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System Product Line Cost and Investment Modeling Applied to UUVs

Acknowledgments

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  - Office of the Deputy Assistant Secretary of Defense for Systems Engineering (ODASD(SE))
  - Naval Postgraduate School Acquisition Research Program

Introduction

- The Constructive Product Line Investment Model (COPLIMO) framework has been applied and extended across Naval domains at NPS.
  - Product line defined as a set of systems that share a **common, managed set of features that satisfy the specific needs** of a particular market segment or mission developed from a common set of core assets in a prescribed way.
- A basic reuse and investment model is elaborated for the product line systems under consideration.
- Cost models are adapted for different system types, processes, and estimation relationships at the systems and software levels.
- Active student research on group capstones and individual theses on combat system product line architectures and costs using Model-Based Systems Engineering (MBSE) methods with COPLIMO variants.
- Virtually all case studies have demonstrated high ROI of product line practices on defined DoD missions.

UUV Case Study Overview

- Research has been investigating the systems and cost-effectiveness of unmanned system product lines integrating Model-Based Systems Engineering (MBSE) methods and parametric cost modeling.
- The modeling framework includes COPLIMO for product line cost estimation and investment analysis, the Constructive Systems Engineering Cost Model (COSYSMO) 2.0 for reuse, MBSE requirements and activity modeling.
- A recent case study investigated the economics of a product line approach to UUVs for strategic missions demonstrating ROI of nearly 500% across the defined DoD missions.

Cost and Investment Modeling

- Using parametric *Constructive* cost models for systems, software and hardware development costs.
- Extended with modeling of product line investment cost and return-on-investment (ROI).
- Investment cost modeling includes factors covering relative costs of developing for reuse and the relative cost of incorporating reused components.
- Each product characterized by portions of mission-unique, modified and black-box reuse.

General Effort Formula for Constructive Cost Models

$$Effort = A * Size^{B} * \prod_{i=1}^{N} EM_i$$

Where

- *Effort* is in Person-Months (PM)
- *A* is a constant derived from historical project data
- *Size* is a measure of the work product
- *B* is an exponent for the diseconomy of scale
- EM_i is an effort multiplier for the i^{th} cost driver. The geometric product of *N* multipliers is an overall Effort Adjustment Factor (EAF) to the nominal effort.

Constructive - A user understands why the model gives the estimate it does, and gains a better understanding of the job being estimated through using the cost model.

Naval Case Studies

System Case Study	Sizing Unit(s)	Equivalent Size Adjustments	Reuse and Investment Model	MBSE models	Empirical Data Used	Baseline System Size for Analysis
Cruise Missile Tiers	system component	reuse category	Basic COPLIMO	OVM, data flows	subsystem costs	20 subsystems
Aegis Ship Software	lines of code	reuse category	Basic COPLIMO		variant lines of code variant cost savings	2.35 MSLOC
ASW Combat System Cross-domain	system component lines of code	reuse category	Basic COPLIMO	requirements models, OVM	system costs system lines of code	18 system components 2.1 MSLOC
DoN UUV Missions	system requirements system interfaces	reuse category complexity level	COSYSMO 2.0	requirements models activity models		57 system requirements 14 system interfaces
Mine Counter Measure UUVs	system requirements system interfaces	reuse category complexity level	COSYSMO 2.0	OVM		16 system components

Models and Tools

Basic COPLIMO

- Supports software product line cost estimation and ROI analysis for full product line life cycle
- Consists of two components
  - Product line development cost model
  - Annualized post-development life cycle extension
- Based on COCOMO II software cost model
  - Statistically calibrated to 161 projects, representing 18 diverse organizations

Basic COPLIMO Black Box Model

For set of products:

- Average product size with COCOMO II cost drivers
- Percent mission-unique, reused-with-modifications, black-box reuse
- Relative cost of reuse (RCR)
- Relative cost of writing for reuse (RCWR) factors

→

Basic COPLIMO

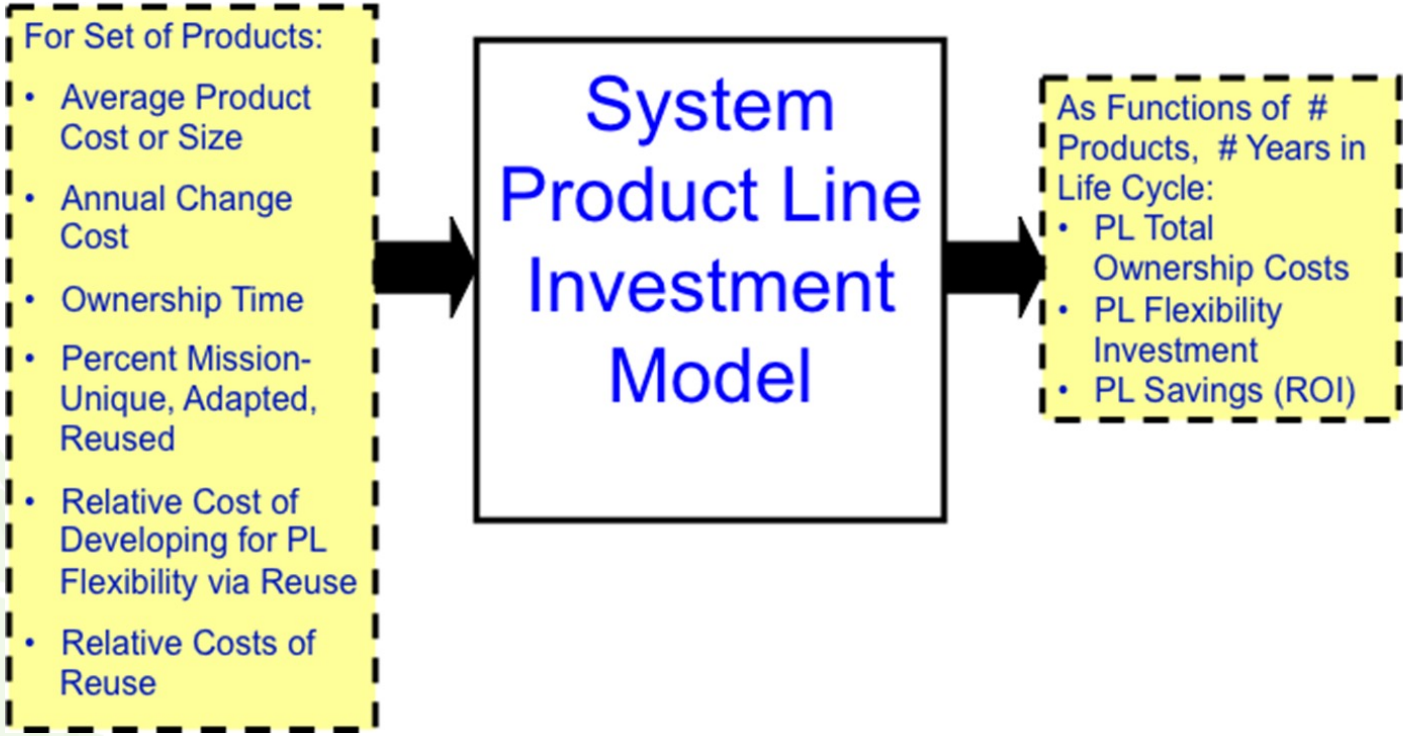
→

As functions of # products, # years in life cycle:

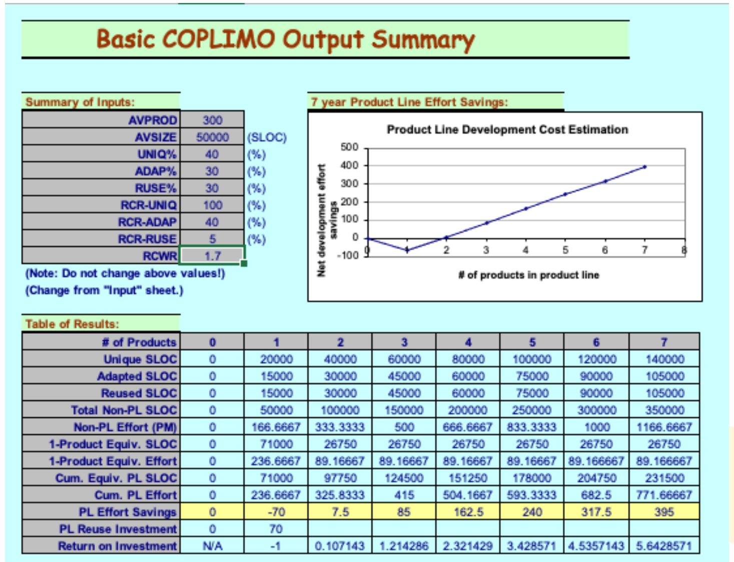
- Non-product line effort
- Product line investment (effort)
- Product line savings (ROI)

System Product Line Investment Model

- Generic system components for software and hardware
- Size-based modeling or direct cost
- Annual change cost and full lifecycle total ownership cost



Selected Tools



Basic COPLIMO Output Summary

Summary of Inputs:

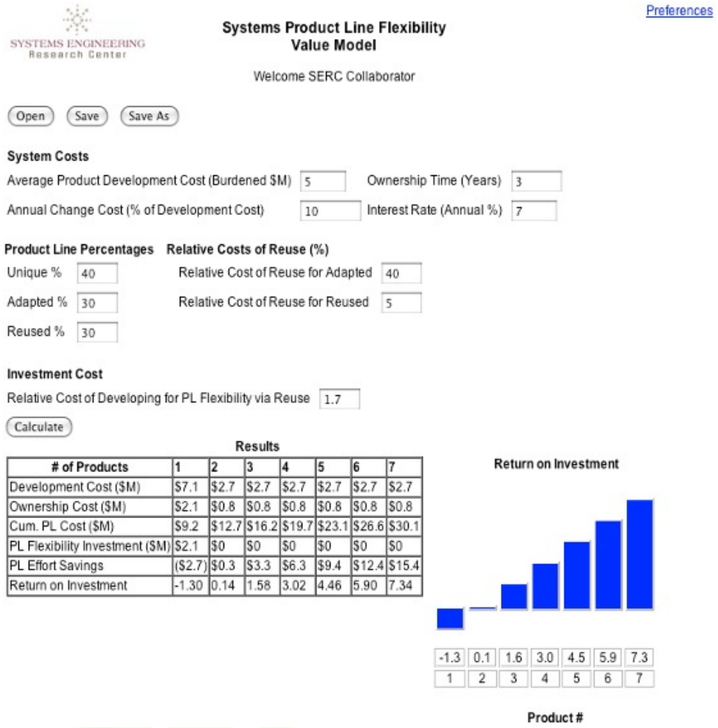
AVPROD	300	
AVSIZE	50000	(SLOC)
UNIQ%	40	(%)
ADAP%	30	(%)
RUSE%	30	(%)
RCR-UNIQ	100	(%)
RCR-ADAP	40	(%)
RCR-RUSE	5	(%)
RCWR	1.7	

(Note: Do not change above values!)
(Change from "Input" sheet.)

7 year Product Line Effort Savings:

Table of Results:

# of Products	0	1	2	3	4	5	6	7
Unique SLOC	0	20000	40000	60000	80000	100000	120000	140000
Adapted SLOC	0	15000	30000	45000	60000	75000	90000	105000
Reused SLOC	0	15000	30000	45000	60000	75000	90000	105000
Total Non-PL SLOC	0	50000	100000	150000	200000	250000	300000	350000
Non-PL Effort (PM)	0	166.6667	333.3333	500	666.6667	833.3333	1000	1166.6667
1-Product Equiv. SLOC	0	71000	26750	26750	26750	26750	26750	26750
1-Product Equiv. Effort	0	236.6667	89.16667	89.16667	89.16667	89.16667	89.166667	89.166667
Cum. Equiv. PL SLOC	0	71000	97750	124500	151250	178000	204750	231500
Cum. PL Effort	0	236.6667	325.8333	415	504.1667	593.3333	682.5	771.66667
PL Effort Savings	0	-70	7.5	85	162.5	240	317.5	395
PL Reuse Investment	0	70						
Return on Investment	N/A	-1	0.107143	1.214286	2.321429	3.428571	4.5357143	5.6428571



SYSTEMS ENGINEERING Research Center

Preferences

Systems Product Line Flexibility Value Model

Welcome SERC Collaborator

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System Costs

Average Product Development Cost (Burdened $M) 5 — Ownership Time (Years) 3
Annual Change Cost (% of Development Cost) 10 — Interest Rate (Annual %) 7

Product Line Percentages: Unique % 40; Adapted % 30; Reused % 30

Relative Costs of Reuse (%): Relative Cost of Reuse for Adapted 40; Relative Cost of Reuse for Reused 5

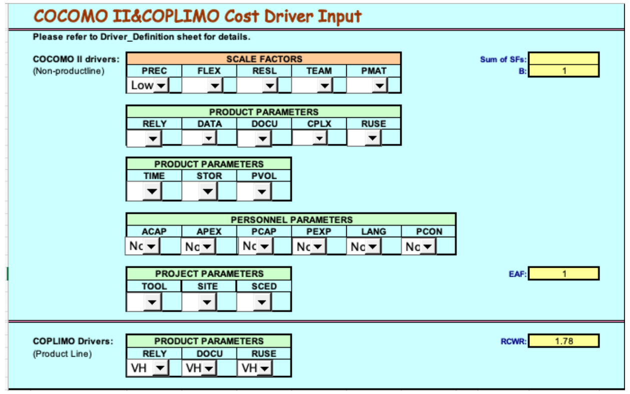
Investment Cost

Relative Cost of Developing for PL Flexibility via Reuse 1.7

Calculate

Results

# of Products	1	2	3	4	5	6	7
Development Cost ($M)	$7.1	$2.7	$2.7	$2.7	$2.7	$2.7	$2.7
Ownership Cost ($M)	$2.1	$0.8	$0.8	$0.8	$0.8	$0.8	$0.8
Cum. PL Cost ($M)	$9.2	$12.7	$16.2	$19.7	$23.1	$26.6	$30.1
PL Flexibility Investment ($M)	$2.1	$0	$0	$0	$0	$0	$0
PL Effort Savings	($2.7)	$0.3	$3.3	$6.3	$9.4	$12.4	$15.4
Return on Investment	-1.30	0.14	1.58	3.02	4.46	5.90	7.34



COCOMO II&COPLIMO Cost Driver Input

Please refer to Driver_Definition sheet for details.

COCOMO II drivers: (Non-productline)

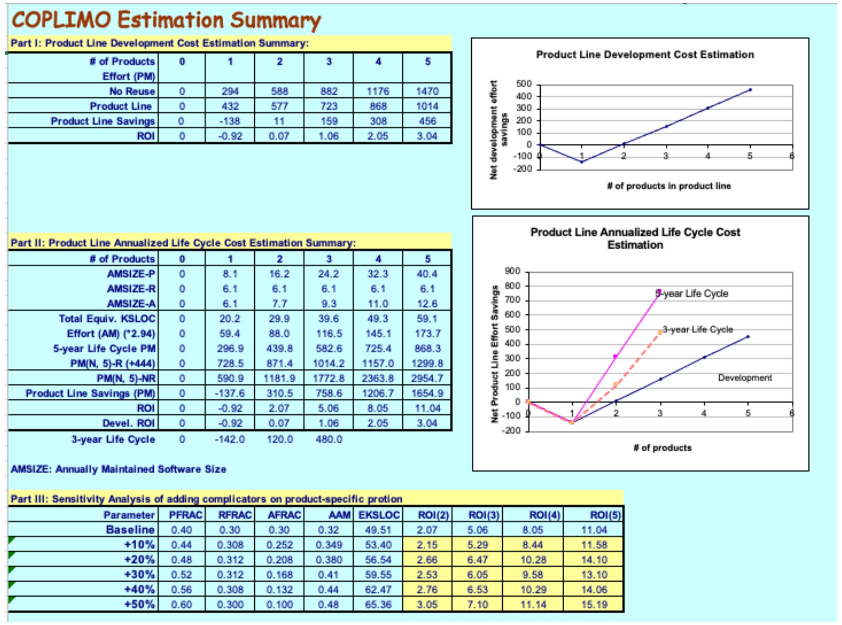
- SCALE FACTORS: PREC (Low), FLEX, RESL, TEAM, PMAT
- PRODUCT PARAMETERS: RELY, DATA, DOCU, CPLX, RUSE
- PRODUCT PARAMETERS: TIME, STOR, PVOL
- PERSONNEL PARAMETERS: ACAP (Nc), APEX (Nc), PCAP (Nc), PEXP (Nc), LANG (Nc), PCON (Nc)
- PROJECT PARAMETERS: TOOL, SITE, SCED

Sum of SFs: | B: 1 | EAF: 1

COPLIMO Drivers: (Product Line)

- PRODUCT PARAMETERS: RELY (VH), DOCU (VH), RUSE (VH)

RCWR: 1.78



COPLIMO Estimation Summary

Part I: Product Line Development Cost Estimation Summary:

# of Products	0	1	2	3	4	5
Effort (PM)						
No Reuse	0	294	588	882	1176	1470
Product Line	0	432	577	723	868	1014
Product Line Savings	0	-138	11	159	308	456
ROI	0	-0.92	0.07	1.06	2.05	3.04

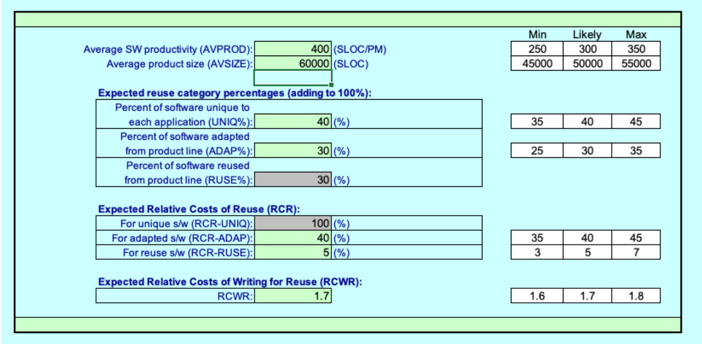
Part II: Product Line Annualized Life Cycle Cost Estimation Summary:

# of Products	0	1	2	3	4	5
AMSIZE-P	0	8.1	16.2	24.2	32.3	40.4
AMSIZE-R	0	6.1	6.1	6.1	6.1	6.1
AMSIZE-A	0	6.1	7.7	9.3	11.0	12.6
Total Equiv. KSLOC	0	20.2	29.9	39.6	49.3	59.1
Effort (AM) (*2.94)	0	59.4	88.0	116.5	145.1	173.7
5-year Life Cycle PM	0	296.9	439.8	582.6	725.4	868.3
PM(N, 5)-R (+444)	0	728.5	871.4	1014.2	1157.0	1299.8
PM(N, 5)-NR	0	590.9	1181.9	1772.8	2363.8	2954.7
Product Line Savings (PM)	0	-137.6	310.5	758.6	1206.7	1654.9
ROI	0	-0.92	2.07	5.06	8.05	11.04
Devel. ROI	0	-0.92	0.07	1.06	2.05	3.04
3-year Life Cycle	0	-142.0	120.0	480.0		

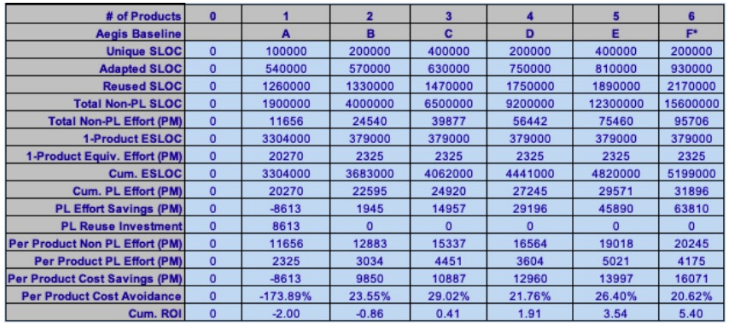
AMSIZE: Annually Maintained Software Size

Part III: Sensitivity Analysis of adding complicators on product-specific protion

Parameter	PFRAC	RFRAC	AFRAC	AAM	EKSLOC	ROI(2)	ROI(3)	ROI(4)	ROI(5)
Baseline	0.40	0.30	0.30	0.32	49.51	2.07	5.06	8.05	11.04
+10%	0.44	0.308	0.252	0.349	53.40	2.15	5.29	8.44	11.58
+20%	0.48	0.312	0.208	0.380	56.54	2.66	6.47	10.28	14.10
+30%	0.52	0.312	0.168	0.41	59.55	2.53	6.05	9.58	13.10
+40%	0.56	0.308	0.132	0.44	62.47	2.76	6.53	10.29	14.06
+50%	0.60	0.300	0.100	0.48	65.36	3.05	7.10	11.14	15.19



	Value	Unit	Min	Likely	Max
Average SW productivity (AVPROD):	400	(SLOC/PM)	250	300	350
Average product size (AVSIZE):	60000	(SLOC)	45000	50000	55000
Expected reuse category percentages (adding to 100%):					
Percent of software unique to each application (UNIQ%):	40	(%)	35	40	45
Percent of software adapted from product line (ADAP%):	30	(%)	25	30	35
Percent of software reused from product line (RUSE%):	30	(%)			
Expected Relative Costs of Reuse (RCR):					
For unique s/w (RCR-UNIQ):	100	(%)			
For adapted s/w (RCR-ADAP):	40	(%)	35	40	45
For reuse s/w (RCR-RUSE):	5	(%)	3	5	7
Expected Relative Costs of Writing for Reuse (RCWR):					
RCWR:	1.7		1.6	1.7	1.8



# of Products	0	1	2	3	4	5	6
Aegis Baseline		A	B	C	D	E	F*
Unique SLOC	0	100000	200000	400000	200000	400000	200000
Adapted SLOC	0	540000	570000	630000	750000	810000	930000
Reused SLOC	0	1260000	1330000	1470000	1750000	1890000	2170000
Total Non-PL SLOC	0	1900000	4000000	6500000	9200000	12300000	15600000
Total Non-PL Effort (PM)	0	11656	24540	39877	56442	75460	95706
1-Product ESLOC	0	3304000	379000	379000	379000	379000	379000
1-Product Equiv. Effort (PM)	0	20270	2325	2325	2325	2325	2325
Cum. ESLOC	0	3304000	3683000	4062000	4441000	4820000	5199000
Cum. PL Effort (PM)	0	20270	22595	24920	27245	29571	31896
PL Effort Savings (PM)	0	-8613	1945	14957	29196	45890	63810
PL Reuse Investment	0	8613	0	0	0	0	0
Per Product Non PL Effort (PM)	0	11656	12883	15337	16564	19018	20245
Per Product PL Effort (PM)	0	2325	3034	4451	3604	5021	4175
Per Product Cost Savings (PM)	0	-8613	9850	10887	12960	13997	16071
Per Product Cost Avoidance	0	-173.89%	23.55%	29.02%	21.76%	26.40%	20.62%
Cum. ROI	0	-2.00	-0.86	0.41	1.91	3.54	5.40

Systems Product Line Flexibility Tool

- Tool at http://coplimo.org/tools/flexibility

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Preferences

Systems Product Line Flexibility Value Model

Welcome SERC Collaborator

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System Costs

Average Product Development Cost (Burdened $M): 5
Ownership Time (Years): 3
Annual Change Cost (% of Development Cost): 10
Interest Rate (Annual %): 7

Product Line Percentages

Unique %: 40
Adapted %: 30
Reused %: 30

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

Results

# of Products	1	2	3	4	5	6	7
Development Cost ($M)	$7.1	$2.7	$2.7	$2.7	$2.7	$2.7	$2.7
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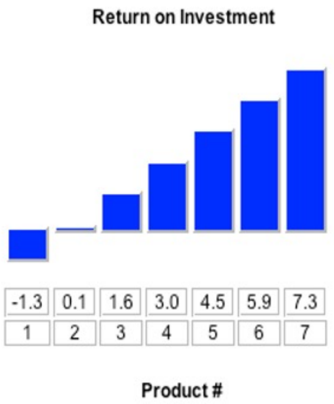
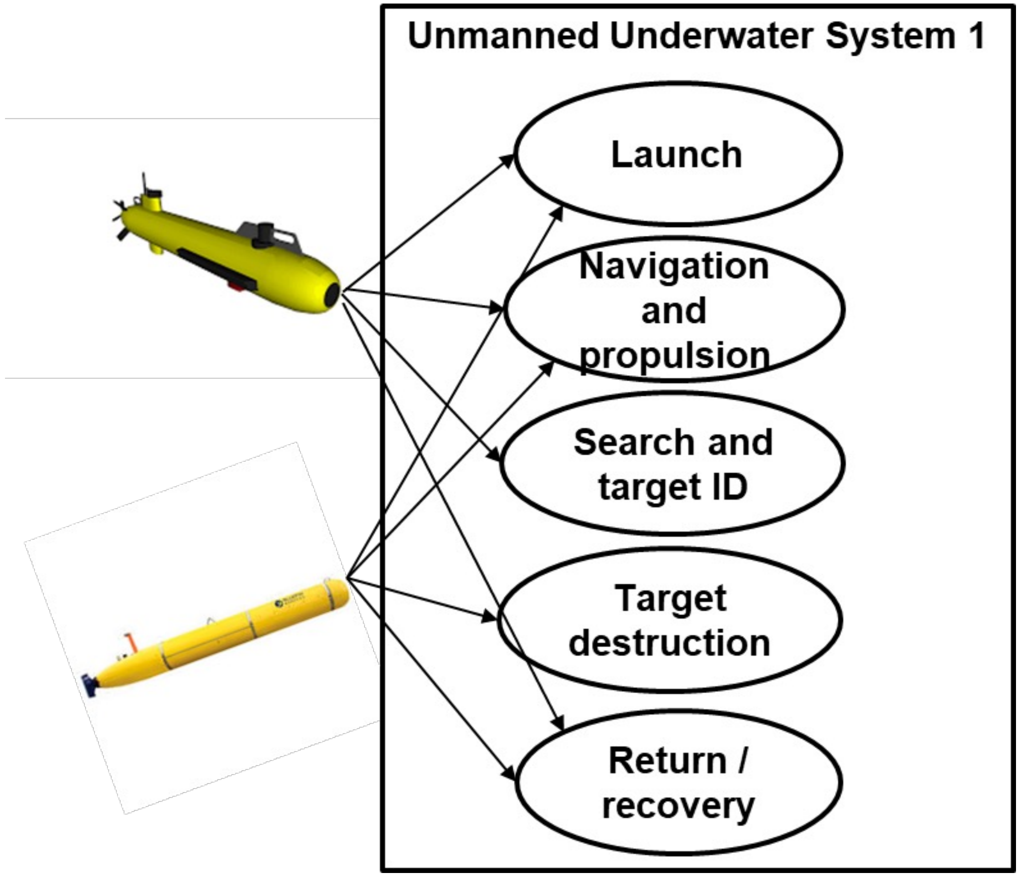
PL Effort Savings	($2.7)	$0.3	$3.3	$6.3	$9.4	$12.4	$15.4
Return on Investment	-1.30	0.14	1.58	3.02	4.46	5.90	7.34



UUV Product Line Case Study

UUV Mission Needs

- The DON requires nine primary missions:
  - Intelligence, Surveillance, and Reconnaissance (ISR)
  - Mine Countermeasures (MCM)
  - Anti-Submarine Warfare (ASW)
  - Inspection and Identification (INID)
  - Oceanography (OO)
  - Communication or Navigation Network Node (CN3)
  - Payload Delivery (PD)
  - Information Operations (IO)
  - Time Critical Strike (TCS).



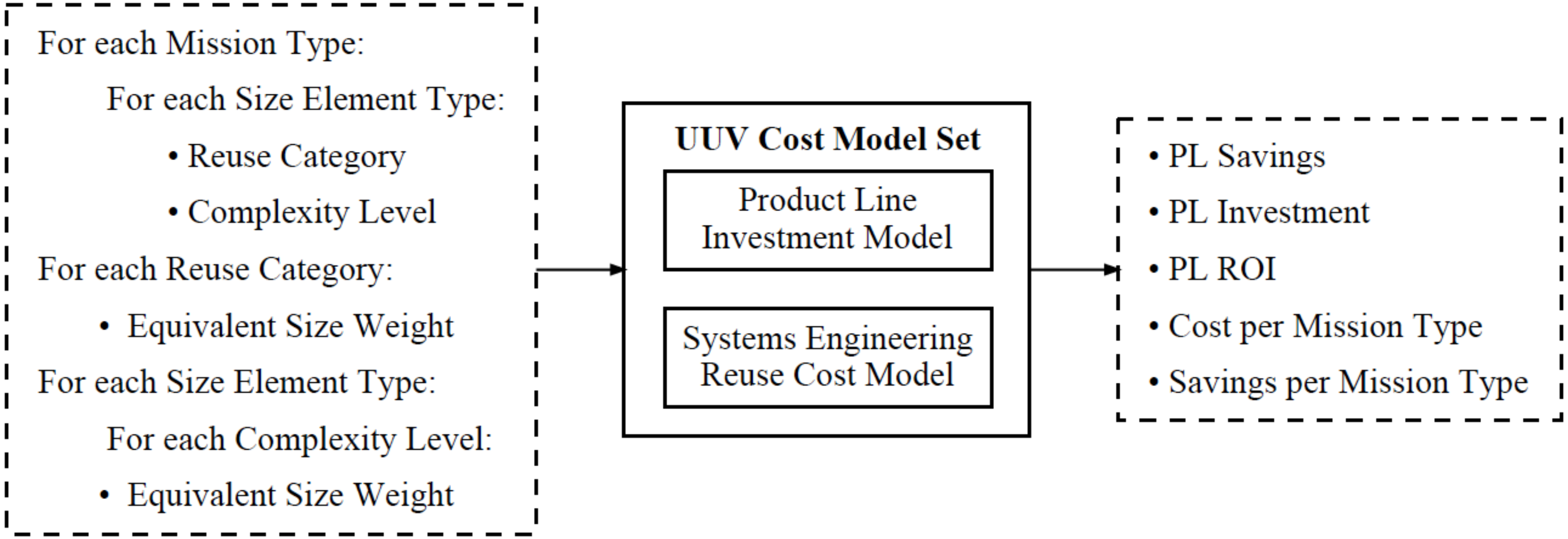
Research Questions

- What is the ROI of a product line approach for UUV systems?
- What is the reuse savings for individual UUV systems?
- What is the size and scope for the resultant systems being developed?
- How much work must be done over time?
- How should the system(s) be architected to best employ reuse?

Method

- Navy UUV mission requirements were elaborated into static requirements models and executable activity models.
- A baseline mission with maximum commonality was identified for initial development and investment from which the other missions would reuse from.
- For each mission type, requirements and interfaces from MBSE models were enumerated and input into the COSYSMO reuse cost model.
  - Each assessed for complexity and reuse type
- Equivalent size for cost model is computed based on weights for complexity and reuse type.
- The savings for subsequent missions are the differences between a traditional non-reuse approach and the product line reuse approach.
- The cumulative ROI is the net savings over time divided by the investment cost based on the relative sizes.

COPLIMO Extended with COSYSMO 2.0 for UUV Missions



Where
Size Element Types = (Requirements, Interface, Algorithms, Scenarios)
Reuse Categories = (New, Designed for Reuse, Modified, Deleted, Adopted , Managed)
Complexity Levels = (Easy, Nominal, Difficult)

COSYSMO 2.0 With Reuse Model

$$PM_{NS} = A \cdot \left[\sum_k \left(\sum_r w_r (w_{e,k}\Phi_{e,k} + w_{n,k}\Phi_{n,k} + w_{d,k}\Phi_{d,k}) \right) \right]^E \cdot \prod_{j=1}^{14} EM_j$$

PM_{NS} = effort in Person Months (Nominal Schedule)

A = calibration constant derived from historical project data

k = {Requirements, Interfaces, Algorithms, Scenarios}

w_x = weight for "easy", "nominal", or "difficult" size driver

r = {New, Design for Reuse, Modified, Deleted, Adopted, Managed}

w_r = weight for reuse category

Φ_x = quantity of "k" size driver

E = represents (dis)economies of scale

EM = effort multiplier for the j^{th} cost driver.

COSYSMO Reuse Categories

Category	***Sub-Category***	***Definition***
I) New		Products that are completely new
	i) Designed for Reuse	Products that require an additional upfront investment to improve the potential reusability
II) Modified		Products that are inherited, but are tailored
	ii) Deleted	Products that are removed from the system
III) Adopted		Products that are incorporated unmodified (a.k.a. "black box" reuse)
	iii) Managed	Products that are incorporated unmodified and with minimal testing

Reuse Categories in MBSE Context

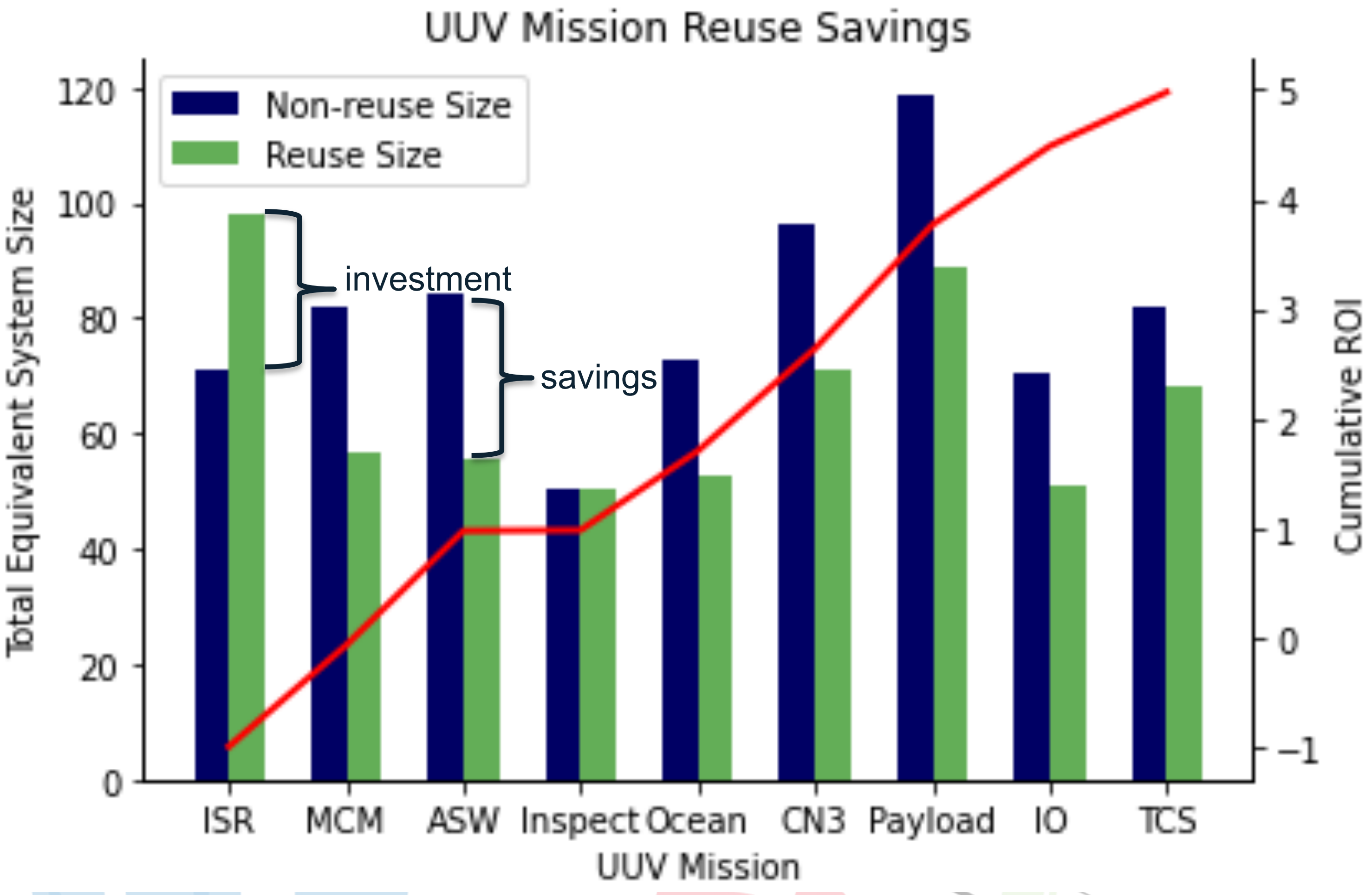
Category	Definition for Requirements	Definition for Interfaces	Weight
New	Similar requirement does not exist in the baseline (completely new)	Similar interface does not exist in the baseline (completely new)	1.00
Designed for Reuse	New requirement and includes extra investment to enable potential reusability	New interface and includes extra investment to enable potential reusability	1.38
Modified	Change to the requirement's Measures of Effectiveness (MOEs)	Interface is tailored to the mission	0.65
Deleted	Similar requirement does not exist in new system	Similar interface does not exist in new system	0.51
Adopted	Change to the requirement's Measures of Performance (MOPs)	Interface is incorporated unmodified with testing	0.43
Managed	Requirement does not change from the baseline	Interface is incorporated unmodified with minimal testing	0.15

Requirements Examples

ISR Req #	ISR (Baseline Requirements)	Complexity	Reuse Category	Rationale
R1.0.1	The UUV shall be capable of completing a mission of 6 duration (in hours)	Difficult	Designed for Reuse	ISR designed for reuse
R1.0.2	The UUV shall be capable of a top speed of 14 knots	Difficult	Designed for Reuse	ISR designed for reuse
R1.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of 1500 meters	Nominal	Designed for Reuse	ISR designed for reuse
R1.0.4	The UUV shall avoid detection	Difficult	Designed for Reuse	ISR designed for reuse
R1.1.1	Mission parameters shall be uploadable to the UUV	Nominal	Designed for Reuse	ISR designed for reuse
R1.1.2	The UUV shall receive remote commands	Nominal	Designed for Reuse	ISR designed for reuse
R1.1.3	The UUV shall commence its mission when commanded	Easy	Designed for Reuse	ISR designed for reuse
R1.1.4	The UUV shall be capable of transmitting data in a host vessel compatible format	Nominal	Designed for Reuse	ISR designed for reuse
R1.1.5	The UUV shall indicate that it is ready for recovery	Easy	Designed for Reuse	ISR designed for reuse

MCM Req #	MCM Requirements	Reuses	Complexity	Reuse Category	Rationale
R2.0.1	The UUV shall be capable of completing a mission of 6 duration (in hours)	R1.0.1	Difficult	Modified	Similar requirement, but mission lengths can vary between ISR and MCM missions.
R2.0.2	The UUV shall be capable of a top speed of 14 knots	R1.0.2	Difficult	Modified	Similar requirement, but mission spec'd requirements can vary between ISR and MCM missions.
R2.0.3	The UUV shall be capable of surviving in an open ocean environment to a depth of 1500 meters	R1.0.3	Nominal	Modified	Similar requirement, but mission depth and environmental conditions can vary between ISR and MCM missions.
R2.0.4	The UUV shall avoid detection	R1.0.4	Difficult	Adopted	Similar requirements to ISR, but mission location and payloads may differ
R2.1.1	Mission parameters shall be uploadable to the UUV	R1.1.1	Nominal	Managed	Mission parameters should use the same hardware and software interfaces across the UUV mission types.
R2.1.2	The UUV shall receive remote commands	R1.1.2	Nominal	Managed	Ability to receive remote commands is a basic function; Processing is covered by separate requirements
R2.1.3	The UUV shall commence its mission when commanded	R1.1.3	Easy	Managed	"Begin Mission" command should not change from mission to mission.
R2.1.4	The UUV shall indicate that it is ready for recovery	R1.1.5	Easy	Managed	UUV will be recovered across all missions.
R2.2	The UUV shall be deployable from pier or vessel	R1.2	Nominal	Managed	UUVs will need to be deployed pierside or from a vessel, similar to ISR.

UUV Product Line Reuse Savings and ROI



ISR: Intelligence, Surveillance, Reconnaissance
MCM: Mine Countermeasures
ASW: Anti-Submarine Warfare
Inspect: Inspection and Identification
Ocean: Oceanography
CN3: Communication or Navigation Network Node
Payload: Payload Delivery
IO: Information Operations
TCS: Time Critical Strike

Conclusions

- System architectures for unmanned systems should focus on the product line, instead of mission specific systems. Plan for the reuse of system components over time.
- 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.
- Case study results indicate a strong ROI when using a product line approach for UUV systems.
- Applying the engineering product line methodology to system architecture design and development needs to happen at the earliest stage of design.

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