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Naval Combat System Product Line Economics

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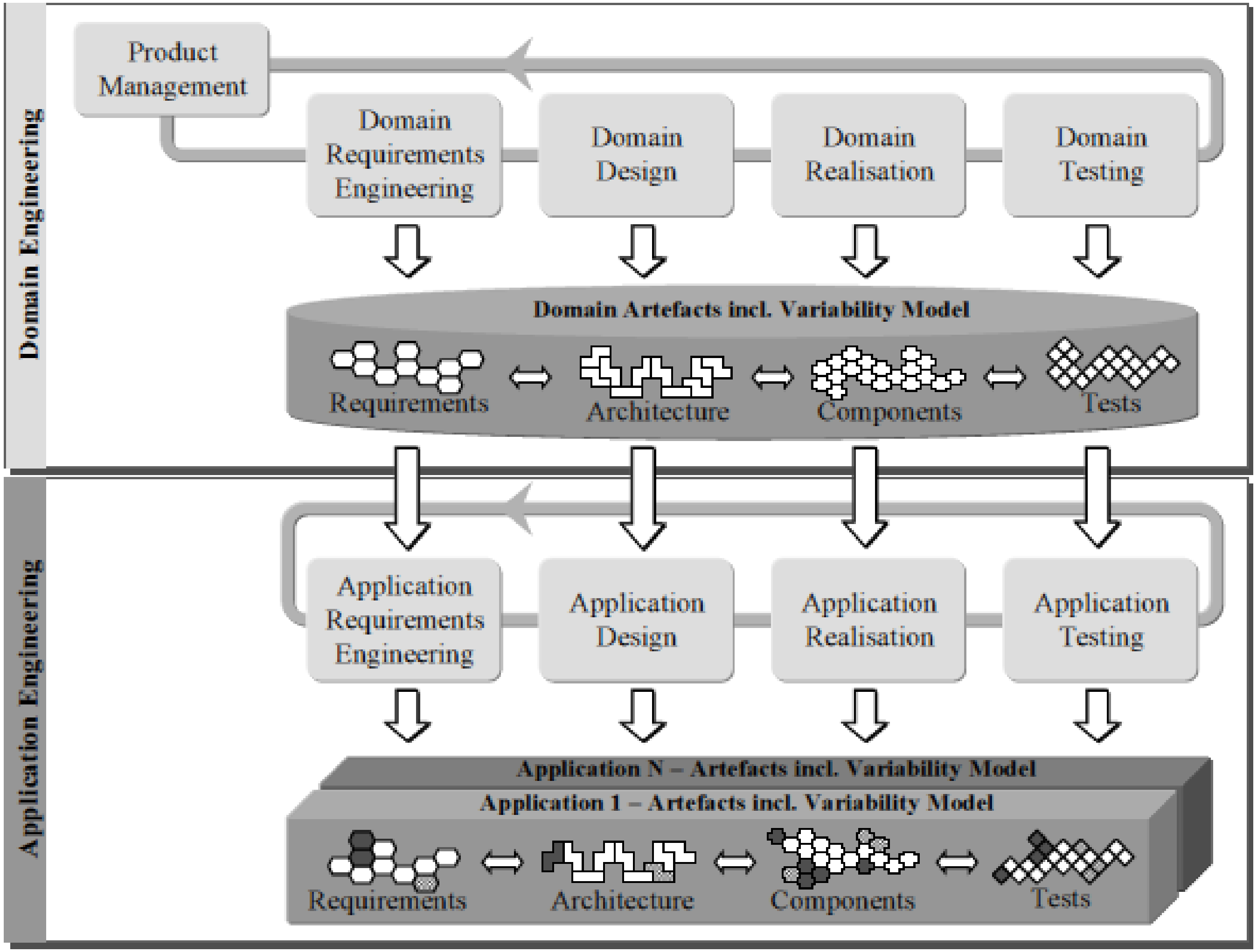
Research Overview

- A Model-Based Systems Engineering (MBSE) approach has been developed that integrates parametric cost and product modeling methods for economic tradeoff analysis of system product lines.
- 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 is being applied to assess the economics of Navy combat system product line architecture approaches in coordinated case studies.

Background and Introduction

- Navy combat systems are currently ship class dependent and acquired as stovepipes, yet there is much commonality among them.
  - This disaggregated nature leads to suboptimal designs and exorbitant costs throughout the system's lifecycle.
- Product line approaches may reduce acquisition costs, increase mission effectiveness, enable more rapid deployment and other benefits across the DoD.
  - 2013 - Navy Surface Warfare Center (NSWC) outlined the importance of "development of reusable product line components into a single combat system architecture"
- Product Line: A set of systems that share a **common, managed set of features that satisfy the specific needs** of a particular market segment or mission and that are developed from a common set of core assets in a prescribed way.
- Product Line Engineering involves planned reuse of common system components including software and hardware
  - Improvements in development time, cost, quality, and engineering productivity

Example Software Product Line Approach



Method Overview

- Describe a general domain model of the given system with common elements
  - Combat systems architectures including sensors, weapons, and hardware/software are formally modeled to identify common functions and variations for different case studies.
- Develop a reference product architecture with variation points
  - Variation points are identified for sensors, HSI / consoles, weapons, and data links with alternative choices for a combat system product line which also serve as cost model inputs.
- Map existing systems to the reference architecture
- Collect empirical costs and map them to system elements from above
  - Empirical cost data from Naval weapons systems programs is allocated to the system functions in the architecture models to calibrate and populate cost model for specific system configurations.
- Tailor the System Constructive Product Line Investment Model (COPLIMO) framework for the reference architecture or develop new cost models for each application, as necessary.

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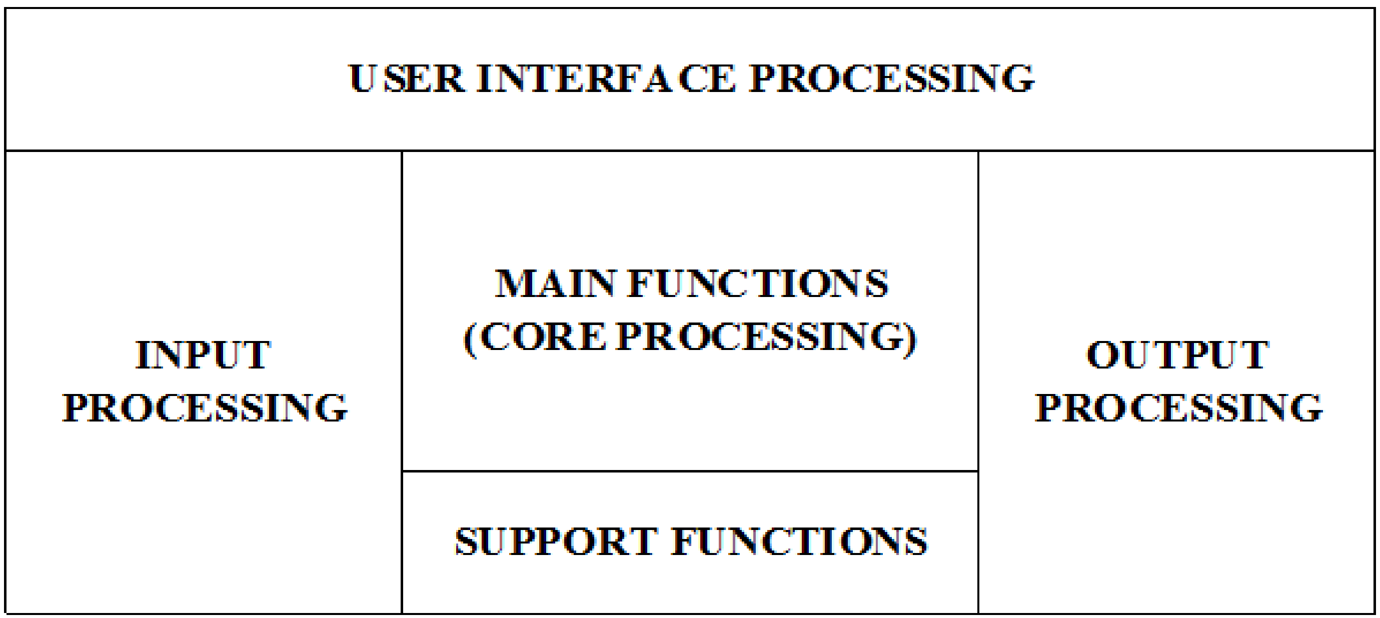
Method Overview (Cont.)

- Use cost model to assess product line economic decisions for the given system.
  - The value of investing in product-line flexibility is quantified using Return-On-Investment (ROI) and Total Ownership Cost (TOC) vs. traditional one-off designs for specific systems and their constituent elements.
- Coordinated case studies are being performed by student capstone teams and on individual theses.
  - Completed
    - 3 Tier Cruise Missile System
  - In-progress:
    - Aegis ship class software product line economics.
    - Ship bridge system product line architecting.
    - ASW product lines for air, surface, and subsurface applications at Newport News.
- An overall business case analysis as a synthesis of case studies for product line practices will be performed with recommendations.

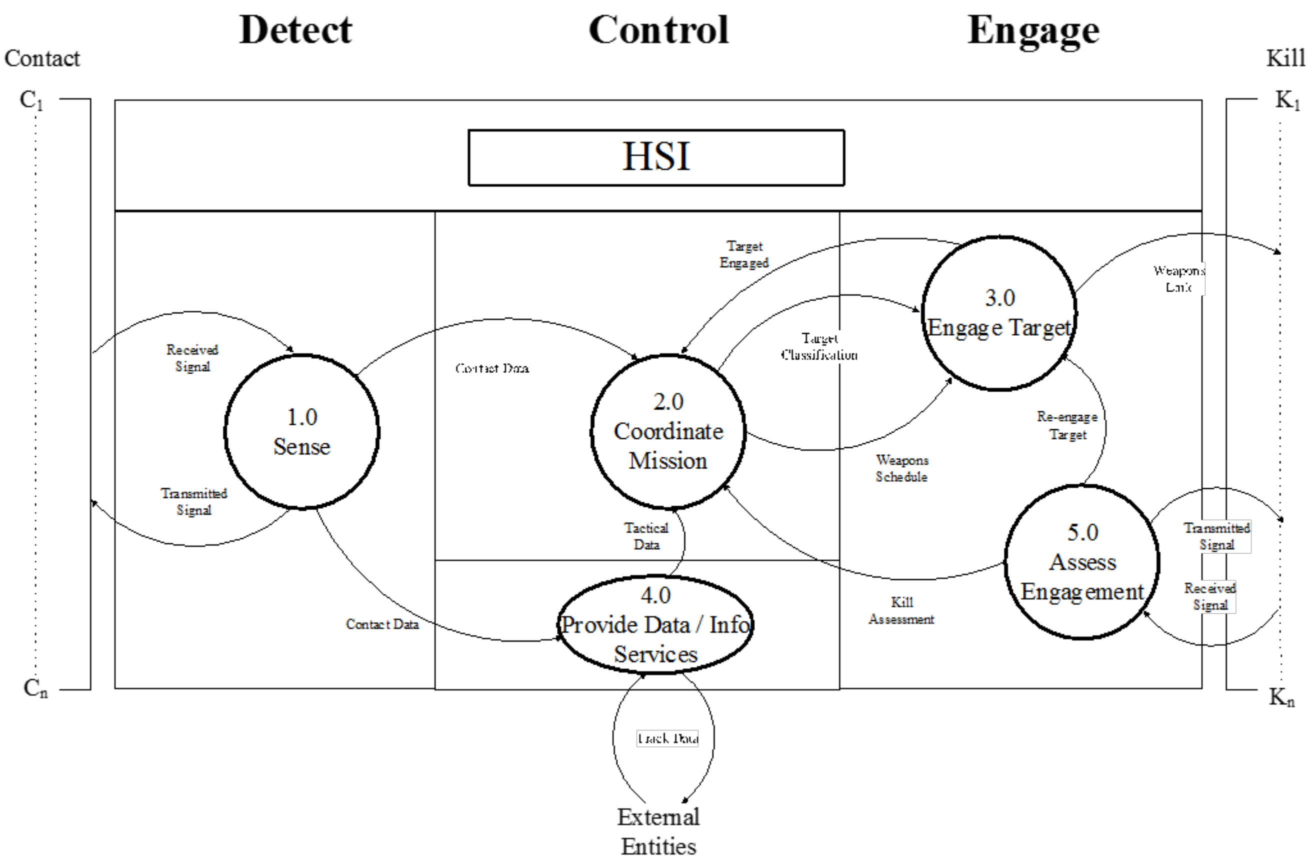
Hatley-Pirbhai Architecture Template

- The architecture modeling uses the Hatley-Pirbhai methodology and an associated architecture template applicable to general DoD combat systems.



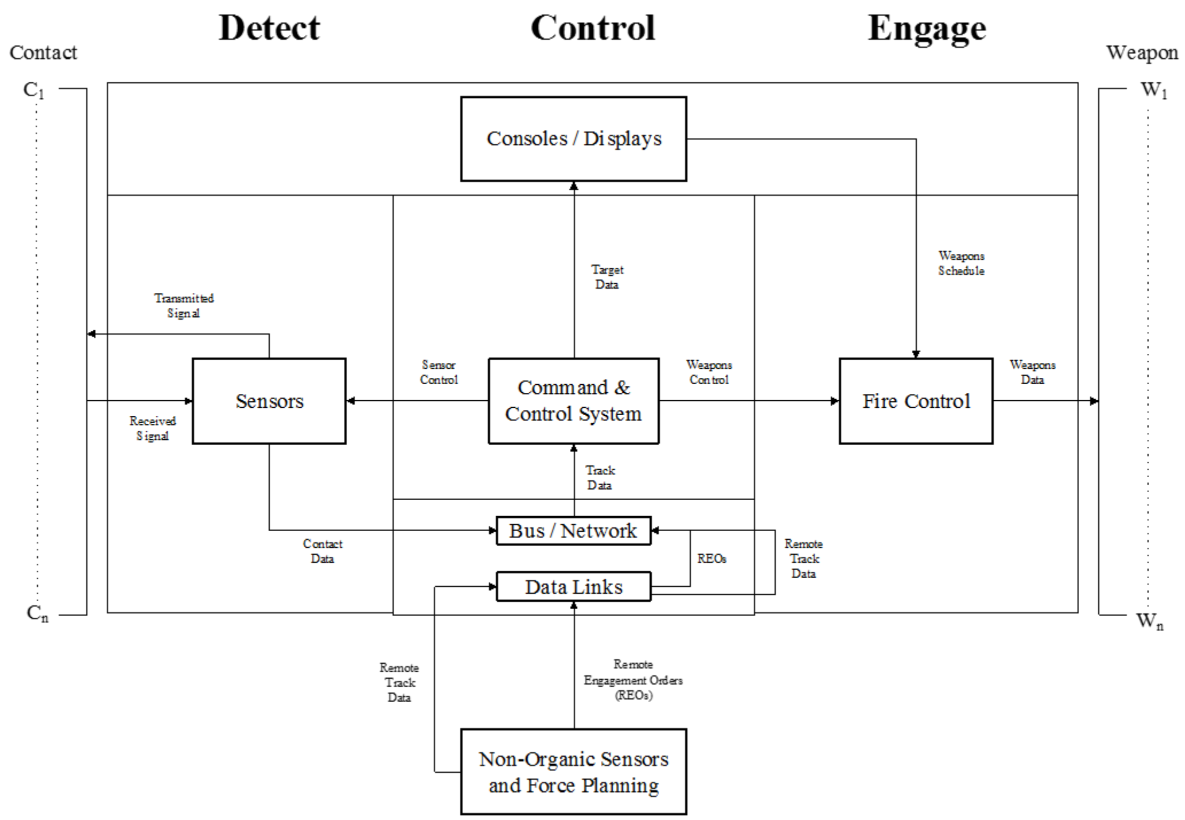
Enhanced Data Flow Diagram (EDFD)

- An Enhanced Data Flow Diagram (EDFD) and related architectural flow diagram (AFD) describe the functional and physical behavior of the combat system.



Architectural Flow Diagram (AFD)

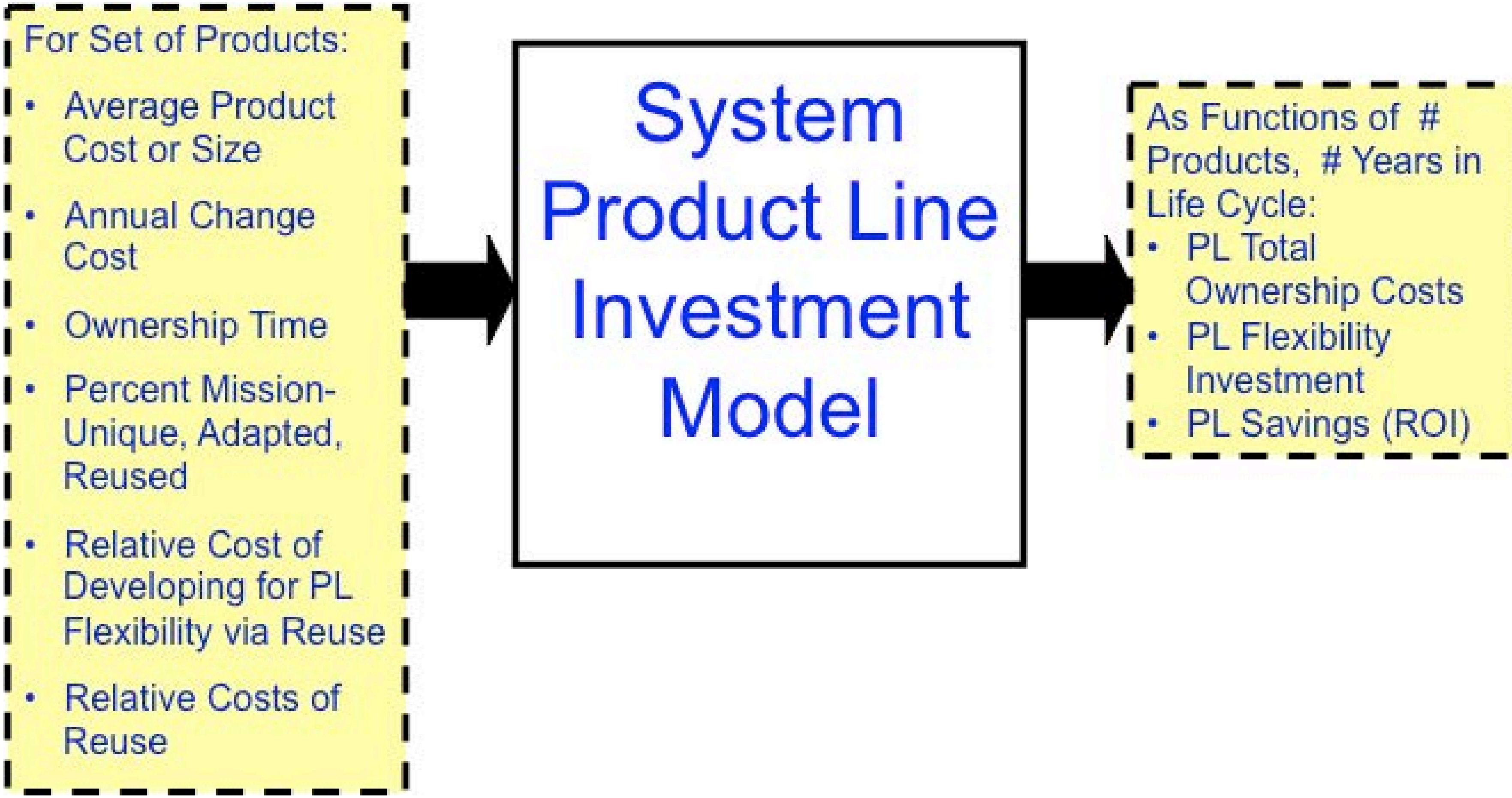
- The Architectural Flow Diagram (AFD) provides a structure for variation point identification necessary for orthogonal variability modeling (OVM) in a product line construct.
  - Variation points are identified for sensors, HSI / consoles, weapons, and data links with alternative choices for a combat system product line which also serve as cost model inputs.



Product Line Cost Modeling

- Total Ownership Cost (TOC) product line models allow decision makers to analyze the economic consequences of alternative system acquisition approaches.
  - They demonstrate 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.
- This research uses a system-level parametric model framework adapted from the Constructive Product Line Investment Model (COPLIMO) to assess the value of investing in product-line flexibility using Return-On-Investment (ROI) and TOC.
- Product line investment modeling addresses 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

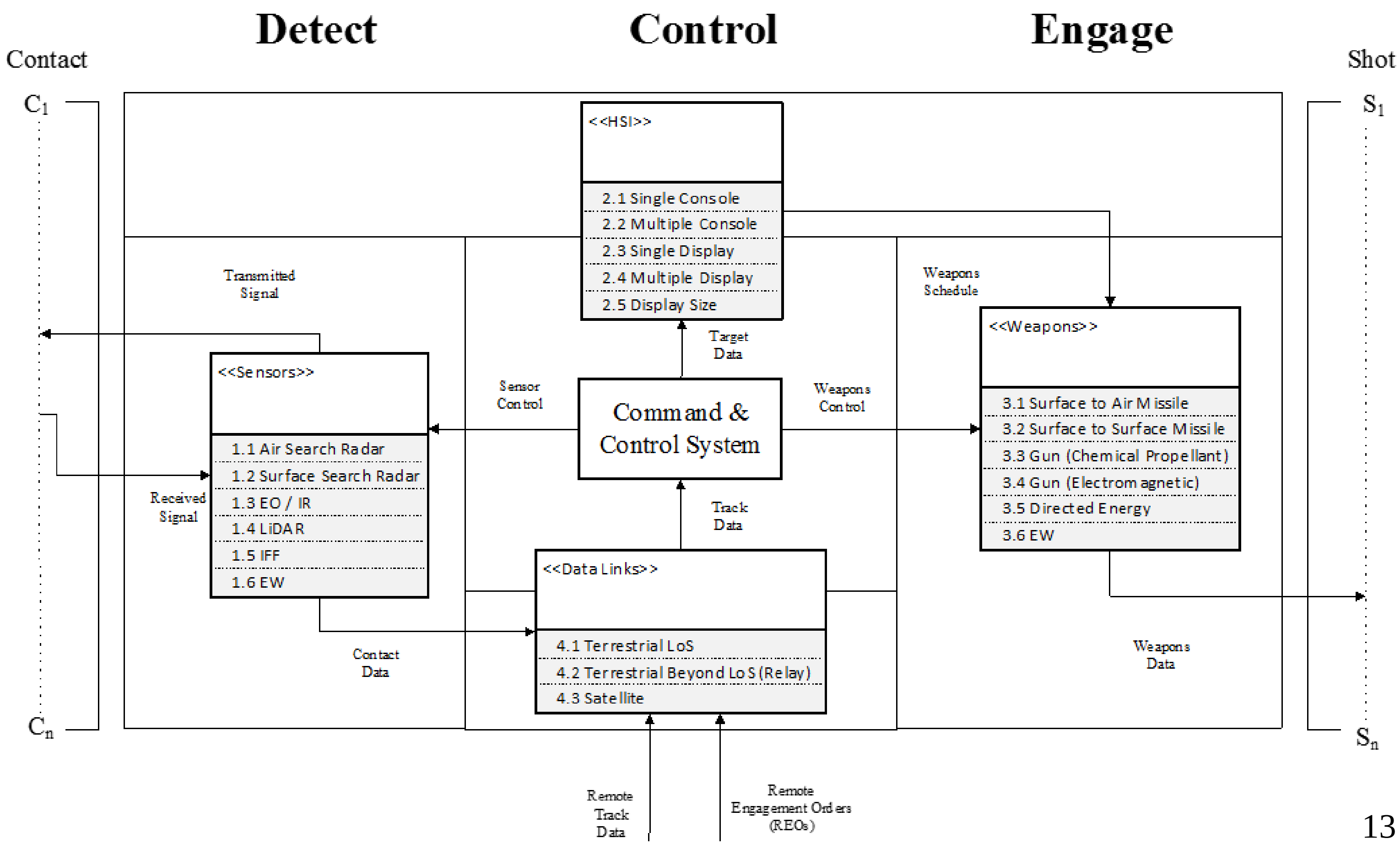
System COPLIMO Inputs/Outputs



Initial Case Study

1. Conducted an architectural analysis of current combat systems (scoped to surface combatant applications)
2. Determined necessary architectural functions and commonalities
3. Modeled a case study 3 Tier Cruise Missile Product Line with increasing capability in each Tier while still utilizing architectural component commonalities
4. Used identified commonalities to determine percentage of unique, reused, and adapted components.
5. Applied percentages to System COPLIMO to determine return on investment of a Product Line approach

Allocated Architectural Flow Diagram



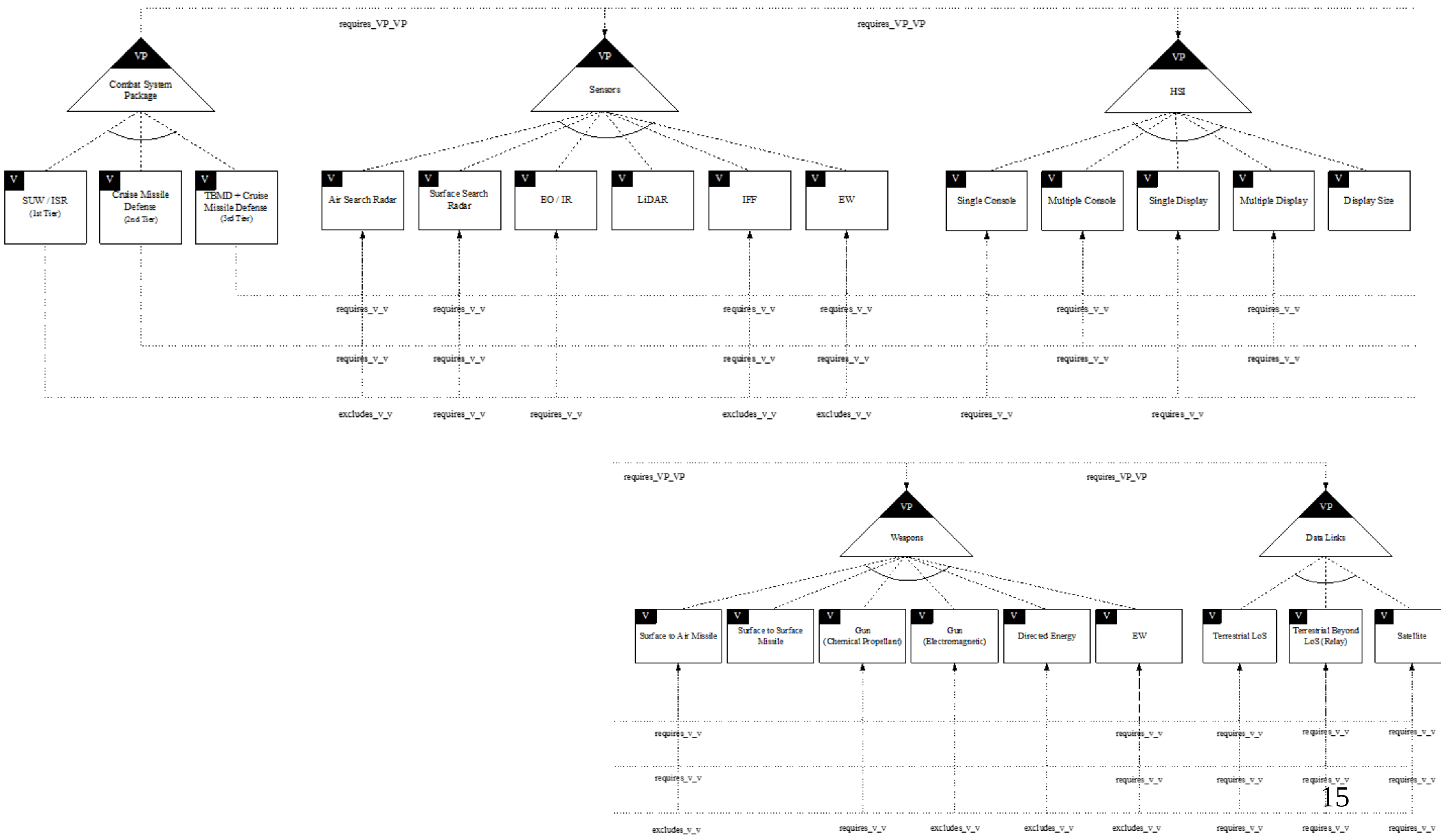
Example Variation Points

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...

Product Line Orthogonal Variable Model



Product Line Components

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.

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System COPLIMO Inputs

- Model Input for Tier 3 Combat System Product Line

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

Cost and Investment Results

- Results for Tier 3 Cruise Missile Product Line

System COPLIMO

System Costs

Average Product Development Cost (Burdened $M) 322 | Ownership Time (Years) 40

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

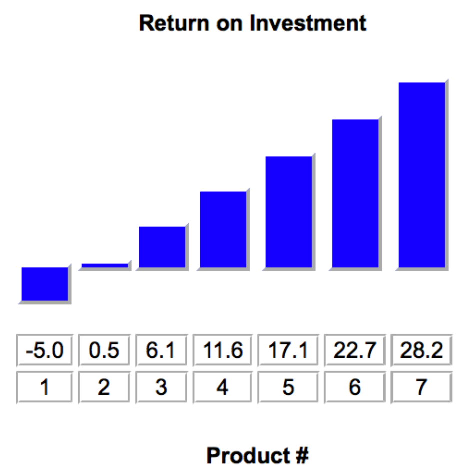
Investment Cost

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)	$1,829.0	$689.1	$689.1	$689.1	$689.1	$689.1	$689.1
Cum. PL Cost ($M)	$2,286.2	$3,147.5	$4,008.9	$4,870.2	$5,731.6	$6,593.0	$7,454.3
PL Flexibility Investment ($M)	$135.2	$0	$0	$0	$0	$0	$0
PL Effort Savings	($676.2)	$72.5	$821.1	$1,569.8	$2,318.4	$3,067.0	$3,815.7
Return on Investment	-5.00	0.54	6.07	11.61	17.14	22.68	28.21



Aegis Case Study Preliminary Results

COPLIMO for Aegis Output Summary

Summary of Inputs:

AVPROD	163	
AVSIZE	2E+06	(SLOC)
UNIQ%	N/A	(%)
ADAP%	N/A	(%)
RUSE%	N/A	(%)
RCR-UNIQ	100	(%)
RCR-ADAP	40	(%)
RCR-RUSE	5	(%)
RCWR	1.78	

Aegis CSL Product Line Effort Savings:

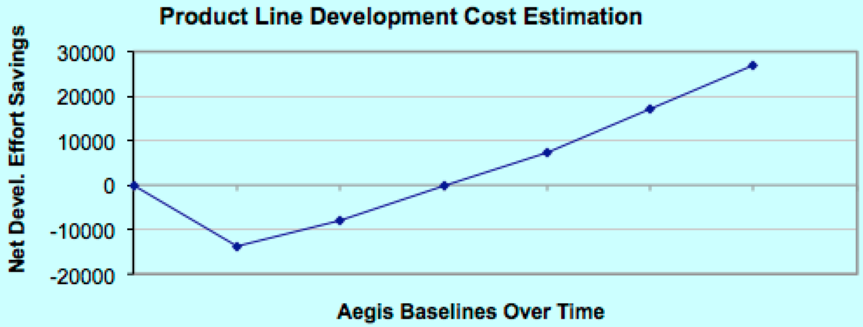


Table of Results:

# of Products	0	1	2	3	4	5	6	
Aegis Baseline		A	B	C	D	E	F*	
Unique SLOC	0	33575	202466	411861	197600	396499	190855	
Adapted SLOC	0	561755	622495	746053	805333	924283	981539	
Reused SLOC	0	1277188	1250023	1328931	1681511	1760161	2099404	
Total Non-PL SLOC	0	1066689	2321131	3898714	5493417	7398031	9319753	
Non-PL Effort (PM)	0	6544	14240	23918	33702	45387	57176	
1-Product Equiv. SLOC	0	3306894	322136	322136	322136	322136	322136	
1-Product Equiv. Effort	0	20288	1976	1976	1976	1976	1976	
Cum. Equiv. PL SLOC	0	3306894	3629030	3951166	4273303	4595439	4917576	
Cum. PL Effort	0	20288	22264	24240	26217	28193	30169	
PL Effort Savings	0	-13744	-8024	-322	7485	17194	27007	
PL Reuse Investment	0	13744						
Return on Investment		-1	-58.38%	-2.34%	54.46%	125.10%	196.51%	

Conclusions

- High level system architecture design for future U.S. Navy combat systems should focus on the product line, instead of platform specific combat systems. Plan for the reuse of system components over time.
- 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.
- Initial case study results indicate a strong ROI when using a product line approach for Naval combat systems.
- Applying the engineering product line methodology to combat system architecture design and development needs to happen at the earliest stage of design.

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Future Work

- Develop 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 be further decomposed into third and fourth levels to provide greater level of detail at the subsystem level.
- Test Enhanced Data Flow and Architectural Flow Diagrams in simulation software, following the detect, control, engage paradigm for different mission scenarios.
- Collect more empirical data to further validate COPLIMO at a system level, instead of using software engineering default calibrations.
- Continue improving cost estimation fidelity
  - Accounting for individual component complexities in effort model.
  - Using product-specific inputs for subsequent products vs. homogeneity of change percentages.

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