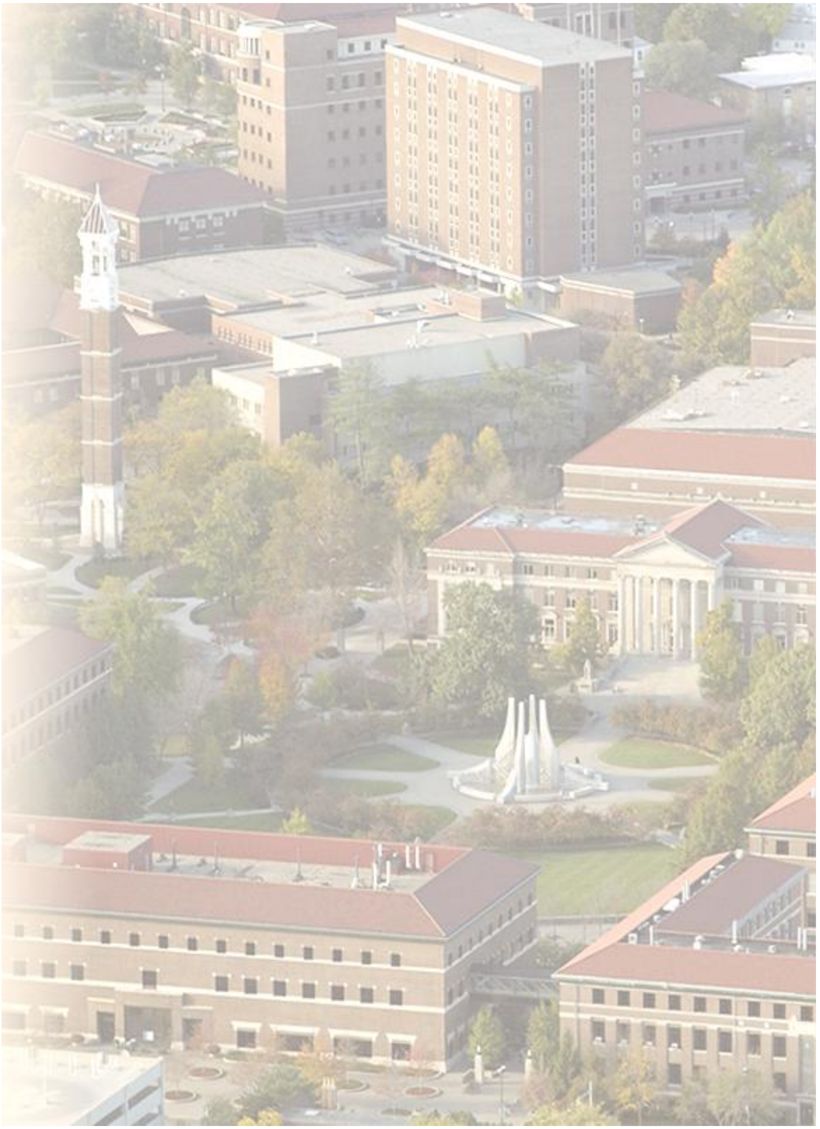
Capability and Development Risk Management in System-of-Systems Architectures: A Portfolio Approach to Decision Making



NPS Acquisition Research Symposium
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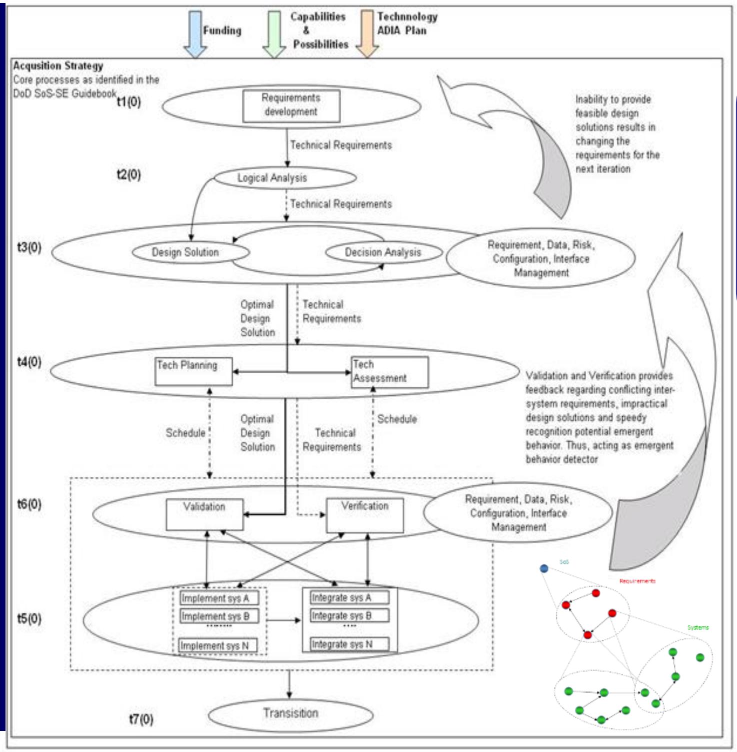
Presentation Outline

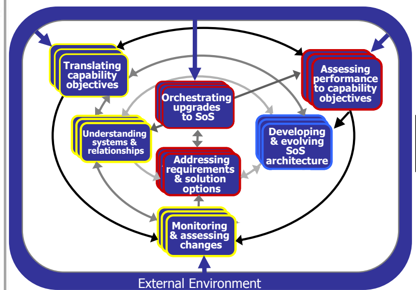
- The Big Picture
- SoS Architecting and Acquisition: Wave Model context
- An Investment Portfolio Approach
  - Mean Variance Approach
  - Mean-Variance: A Robust Version
- Concept Problem: Simple Littoral Combat Ship (LCS)
  - Robust Portfolio application
  - Multiple risk measures
- Future Work

The Big Picture ....

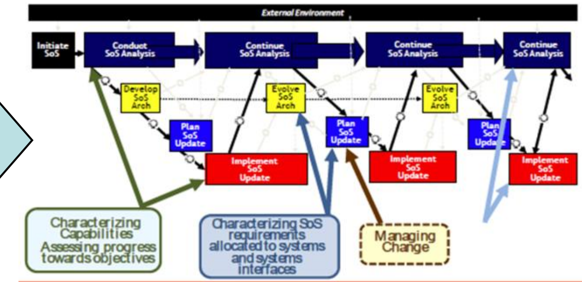
DoD SoSE Guidebook

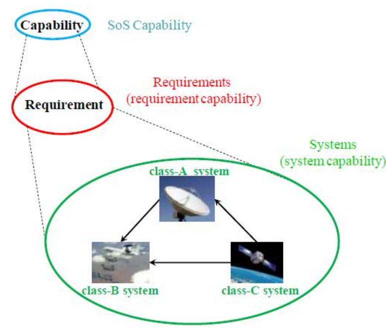


Trapeze

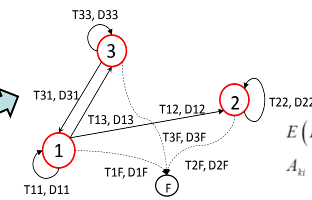


Wave Model





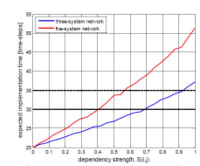
Markov

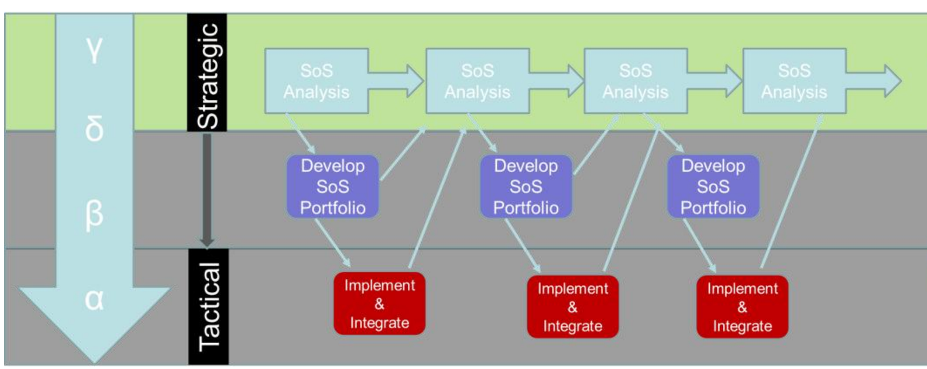


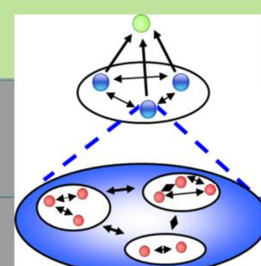
$$E\left(F \mid x_j(0)\right) = cA\left(I - A\right)^{-2} b$$

$$A_{ki} = P\left(x_k(n+1) \mid x_i(n)\right)$$

CEM

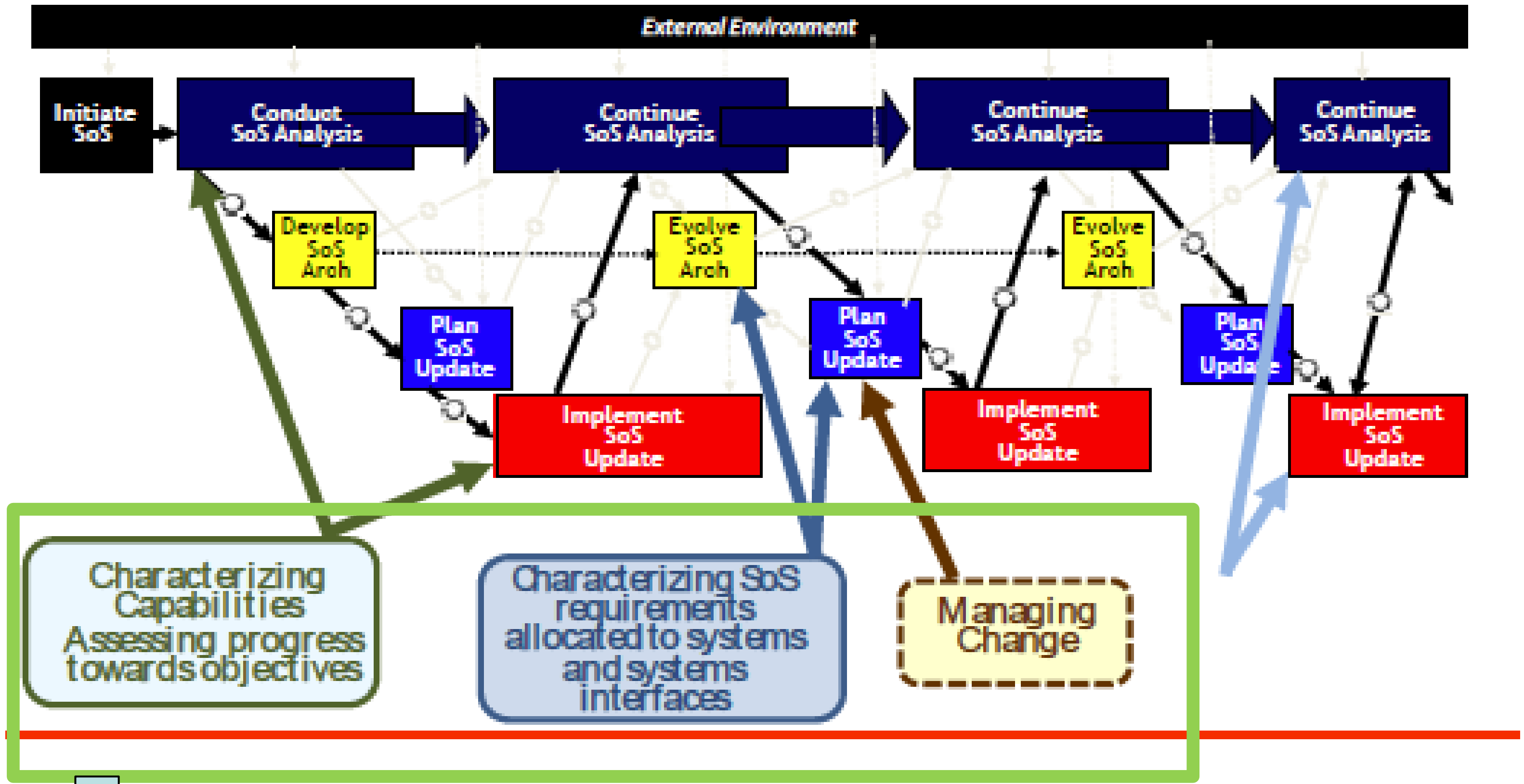






Methods	Nature	Inputs
CEM	Discrete Event Simulation	Probabilities, Connectivities
Markov	Probabilistic Graphical	Probabilities, Connectivities
Bayesian Network (BN)	Probabilistic Graphical	Conditional Distribution Connectivity
Portfolio Approach	Decision/Analysis based	Capabilities, Requirements, Connection rules

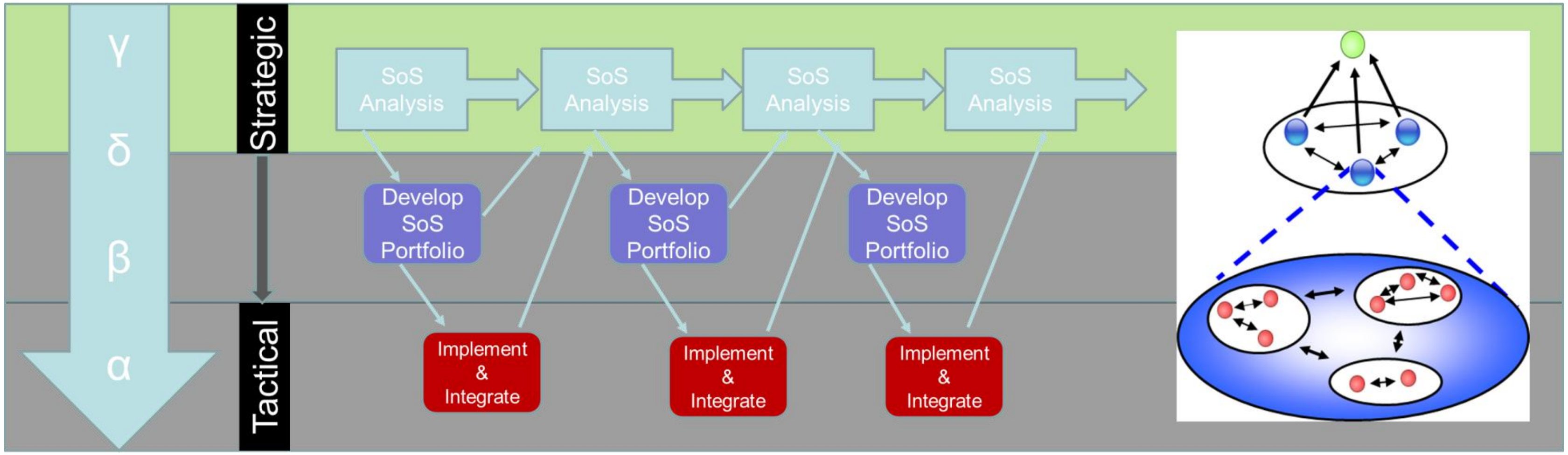
Wave Model*: SoS Architecture Development



How do we support these actions for SoS acquisitions?

*adapted from Dahmann et. al, "Integrating Systems Engineering and Test & Evaluation in System of Systems Development" IEEE Vancouver, 2011

Wave Model: Acquisition and Architecture

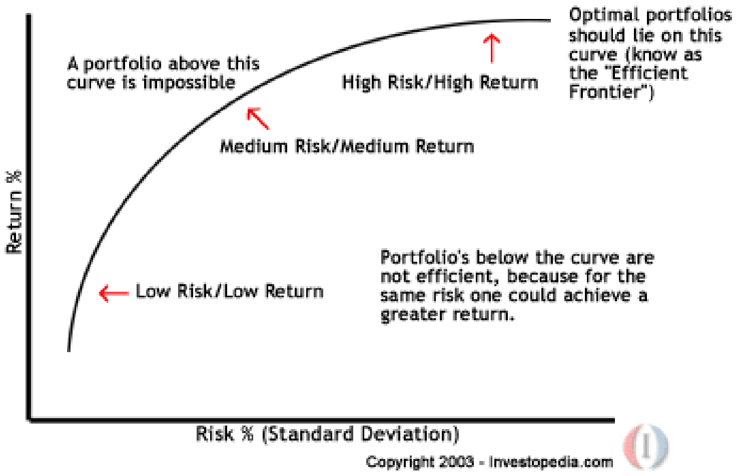


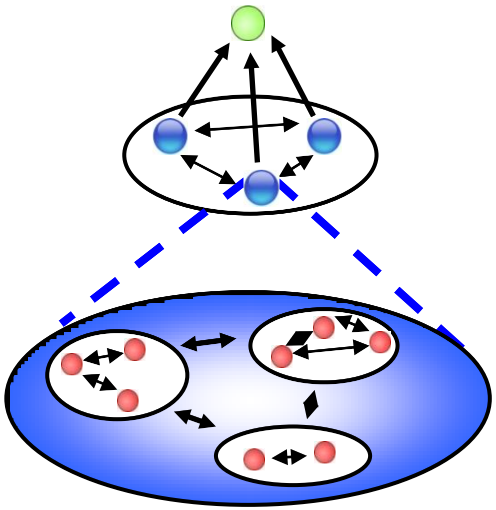
- How to leverage acquiring capabilities against associated risk?
  - Evolving requirements, Open Architectures (OA)
- What about system interdependencies?

- What about acquisition uncertainty considerations?
  - SRL, TRL, operational/developmental characteristics

A Portfolio Approach: Background

- Classical **Mean-Variance optimization** among techniques adopted by financial engineering and operations research.
- Balance **expected profit (performance) against risk (variance)** in investments
- Generates efficiency frontier of optimal portfolios given investor risk averseness
- Extends current frameworks (Housel, Mun, et.al)
- Systems (nodes) can be modeled as potential investment assets→ how do we invest?





Nodes = systems

Mean-Variance Portfolio Approach

Objective

Maximize Performance Index

Capability | Risk | Cost

$$\max\left(\underbrace{\sum_q\left(\frac{S_{qc}-R_c}{R_c}\cdot w\cdot X_q^B\right)}_{\text{Capability}}\underbrace{-\lambda\left(X_q^F\right)^T\Sigma_{ij}X_q^F}_{\text{Risk}}\underbrace{-\sum_q\left(C_qX_q^B\right)}_{\text{Cost}}\right)$$

Constraints

Portfolio Fraction

$$X_q^F=\frac{X_q^BC_q}{\text{Budget}}\ \text{(Portfolio Fractions)}$$

Portfolio Total Budget

$$\sum_q C_qX_q^B+\varepsilon=\text{Budget}\ \text{(Budget Constraint)}$$

Requirements Satisfaction

$$\sum_q S_{qC}X_q^B\geq\sum_q S_{qR}X_q^B\ \text{(Satisfy All System Requirements)}$$

Selection Rules (Compatibility)

$$X_1^B+X_1^B+X_1^B=1\ \text{(ASW System Compatibility)}$$

$$X_4^B+X_5^B=1\ \text{(MCM System Compatibility)}$$

$$X_6^B+X_7^B=1\ \text{(SUW System Compatibility)}$$

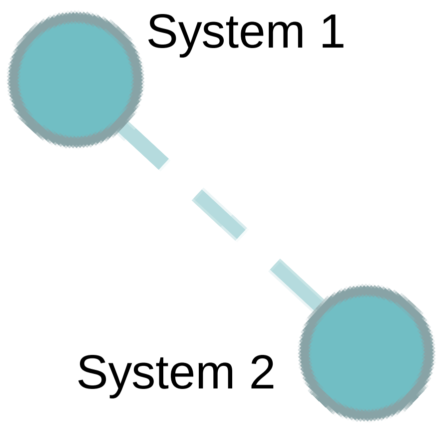
$$X_8^B+X_9^B+X_{10}^B=1\ \text{(Package System Compatibility)}$$

Uncertainty in Covariance (Interdependencies)

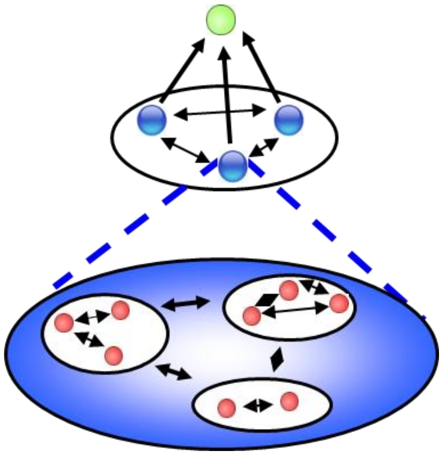
$$\Sigma_{ij}^L\leq\Sigma\leq\Sigma_{ij}^U$$

Portfolio Uncertainty

- Sources of uncertainty
  - **System Capability**: Actual performance of system individually and as a whole SoS entity
  - **System Interdependence**: Interdependency variances/covariances?



- Addressing uncertainty
  - Operations Research/Financial Engineering Methods to address uncertainty measures
  - Introduce uncertainty in interdependencies and individual asset performances
  - Introduce SoS connectivity in portfolio space



Mean-Variance Portfolio: Robust Approach

Objective

Maximize Performance Index

Capability | Risk | Cost

$$\max\left(\sum_q\left(\frac{S_{qc}-R_c}{R_c}\cdot w\cdot X_q^B\right)-\lambda\left\{\langle\bar{\Lambda}\Sigma\rangle-\langle\underline{\Lambda}\Sigma\rangle\right\}-\sum_q\left(C_q X_q^B\right)\right)$$

Constraints

Portfolio Fraction

$$X_q^F=\frac{X_q^B C_q}{\text{Budget}}\ \text{(Portfolio Fractions)}$$

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$$X_8^B+X_9^B+X_{10}^B=1\ \text{(Package System Compatibility)}$$

Reformulate as SDP (Tutuncu & Koenig 2004)

$$\begin{bmatrix}\bar{\Lambda}-\underline{\Lambda} & X_q^F\\ X_q^{F\,\prime} & 1\end{bmatrix}\succeq 0\ \text{(Linear Matrix Inequality)}$$

$$X_q^B\in\{0,1\}\ \text{(binary)}$$

Robust Portfolio Case Study: Simple LCS Portfolio

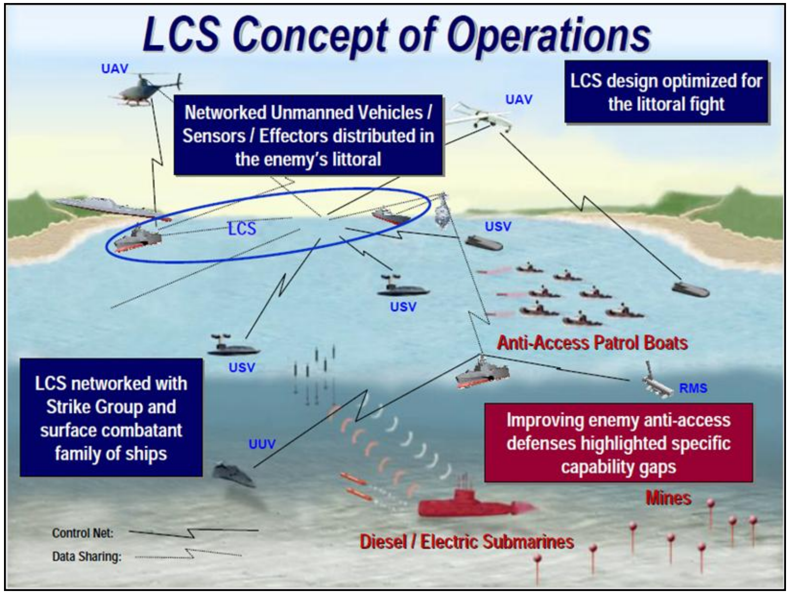


Table 2: System interdependency and development risk (covariance)

	able Depth	ti Fcn Tow	tweight tow	MCS II	IDS (MH-60)	S Missiles	fin Missiles	kage System 1	kage System 2	kage System 3
Package System 2	0	0.1	0	0.2	0	0.1	0	0	0.3	0
Package System 3	0	0	0.2	0	0.3	0	0	0	0	0.2

Diagonal : System Variance

Off Diagonal : System Interdependency

Table 1: Individual system information

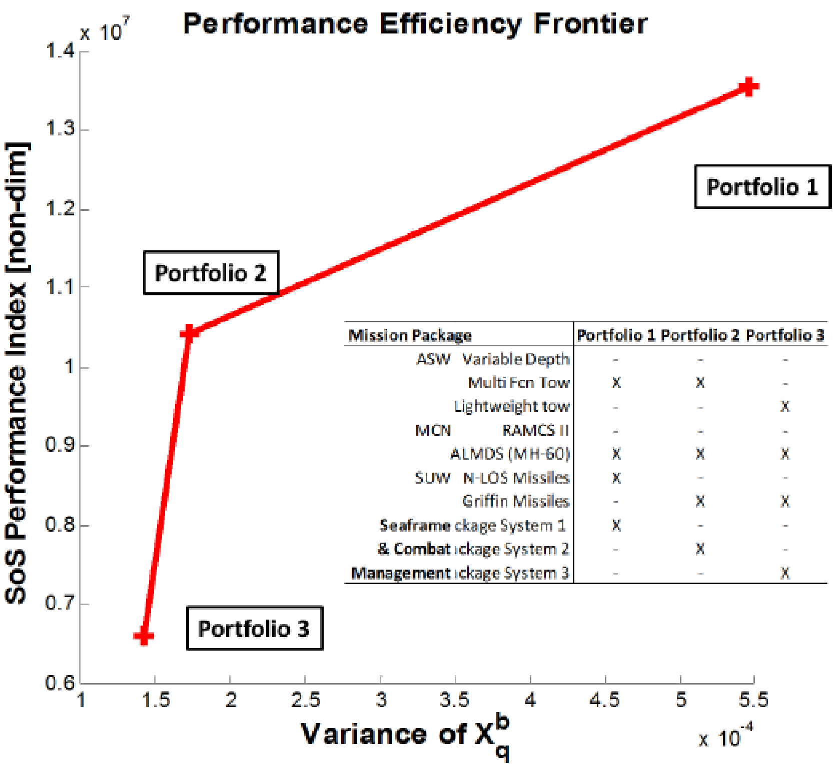
Capability

Requirement

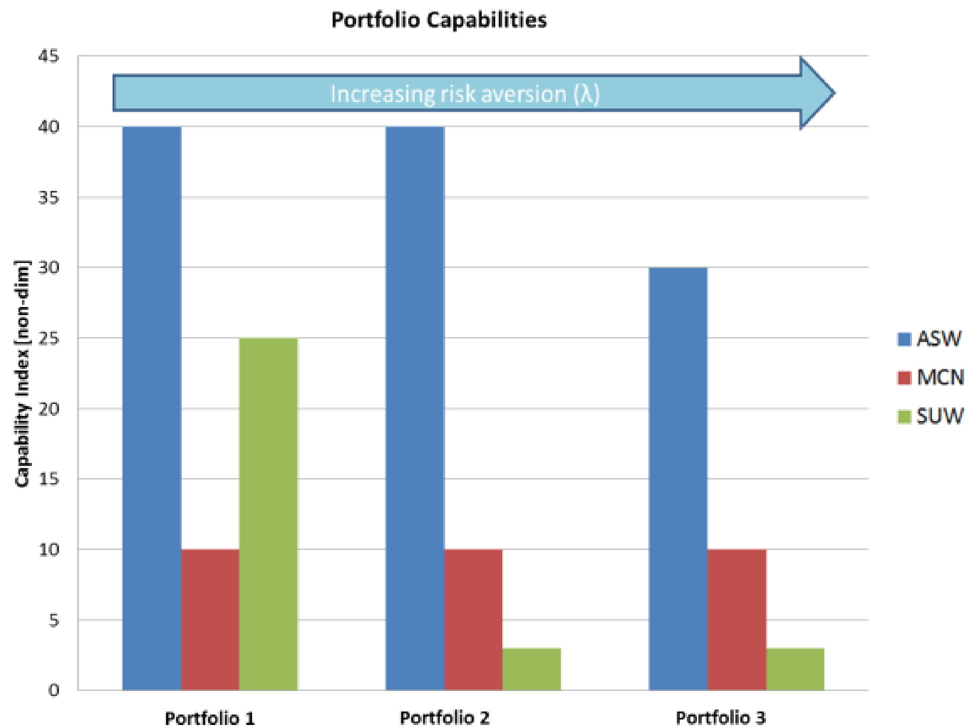
		System Capabilities					System Req		Develop. Time	Acq. Cost
		Weapon Strike Range	Threat Detection Range	Anti Mine Detection Speed	Comm. Capacity	Air/Sea State Capacity	Air/Sea State	Comm.	(Years)	($)
Package										
ASW	Variable Depth	0	50	0	0	0	0	250	3	3000000
	Multi Fcn Tow	0	40	0	0	0	0	150	2	2000000
	Lightweight tow	0	30	0	0	0	0	100	4	4000000
MCN	RAMCS II	0	0	40	0	0	3	200	1	1000000
	ALMDS (MH-60)	0	0	30	0	0	4	100	2	2000000
SUW	N-LOS Missiles	25	0	0	0	0	0	200	3	3000000
	Griffin Missiles	3	0	0	0	0	0	100	4	4000000
Seaframe	'ackage System 1	0	0	0	400	4	0	0	3	3000000
& Combat	'ackage System 2	0	0	0	300	4	0	0	4	4000000
Management	'ackage System 3	0	0	0	250	3	0	0	5	5000000

Image from: Presentation slides by RDML Vic Guillory of OPNAV at Mine Warfare Association Conference (titled "Littoral Combat Ship", 08-May-07)

Robust Portfolio Case Study: Simple LCS Portfolio

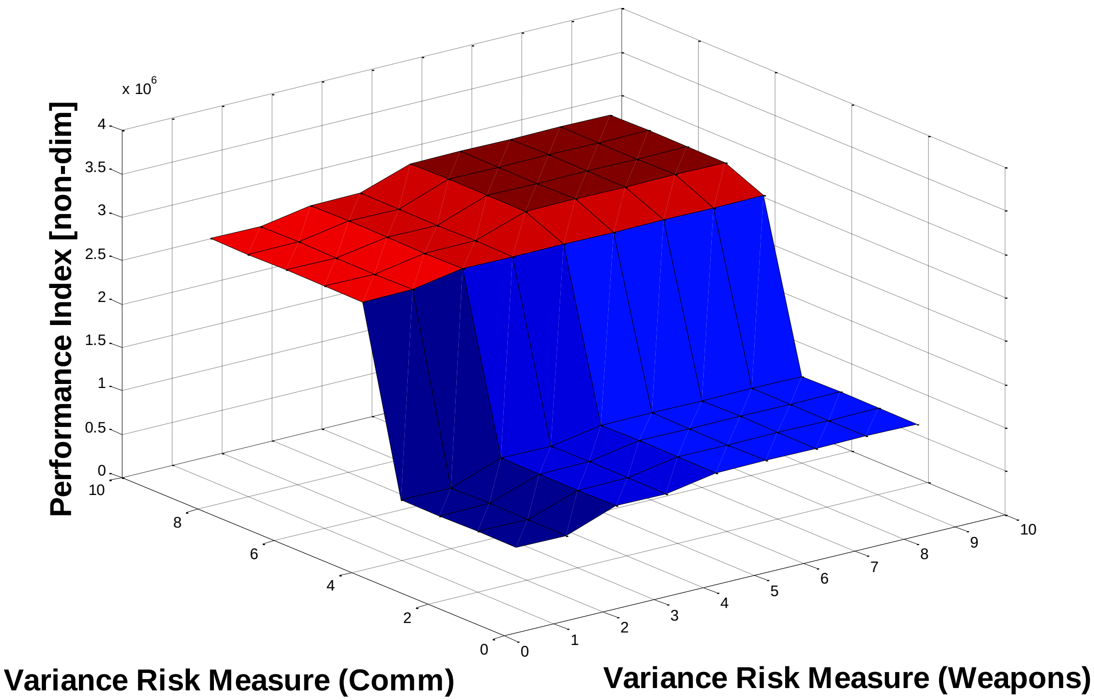


Mission Package		Portfolio 1	Portfolio 2	Portfolio 3
ASW	Variable Depth	-	-	-
	Multi Fcn Tow	X	X	-
	Lightweight tow	-	-	X
MCN	RAMCS II	-	-	-
	ALMDS (MH-60)	X	X	X
SUW	N-LOS Missiles	X	-	-
	Griffin Missiles	-	X	X
Seaframe	ckage System 1	X	-	-
& Combat	ıckage System 2	-	X	-
Management	ıckage System 3	-	-	X



Portfolio Approach: LCS Multiple Risk Measures

- Layered measure of risk (e.g. weapons vs. communications layer).
- Separate covariance for each measure of risk



Comm. Variance (Risk) Constraint

$$\sqrt{\left(X_i^B\right)^T \Sigma_{ij}^{comm} X_i^B} \le \sigma_{comm}$$

Weapon Variance (Risk) Constraint

$$\sqrt{\left(X_i^B\right)^T \Sigma_{ij}^{weapons} X_i^B} \le \sigma_{weapon}$$

Summary/Conclusion

- RMVO promising framework to leverage SoS performance against risk
- Considers uncertainty and system interdependencies explicitly in portfolio construction
- Needs more realistic data (performance, interdependencies) for real world application and verification

Portfolio Approach: Future Work

- Extend to multi-period considerations
  - How do I make investment decisions in changing environments?
  - Can I hedge my bets for future anticipations?
    - (e.g. price of steel in LCS program?)
  - Do my decisions now allow me to <u>learn</u> for the future?
    - Similar technologies, frameworks ➔ knowledge space?

$$\max \underbrace{\left(\sum_q \left(\frac{S_{qc} - R_c}{R_c} \cdot w \cdot X_q^B \right) - \lambda \left(X_q^F \right)^T \Sigma_{ij} X_q^F - \sum_q \left(C_q X_q^B \right) \right)}_{A}{}_t + E\left(A_{t+1} \mid w_{t+1}, \Sigma_{t+1}, \lambda_{t+1} \right)$$

Capability vs. Risk now

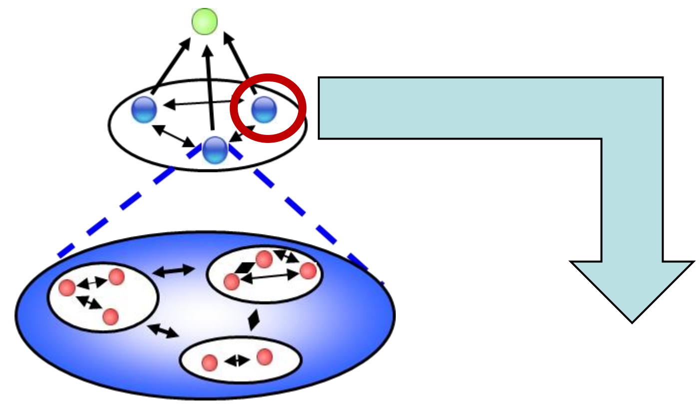
Effect on Capability Later

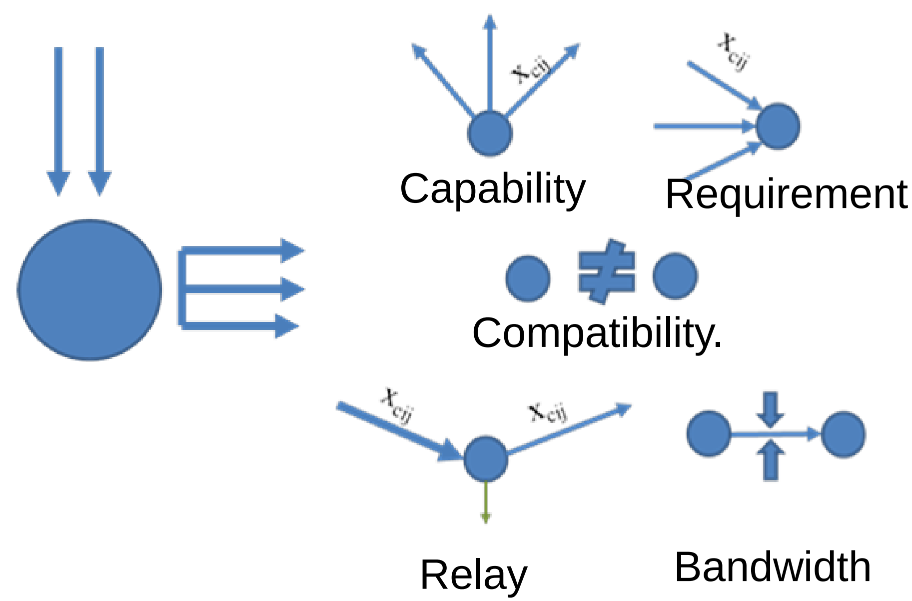
- Application to more realistic world SoS portfolio problems

Extra/Backup Slides

Portfolio Approach: SoS Modelling Additions

- Model individual system as 'nodes'
  - Functional & Physical representation
- Rules for node connectivity (this is currently not addressed elsewhere, e.g., RT-18)
  - Compatibility between nodes
  - Bandwidth of linkages
  - Supply (Capability)
  - Demand (Requirements)
  - Relay capability





Extension to SoS Interconnectivities

Maximize Capability Performance Index

$$\max\left(\frac{\sum_i S_{ic}\cdot w\cdot X_i^B - R_c}{R_c}\right)$$

s.t.

Sufficient Capabilities Supplied

$$\sum_i X_{cij} \geq X_j^B S_{rj}$$

Individual System Requirements met

$$\sum_i X_{cij} \geq X_j^B S_{rj}$$

Connectivity Rules Obeyed (Big-M formulation)

$$X_1 + \cdots + X_n = 0$$

$$\sum_c X_{cij} - X_{ij} M \leq 0$$

$$M \sum_c X_{cij} - X_{ij} \geq 0$$

$$\sum_i X_{cij} - \sum_j X_{cij} - X_j^B S_{rj} = 0$$

Risk Tolerance (per measure of risk)

$$\sqrt{\left(X_i^B\right)^T \Sigma_{ij} X_i^B} \leq \sigma_{critical}$$

$$X_{cij} \leq \text{Limit}_{cij}$$

$$X_{cij} = 0 \quad c \in \text{capability}$$

$$\Sigma_{ij}^L \leq \Sigma_{ij} \leq \Sigma_{ij}^U$$

$$X_{cij}, X_j^B \in \text{binary } \{0,1\}$$