost factors in COPLIMO. Overall results indicate a high ROI for the Navy to invest in a generic ASW combat system product line.

THIS PAGE LEFT INTENTIONALLY BLANK

# Conclusions and Future Work

DoD systems within and across domains exhibit much functional commonality but are largely acquired independently, leading to suboptimal designs and unnecessary costs. A product line approach can reduce costs, increase mission effectiveness, and accelerate deployment. Product line investment returns accrue from reusing common pieces in different systems that share features. An associated product line architecture and cost modeling framework were created to support related acquisition decisions.

Cost models help evaluate the trade-offs of different architectural options and determine when product line approaches are justified. The added granularity of Detailed COPLIMO offers increased value for DoD decision-makers for trade-off analysis supporting individual projects up through the product line level.

The case studies all demonstrated high ROI within and across domains for product line architectures. But not all attempts at product line reuse will generate large savings. Domain engineering needs to be done well to identify product line portions most likely to be mission-specific, fully reusable, or reusable with adaptation. Product line architecting needs to be done well to encapsulate the sources of product line variation effectively.

System product line architecture and cost modeling are applicable across all application domains where related systems share features. Thus, many DoD agencies, other governments, and industries can benefit from a generalized capability to analyze the economic consequences of their product line architecture options. The innovative method for coupling cost modeling and architectural modeling has wide application.

The systems engineering modeling methods are transferable in several ways. The modeled generic system architecture containing the detect, control, engage paradigm as a central premise of combat systems is the same across many DoD application domains beyond the Navy. The architecture model can thus be used as a template for many DoD system product lines. The entire general method can also be used for different non-combat system types with relevant architecture models.

THIS PAGE LEFT INTENTIONALLY BLANK

# References

[1] R. Hall, "Utilizing a model-based systems engineering approach to develop a combat system product line," M.S. thesis, Naval Postgraduate School, Monterey, CA, USA, June 2018.

[2] B. Boehm, A. W. Brown, R. Madachy, and Y. Yang, "A software product line life cycle cost estimation model," *Proc. of the 2004 Intl. Symp. on Empirical Software Eng.*, 2004.

[3] B. Boehm, C. Abts, W. Brown, S. Chulani, B. Clark, E. Horowitz, R. Madachy, D. Reifer and B. Steece, *Software cost estimation with COCOMO II*. Prentice-Hall: Upper Saddle River, NJ, USA, 2000.

[4] SERC RT18 - Valuing flexibility phase II, A013 Final Technical Report SERC-2012-TR-10-2, 2012

[5] B. Boehm, J. Lane, and R. Madachy, "Total ownership cost models for valuing system flexibility," *2011 Conf. on Sys. Eng. Research*, Los Angeles, CA, USA, April 2011.

[6] Q. Redman, A. T. Crepea, and G. Stratton, "Weapon design trade-off using life cycle costs," Raytheon Corporation, 2008 [Online]. Available: http://www.galorath.com/images/uploads/3_-_Quentin_Redman_-_Design_trades_using_Life_Cycle_Costs_short_version.pdf

[7] J. Koskinen, "*Software maintenance costs*," Jyväskylä, Finland: University of Jyväskylä, 2010. [Online]. Available: http://users.jyu.fi/~koskinen/smcosts.htm

[8] D. L. Parnas, "Designing software for ease of extension and contraction," *IEEE Trans. Software Engineering*, vol. 5, no. 2, pp 128–138, 1979.

[9] K. Chance, "Naval combat systems product line economics: Extending the constructive product line investment model for the Aegis Combat System," M.S. thesis, Naval Postgraduate School, Monterey, CA, USA, June 2019.

[10] V. Manfredo, T. Jackson-Henderson, and N. Fraine, "Naval ASW Combat System product line architecture economics," M.S. capstone, Naval Postgraduate School, Monterey, CA, USA, June 2019.

[11] R. Madachy, and J. M. Green, "Naval combat system product line economics," *16th Ann. Acquisition Research Symp.*, Monterey, CA, USA, May 2019.

[12] R. Madachy, and J. M. Green, "An MBSE approach for system product line architecture modeling and economic analysis," *Proc. of the 2018 INCOSE San Diego Mini-Conf.*, San Diego CA, USA, December 2018.

[13] B. Clark and R. Madachy, eds. *Software cost estimation metrics manual for defense systems*. Software Metrics Inc.: Haymarket, VA, USA, 2015.

Acquisition Research Program
Graduate School of Defense Management
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net