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Naval Combat System Product Line Architecture Economics

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Abstract

Navy combat systems are currently ship class dependent and acquired as stovepipes, yet there are many commonalities among them. This disaggregated nature leads to suboptimal designs and exorbitant costs throughout the system's life cycle. Product line approaches may reduce acquisition costs, increase mission effectiveness, enable more rapid deployment, and provide other benefits across the DoD.

A method for economic tradeoff analysis of system product lines is presented as a model-based systems engineering (MBSE) approach that integrates parametric cost modeling with architecture modeling. The modeling framework includes both a reference architecture and cost model for a general combat system product line.

The economic value of investing in product line flexibility is assessed with the System Constructive Product Line Investment Model (COPLIMO). Empirical DoD cost data is allocated to system functions in the architecture models to calibrate the cost model and populate it for specific system configurations. It is then used to assess the costs and benefits of product line architecting versus traditional one-off designs.

Results of case studies to-date indicate a strong ROI when using a product line approach. Further case studies are ongoing, and the framework will be generalized for other DoD domains to assess product line practices and economics.

Introduction

This ongoing research is assessing economic consequences of product line architecture approaches and refining a framework for others to use similarly. It is being conducted in the Department of Systems Engineering at the Naval Postgraduate School with student involvement.

The technical approach employs parametric cost modeling, empirical data collection of DoD programs for model calibration, application of model-based systems engineering methods to product line architectures, and integration of the modeling methods. The product line options are assessed with economic measures of return-on-investment.

A primary contribution is the integration of parametric cost modeling within MBSE for economic tradeoff analysis of system product lines. Product line costs and benefits are assessed across all life cycle phases to address total ownership cost (TOC).

The research problem being addressed is how to best architect Naval combat systems to be most economical while meeting mission needs. The research is relevant to public procurement policy and management in terms of how combat systems and associated acquisition processes can improve by focusing on product line efficiencies. The goals of improving acquisition processes, increasing combat system mission effectiveness, meeting cost and schedule budgets drive the research questions. The answers to the questions will inform whether the goals are achieved. The questions can be answered by quantitative indicators provided by the cost models and empirical data. The following elements facilitate better-informed acquisition decisions.

Goals:

- Improve combat system acquisition processes
- Meet cost budgets
- Provide rapid capability within schedule constraints
- Improve cost and schedule prediction of system product lines

Questions:

- What are the economic returns of combat system product line architectures versus one-off system designs?
- What is the optimal design approach for product line system development for naval combat systems?
- What system modeling concepts can be implemented for product line architectures that support analyses of both mission effectiveness and cost?
- What are relevant cost factors for product line development?
- Can the results be generalized and/or models used for other Naval and DoD domains?
- What are the limitations and refinements needed to apply the models across domains?

Metrics:

- Product line architecture return-on-investment
- System development and change costs
- Architectural variance points

To address the above goals, combat systems architectures are being formally modeled to identify common functions and variations for different case studies. Empirical cost data from Naval weapons systems programs collected from DoD databases are then allocated to the same system functions in the architecture models. The data is being used to calibrate the parametric product-line investment model and populate it for specific system configurations. It can then be used more generally to assess costs and benefits of product line architecting approaches versus traditional one-off designs for specific systems and their constituent elements.

When TOC is 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 value of investing in product-line flexibility using return-on-investment (ROI) and TOC is assessed with System COPLIMO.

We are first assessing the economics of Navy combat system product line architecture approaches with domain case studies and associated economic analyses. The case studies and analyses are at a system-level, sub-system or component level. Systems and all their constituent elements including software, hardware, facilities, or personnel are modeled.

An overall economic business case analysis for product line practices in DoD acquisition will be performed as a synthesis of the case studies covering combat system elements including hardware and software at various system levels. Insights gained from the cost model will provide for more informed acquisition decision-making, and recommendations will be discussed.

Cross Domain Applicability

The method for coupling cost modeling and architectural modeling has wide application across DoD domains. The concept and execution of product line architectures extends across all system application domains where related systems share features. Similarly, many DoD domains and industries can benefit with the capability to analyze the economic consequences of their product line architecture options. It is valid for all the services, the intelligence community, other government operations, and commercial industry across numerous domains (though some already leverage product line architectures).

The systems engineering modeling methods for product architecture and cost modeling 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 general method can also be used for different non-combat system types with relevant architecture models.

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. A cross-domain analysis is first being performed within the Navy and the lessons extrapolated. Tools and guidance will be provided for others to adapt and use the framework for investment analysis of product line architecting in different environments.

Background and Previous Work

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 large 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 effectively encapsulate the sources of product line variation. Cost models help evaluate the tradeoffs of different architectural options and determine when product line approaches are justified.

System Architecting for Change

Composable systems allow for selecting and assembling components in different ways to meet user requirements. In order 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 (Parnas, 1979) 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.

The methods of MBSE have been demonstrated for implementing these product line best practices. Our integrated method extracts cost elements from the architecture models.

Parametric Cost Modeling for Product Line Economics

Product line models for TOC provide strong capabilities for analyzing 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 initial basic version of COPLIMO was designed to assess the costs, savings, and return-on-investment associated with developing and reusing software product line assets across families of similar applications (Hall, 2018). Several extended parametric models adapted from COPLIMO have been employed since then.

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 return-on-investment for product lines by focusing only on development versus 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, tailored for strategic software product line decision issues with available supporting industry data (Boehm et al., 2000).

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

- The relative cost of developing for product lines: 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 original COPLIMO was developed as a detailed model for software product lines and was also extended for software quality. The software model was later modified for systems-level product lines on the DoD System Engineering Research Center's (SERC's) *Valuing Flexibility* research project (SERC, 2012; Boehm, Lane, & Madachy, 2011). It was demonstrated for representative DoD system types using empirical system maintenance data.

The System COPLIMO framework is a model extension at the systems level, used to assess flexibility and ROI tradeoffs (SERC, 2012; Boehm, Lane, & Madachy, 2011). 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 of and normalized to net present value at specified interest rates. Figure 1 shows the model inputs and outputs as a black box.

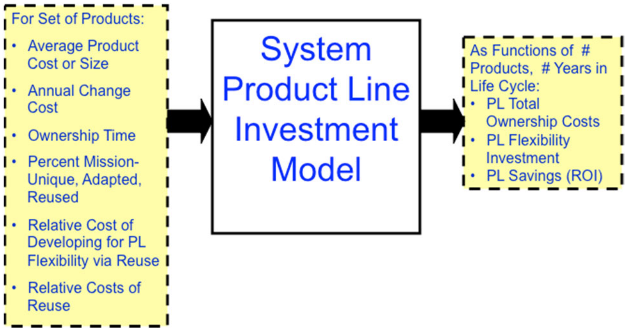


Figure 1. System COPLIMO Inputs and Outputs

The general model was enhanced to handle specific DoD application domains with Monte Carlo simulation capabilities. We incorporated the life cycle cost ratios for Operations and Support (O&S) for hardware and software system types derived from Redman, Crepea, and Stratton (2008) and Koskinen (2010). Choosing system type impacts the general model inputs for Ownership Time and Annual Change Cost based on the O&S cost ratios. The user chooses a system type and ownership time, which invokes a calculated annual change costs for the relevant domain.

The software product line model was then enhanced and adopted for NAVAIR avionics software. The product line research at NAVAIR involved cost and ROI modeling of avionics software development on the Future Airborne Capability Environment (FACE). COPLIMO helped validate product line costing efforts across different airborne platforms.

Subsequently we devised an integrated method for representing architectural variants to enumerate as parametric inputs for the System COPLIMO cost model described next.

Method

The technical approach integrates parametric cost modeling with MBSE product modeling methods to enable economic tradeoff analysis of system product lines. Product line architectures of common system designs for future Navy combat systems are modeled including hardware and software architectural options. A functional decomposition of current Navy combat system suites provides the framework for product lines incorporating the commonalities needed for effective combat capabilities regardless of platform or ship class.

Navy combat systems have a variety of configurations that include sensors, weapons, and hardware/software integrations to accomplish similar goals. These common elements and their interfaces are modeled as flexible product lines. Our method assumes each system utilizes the generic detect, control, engage paradigm as the central premise of the combat system architecture, both functional and physical. This is our modeling starting point.

The modeling sequence below is used for a given system product line and undertaken in the case studies:

1. Describe a general domain model of the given system with common elements.
2. Develop a reference product architecture with variation points.
3. Map existing systems to the reference architecture.
4. Collect empirical costs and map them to system elements from above. Develop new cost models for each application, as necessary.
5. Tailor the COPLIMO framework model for the reference architecture.
6. Assess product line economics for the given system.

Product Line Architecture Modeling

The system architecture modeling uses the Hatley-Pirbhai structured methodology and an associated architecture template. See Figure 2 for the Hatley-Pirbhai architecture template that is instantiated for each system.

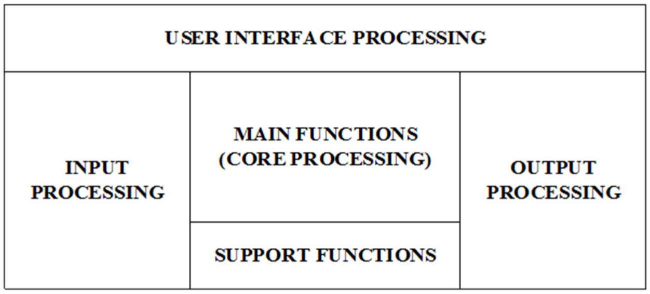


Figure 2. Hatley-Pirbhai Architecture Template

An Enhanced Data Flow Diagram (EDFD) in Figure 3 and related Architectural Flow Diagram (AFD) in Figure 4 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, in the EDFDs and AFDs.

The AFD provides a structure for variation point identification necessary for orthogonal variability modeling (OVM) in a product line construct. Variations points are identified for sensors, HSI/consoles, weapons, and data links with alternative choices for a combat system product line.

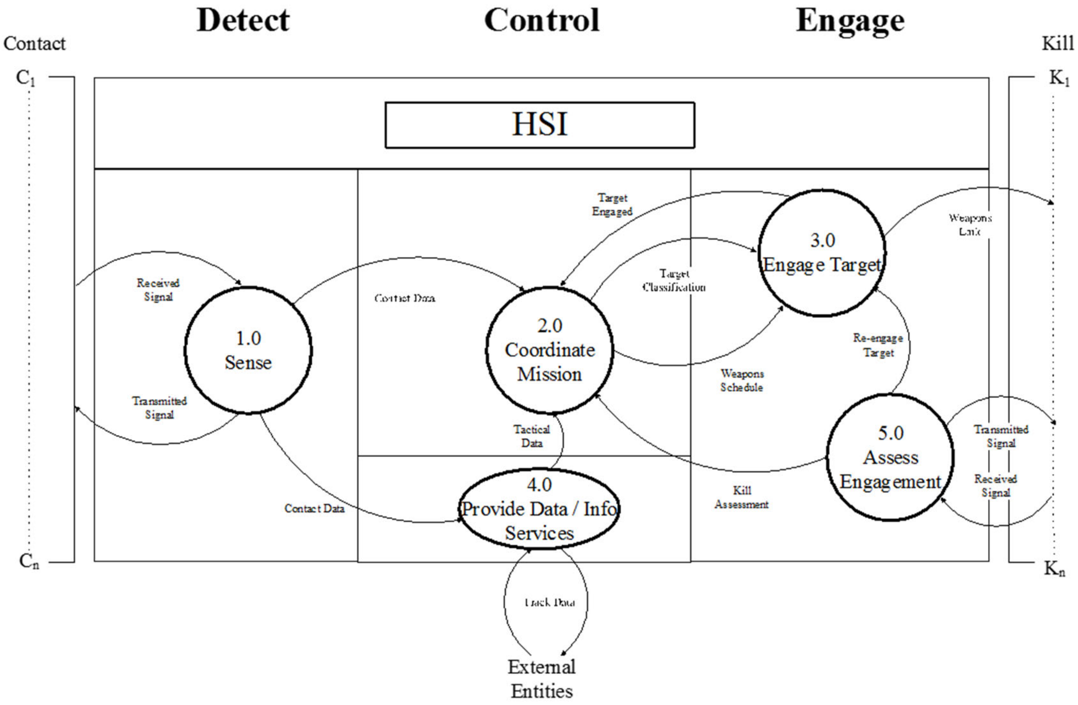


Figure 3. Enhanced Data Flow Diagram (EDFD)

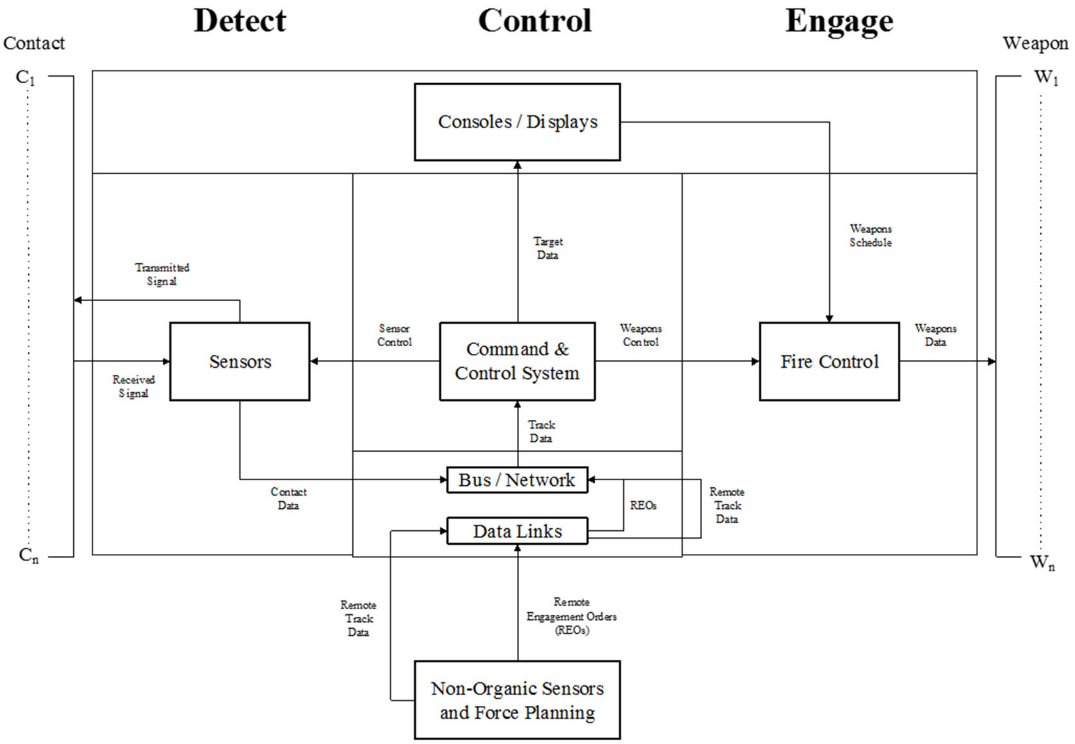


Figure 4. Architectural Flow Diagram (AFD)

The AFD provides the structure for variation point identification necessary for orthogonal variability modeling (OVM) in the product line construct. Variations points are identified for sensors, HSI/consoles, weapons, and data links.

The variation points and associated variants are presented as OVMs, showing alternative choices for each variation point. The variation point OVMs are 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. The notation for an OVM is shown in Figure 5. See the case study section for an applied OVM example.

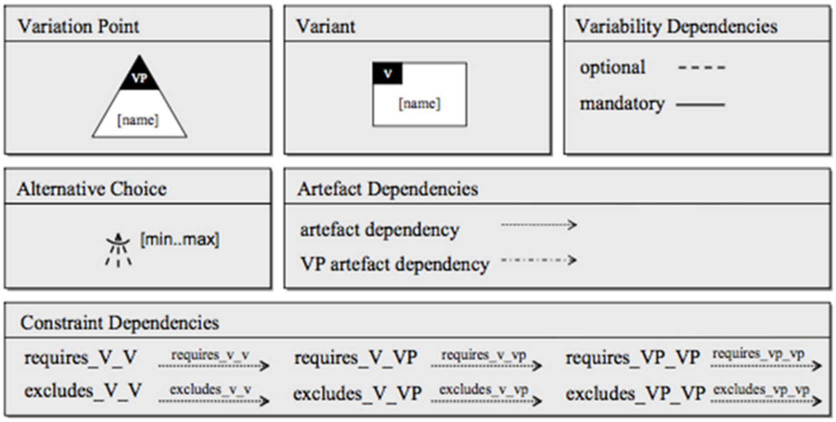


Figure 5. OVM: Halmans and Pohl Notation

An OVM uses graphic notation (Halmans and Pohl notation) to display the variability within a product line. The two classes within the OVM are the variation point and variant. Variability dependencies show the association between the variation point and variant classes.

Variation points and variants must follow the following associative conditions:

1. Each variation point must be associated with at least one variant.
2. Each variant must be associated with at least one variation point.
3. A variation point can offer more than one variant.
4. A variant can be associated with different variation points.

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 Hall (2018) were obtained in President's Budget Submission reports (DoD, 2016) and DOD selected acquisition reports (DoD, 2015) for chosen programs. 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 (DoD, 2011). 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 (Clark & Madachy, 2015). Software maintenance SRDRs can provide insight into annual system change costs and percentages.

Tiered Combat System Case Study

The concept for the integrated method of representing architectural variants to enumerate as parametric inputs for the System COPLIMO cost model was first proven in a student master's thesis. In Hall (2018), it was applied to successive tiers of a cruise missile **combat system product line** using rigorously collected actual system costs. The tiers were modeled as product line architectures suitable for further system development activities and automatic cost estimation.

The modeling sequence undertaken for the case study is detailed in Figure 6 and as follows:

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 3 Tier Product Line with increasing capability in each tier while still utilizing architectural component commonalities.
4. Use identified commonalities to determine percentage of unique, reused, and adapted components.
5. Apply percentages to System COPLIMO to determine return on investment of a product line approach.

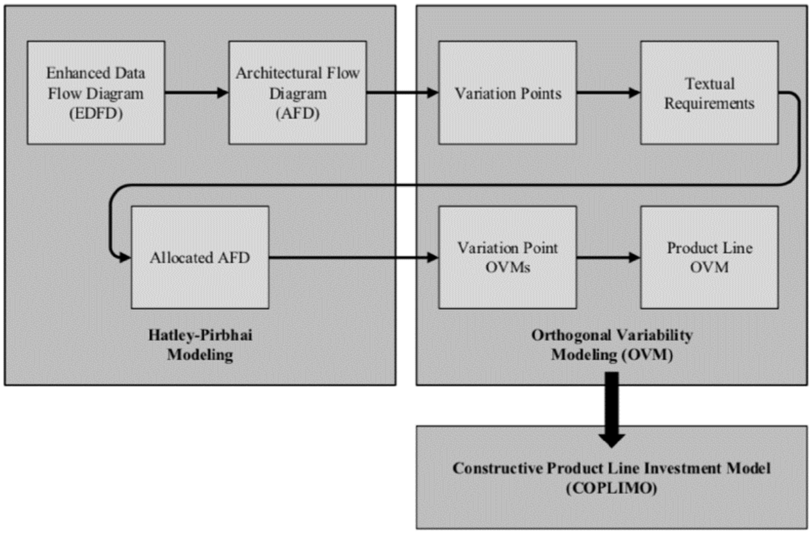


Figure 6. Modeling Sequence for Tiered Combat System Product Line Analysis

The System COPLIMO tool used in Hall (2018) was an adaption of the system-level product line flexibility tool described in Boehm et al. (2000). 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.

First tier includes a 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 7.

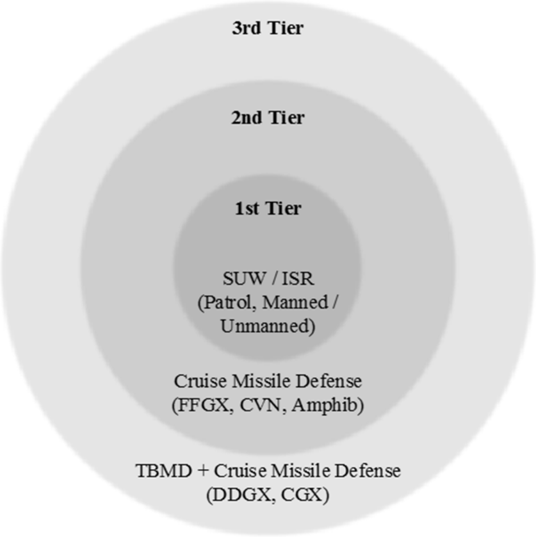


Figure 7. Combat System Product Line Tiers

The combat system 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 a variation point. Textual requirements do not specify what the variant is. Textual requirements were generated for all variation points based on review of current combat system mission capabilities. An example is shown in Figure 8.

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 8. Example Textual Requirements for Sensors Variation Point

Physical components identified from textual requirements were then assigned to the AFD. Components are variants which will be used for orthogonal variability modeling. These components are general, for example, without specifying specific types of sensors. Figure 9 shows the allocated AFD.

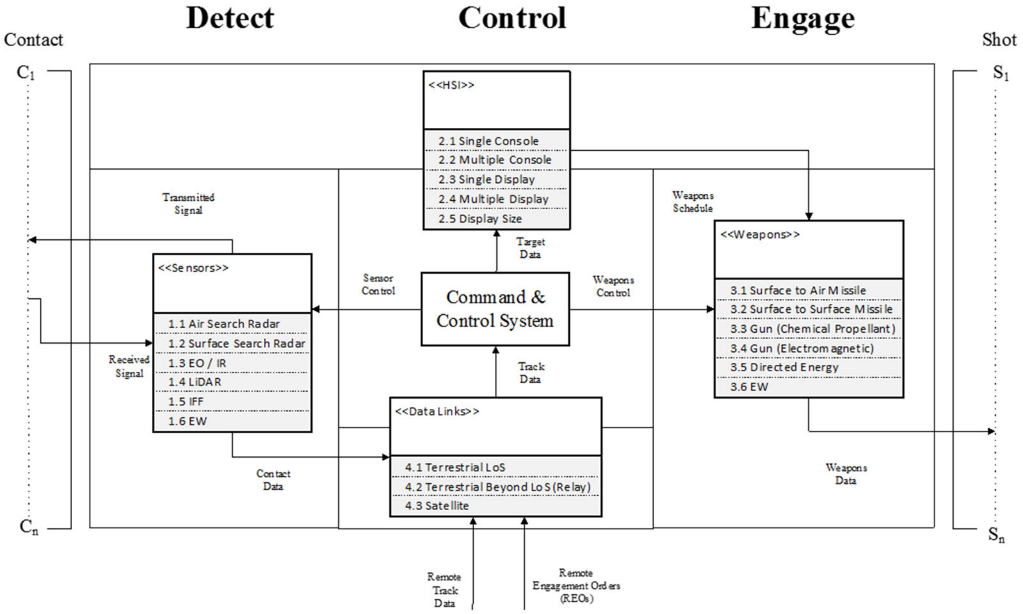


Figure 9. Allocated Architectural Flow Diagram

OVMs were then generated for the variation points. See Figure 10 for the sensors OVM. The product line OVM in Figure 11 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 11.

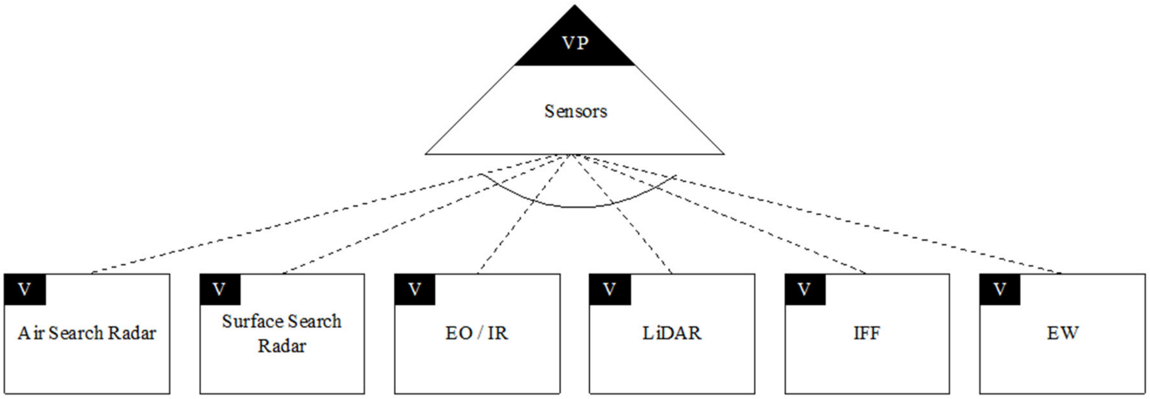


Figure 10. Sensor Variation Point Orthogonal Variability Model

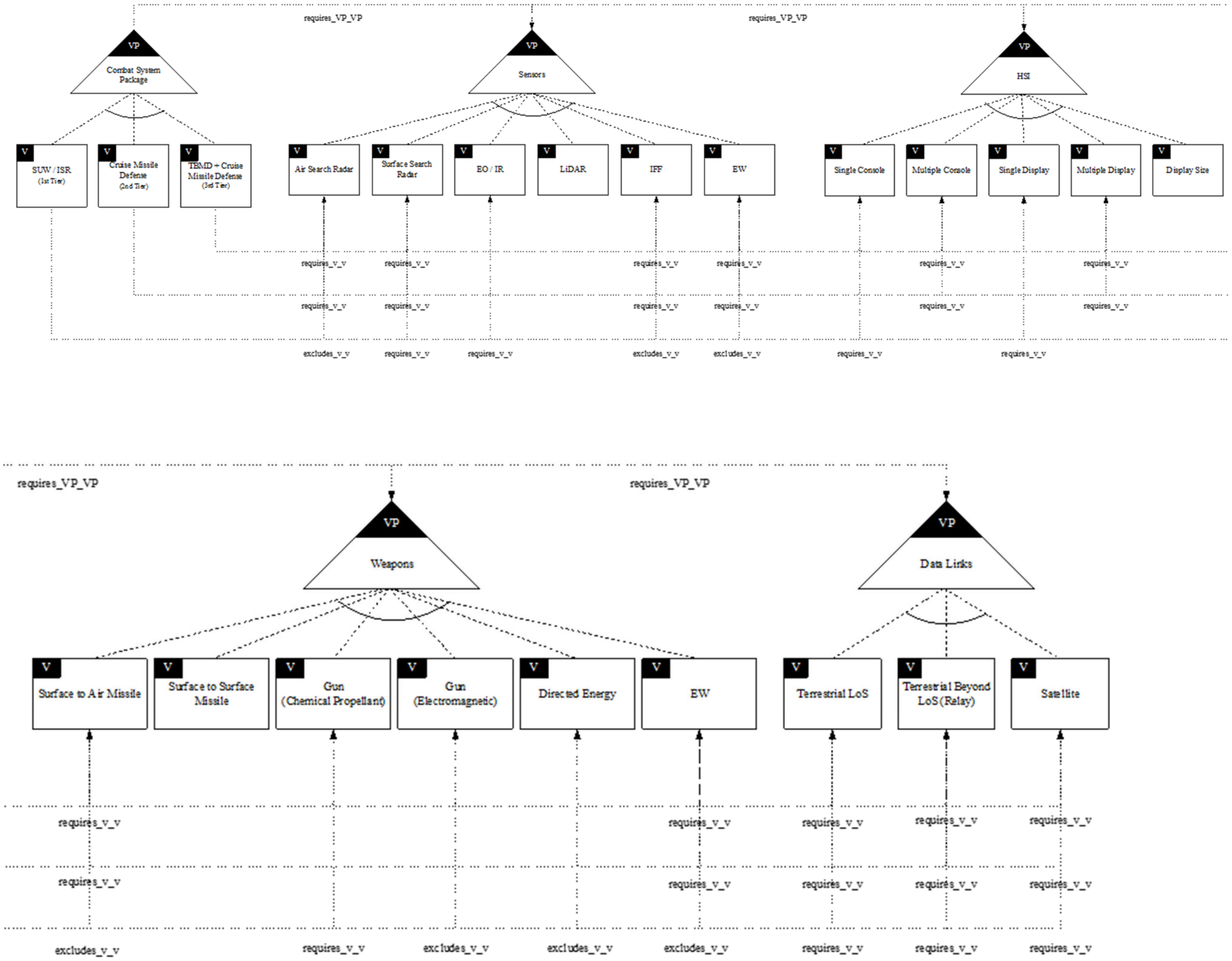
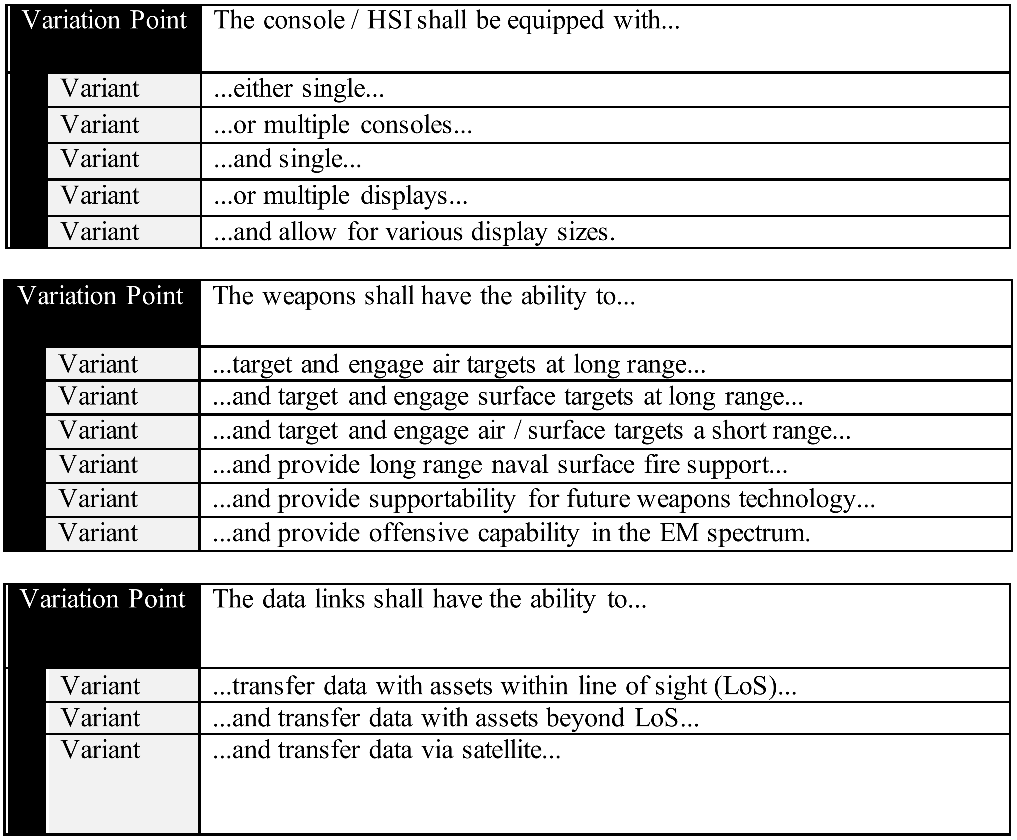


Figure 11. Combat System Product Line Orthogonal Variability Model (Portion)

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 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 12.



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 12. Variation Points

The product line components are enumerated in Figure 13. They are classified as adapted, reused, or mission-unique to specify for COPLIMO. The COPLIMO model inputs and their rationales are shown in Figure 14. These inputs model the Tier 3 Capability for Theater Ballistic Missile Defense and Cruise Missile Defense Capable.

Variation Point: Sensors		
Product Line Classification	**Variant**	**Justification**
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.

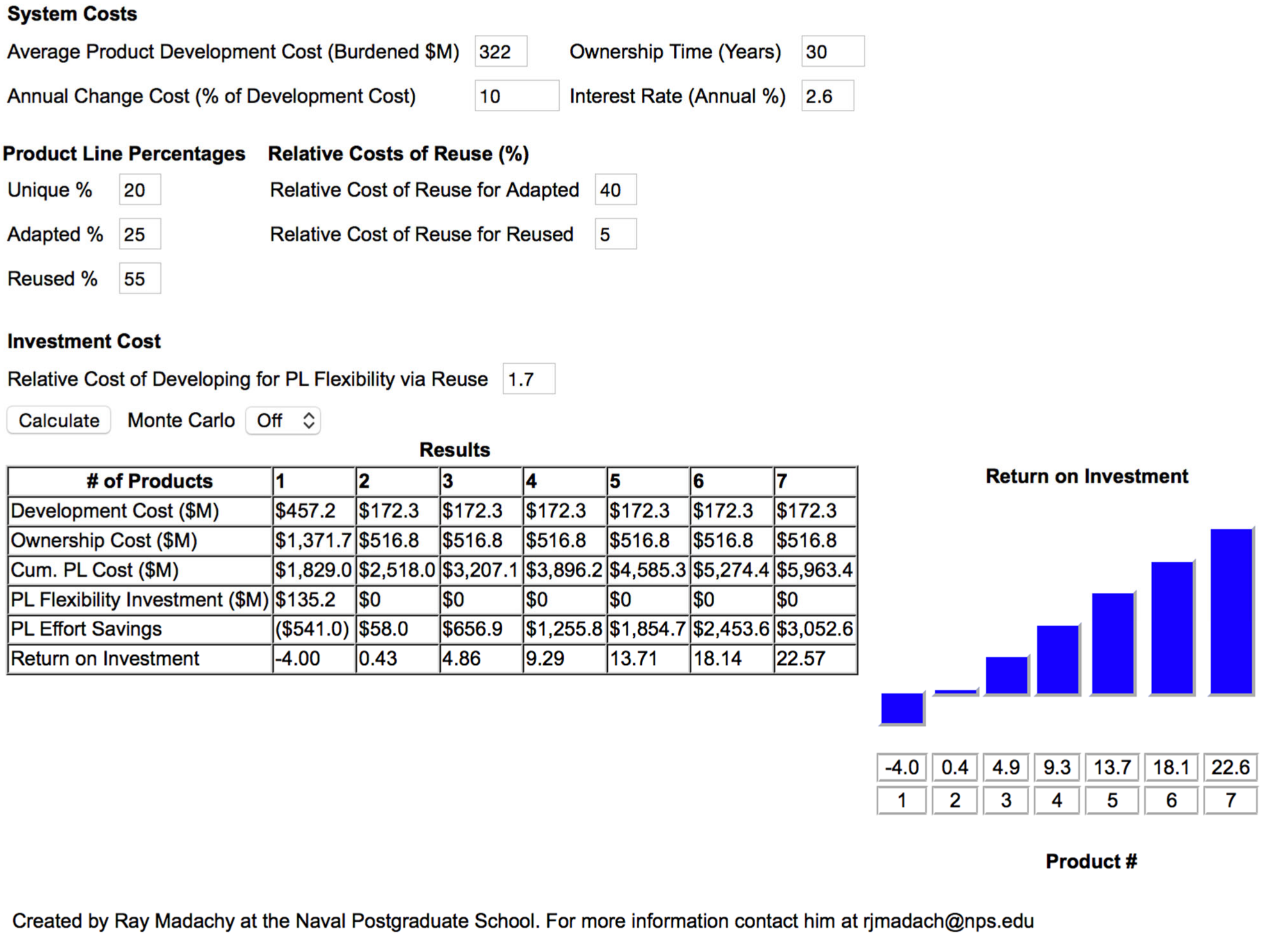
Figure 13. Product Line Components

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, U.S. 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

Figure 14. Model Input for Tier 3 Combat System Product Line

An example product line investment analysis for the tiered product line using System COPLIMO is shown in Figure 15. Inputs were based on rigorous data collection for cruise missile programs from the DoD databases.

The return on investment (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 missile 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

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 15. System COPLIMO Results for Tier 3 Cruise Missile Defense Product Line Investment

Current Case Studies

Coordinated case studies are currently being performed by student capstone teams and on individual theses. The research is divided into a set of sub-problems driven by the level of student involvement for each thesis or group capstone project. They cover different combat systems at varying levels within the system architectures.

The current case studies in-process involve the following:

- Aegis ship class software product line economics
- Ship bridge system product line architecting
- ASW product lines for air, surface, and subsurface applications

A capstone based in Newport, RI is addressing cross-domain applicability. They are investigating the product line potential for ASW systems to include air, surface, and subsurface applications (SH-60, Trident, Virginia, SQQ-89). Currently they are developing the reference architectures for the ASW systems to capture the variability for each of the platform applications for the cost model.

The ship bridge product line case study has extensively researched surface ship control to investigate the cause of the collisions involving the McCain and the Fitzgerald. An overarching process common to all ships and a notional reference architecture for a common ship control for all ships is being developed.

For the Aegis software product lines, substantial data has been collected from the contractor and government program office. Preliminary results indicate substantial savings which are being analyzed and documented. SRDR data is also being sought for more thorough and crosschecking analysis of software size and cost. A revision of COPLIMO will be done for the case study specifics.

We will synthesize the results of the case studies covering different system elements including hardware, software, etc. at various system levels. Specific product line practices and economics are expected to vary by subsystem-type.

Conclusions and Future Work

Results of the case studies to-date indicate a strong ROI when using a product line approach for Naval combat systems. We have found that high-level system architecture design for future U.S. Navy combat systems should focus on the product line, instead of platform specific combat systems. They should plan for the reuse of system components over time.

Applying the engineering product line methodology to combat system architecture design and development needs to happen at the earliest stage of design. System COPLIMO provides a trade space for determining initial investment and future return on investment (ROI) with respect to product line systems versus non-product line systems. Integrated modeling as this should be done to support early architectural decisions.

Further case studies are ongoing, and the framework will be generalized for other DoD domains to assess product line practices and economics. Future work includes developing engineering product line models for additional warfare areas such as anti-submarine warfare (ASW), electronic warfare (EW), cyber warfare, and others. Functional and physical architectural hierarchy can also be further decomposed into third and fourth levels to provide greater level of detail at the subsystem level.

Thus far our product models have been static. However, even greater insight is possible with dynamics models. For example, we can test executable EDFDs and AFDs in simulation software, following the detect, control, engage paradigm for different mission scenarios.

We will collect more empirical data to further validate COPLIMO at a system level, instead of using software engineering default calibrations. To further improve cost estimation fidelity, we will account for individual component complexities in the effort model. We will also model with product-specific inputs for individual products in a line versus homogeneity of change percentages.

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