A Portfolio Approach to System-of-Systems Acquisition and Architecture

System of Systems Engineering Collaborators Information Exchange (SoSECIE)

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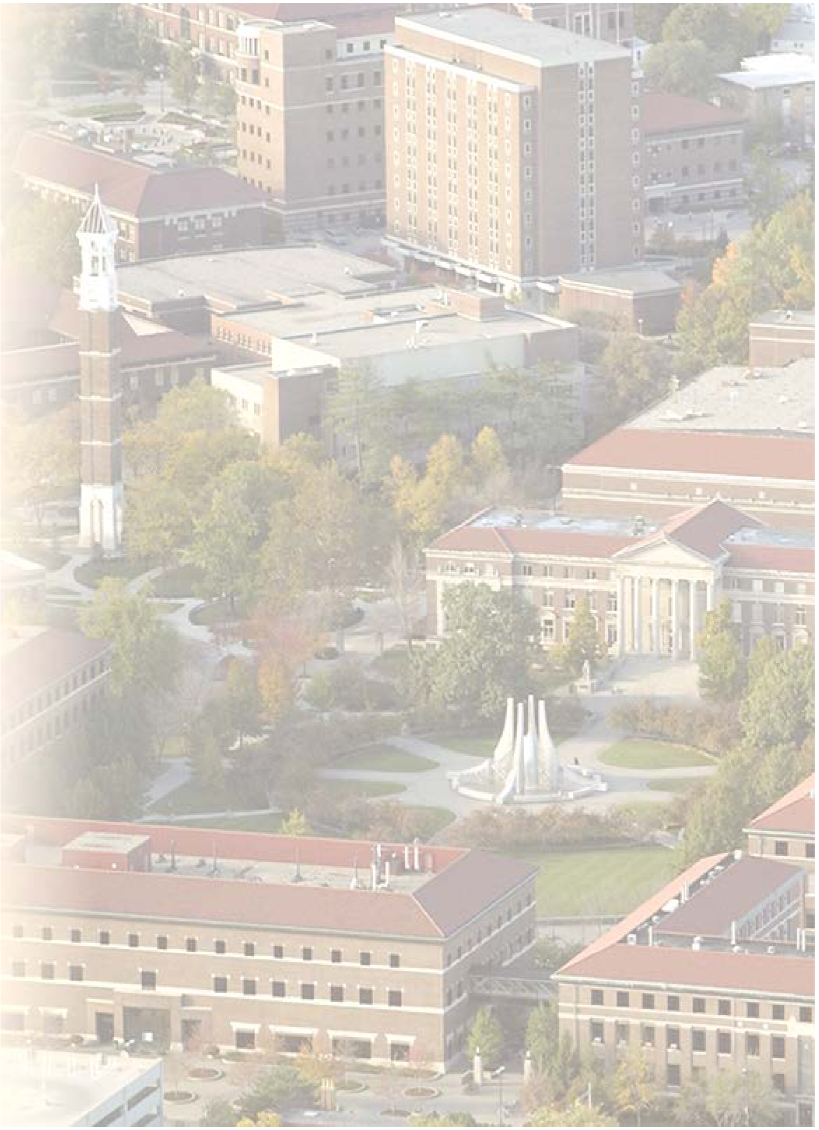
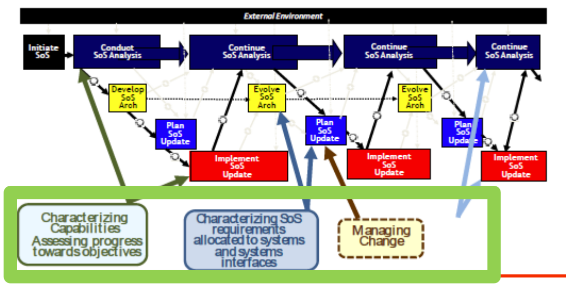
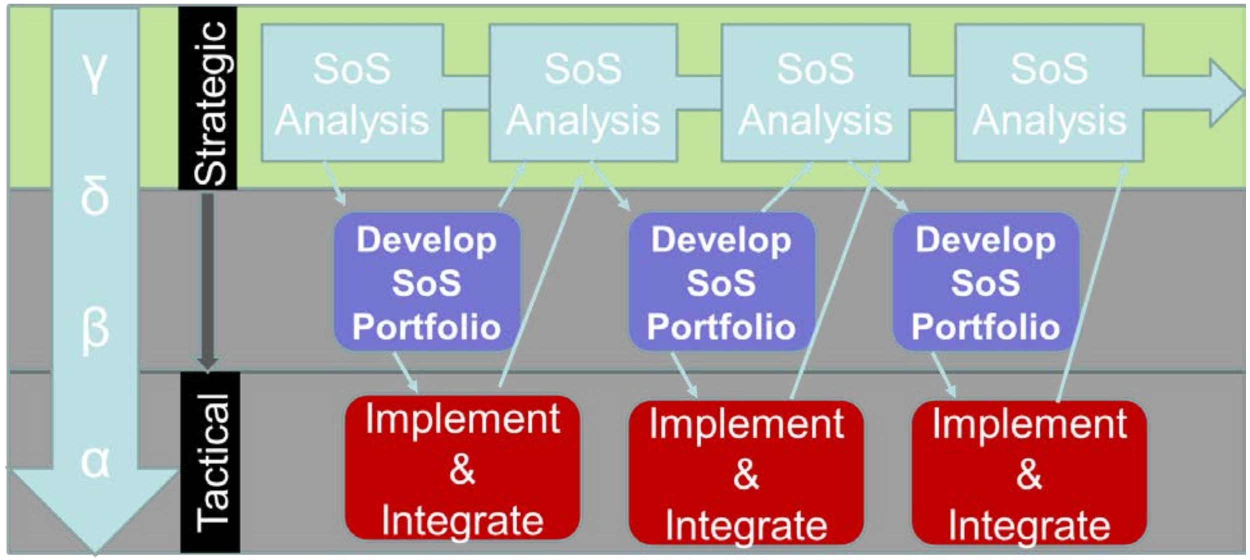


Outline of Presentation

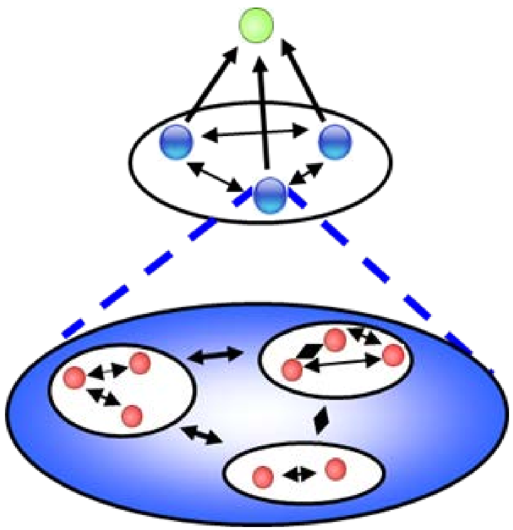
- SoS: A Wave Model Perspective
  - An Analytic Workbench perspective
- An Investment Portfolio Approach
  - Relationship to SoS architectures
  - Addressing uncertainty through robust approaches
  - Two approaches – NWS case examples
- Current Efforts
  - Piecewise linear, ABM simulation data
- Summary and Conclusions

SoS: A Wave Model Perspective





SoS Capability



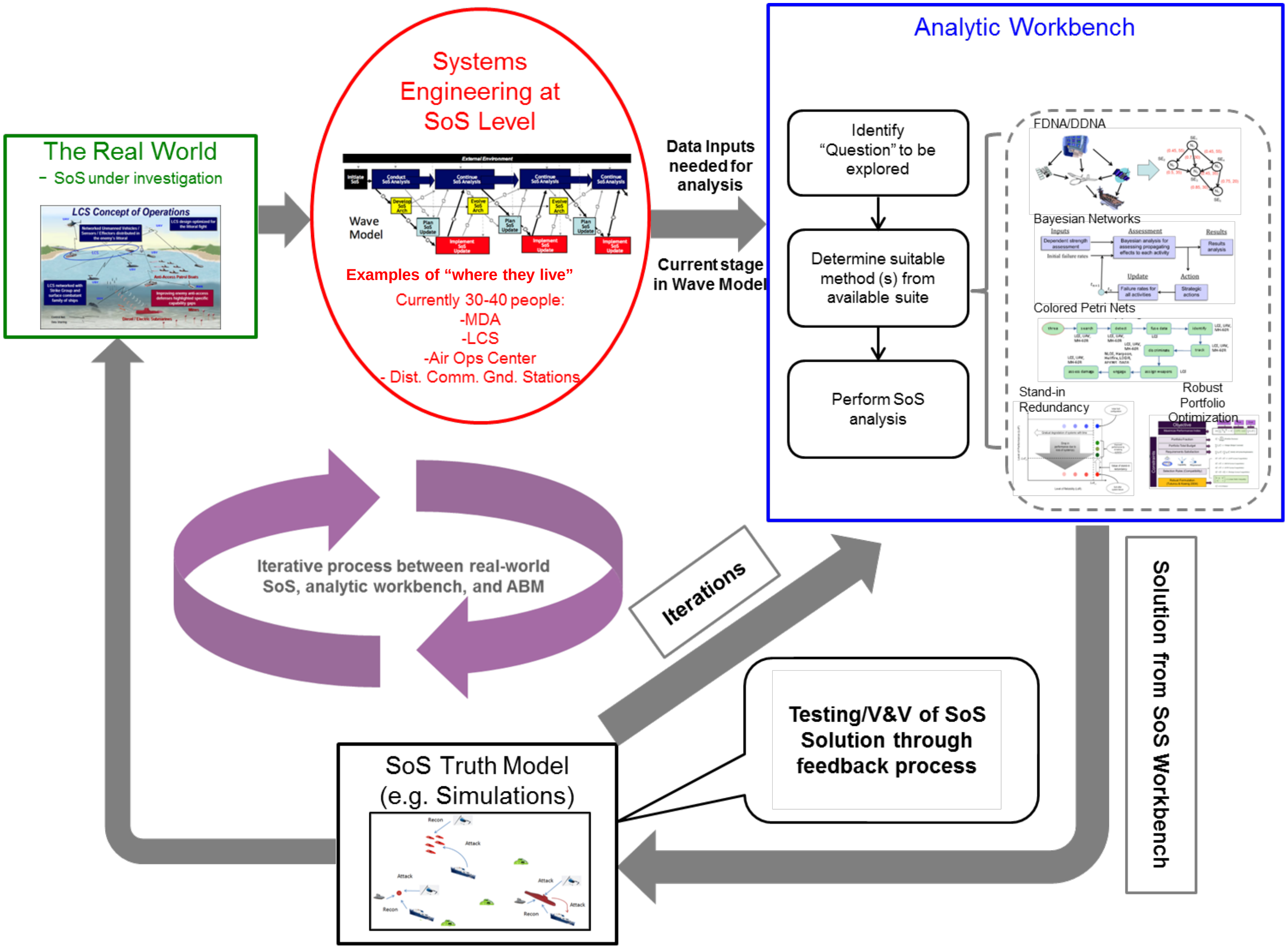
α-level systems

How do we support these actions for SoS acquisitions/evolution?

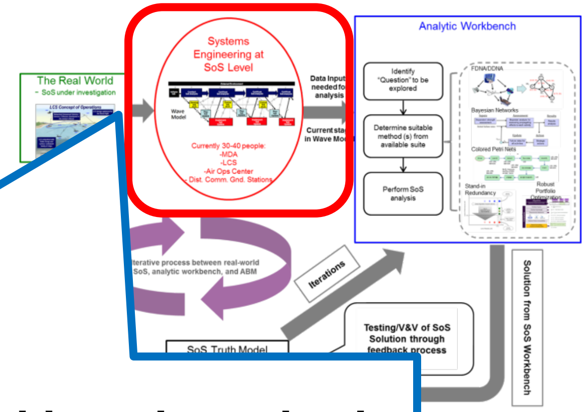
Combinatorial complex trade-spaces - across range of metrics: cost, performance, risks

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

SoS Analytic Workbench (sponsored by DoD SERC UARC)



Analytic Workbench – Archetypal Analysis



Archetypal Analysis

<u>Discrete Event Analysis</u>
Evaluating event-trigger based interactions between SoS elements in an architecture

<u>Data Driven Analysis</u>
Historical/Simulation data that drives interconnected SoS elements performance

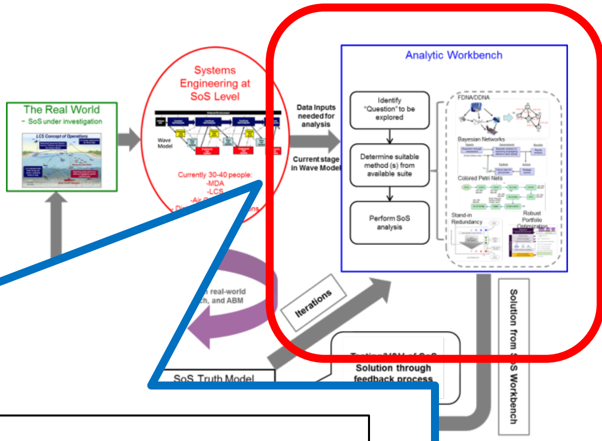
<u>Combinatorial Analysis</u>
Selection of *collections* of compatible systems to achieve *optimal* performance

<u>Risk Management</u>
Assessing potential consequences of architecture configurations (e.g. if a system goes down, what effect on overall SoS)

Mapping to Workbench Methods

	FDNA	Bayesian Networks	Robust Portfolio Optim.	Colored Petri Nets	Stand-In Redundancy
Discrete Events		x		x	
Data Driven	x	x	x		
Combinatorial			x		x
Risk Management	x	x	x		x

Analytic Workbench – Inputs for SoS Analysis

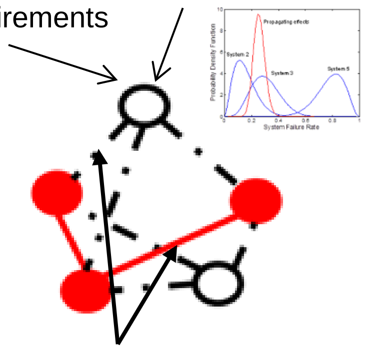


Data elements for analysis

Methods	Required Input Data Elements
FDNA	COD, SOD, Inter-system connectivities
Bayesian Networks	Inter-system directional connectivities Probability distributions of system capabilities
Robust Portfolio Optimization	Capabilities, development risk, Compatibilities, System cost
Petri Nets	Discrete event rules, System capabilities, Connectivities
Stand-In Redundancy	System capabilities, development risk, Inter-system compatibilities

Candidate System
>Capabilities
>Requirements

Distribution of Performance,/ Failure Rate



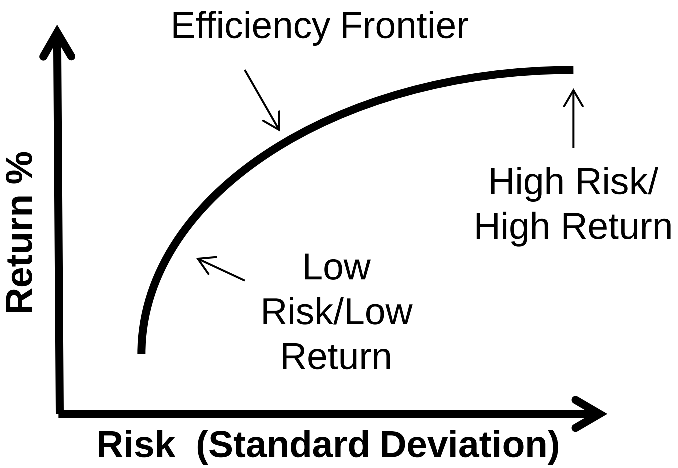
Connectivity, COD, SOD

Legend

COD	Criticality of Dependency
SOD	Strength of Dependency
Connectivity	Connection between systems based on individual capabilities

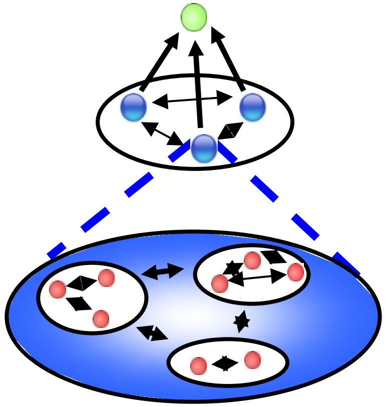
A Portfolio Approach

- Finance/Economics – balance of **expected profit (performance) against risk (variance)** in investments



- Generates efficiency frontier of optimal portfolios given investor level of risk averseness

- Optimization methods to identify optimal 'portfolio' of investments on efficiency frontier



Nodes = systems

- More recent works address uncertainties in estimated expected profit and variances

A Portfolio Approach: SoS Architectures

- Treat SoS as 'portfolio' of interconnected systems

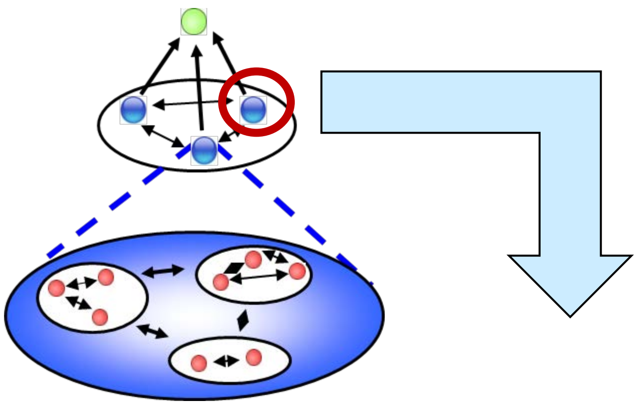
- Analyze operational 'layers' under uncertainty
- Model individual systems as 'nodes'

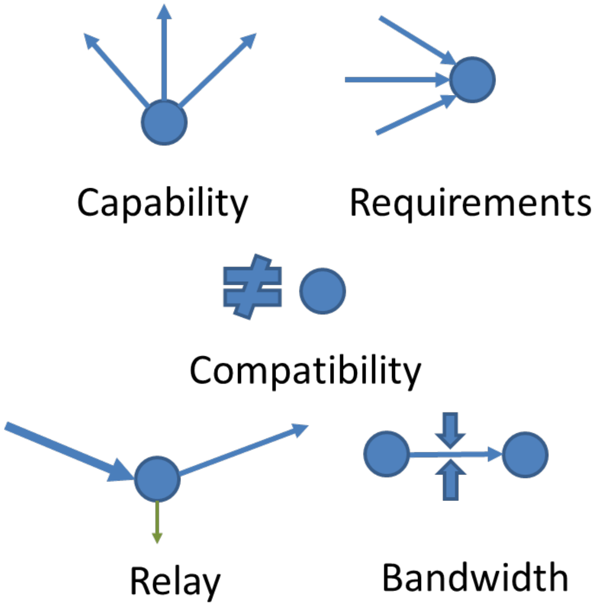
  - Functional & Physical representation

- Base rules for node connectivities:

  - Compatibility between nodes
  - Bandwidth of linkages
  - Supply (Capability)
  - Demand (Requirements)
  - Relay capability

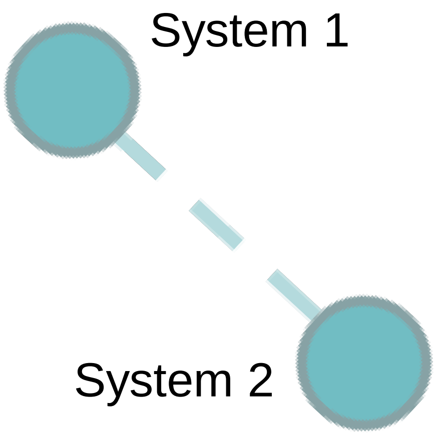
- Can represent objective and constraints of behaviors as mathematical program



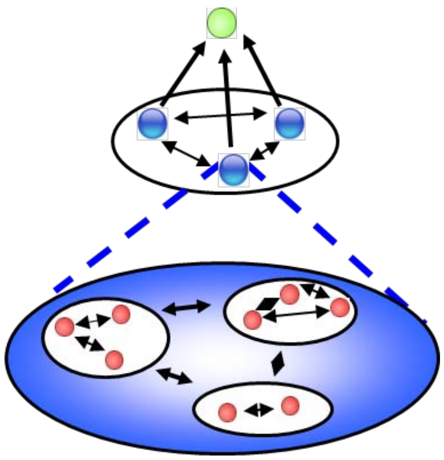


SoS Architecture: Uncertainties

- Sources of uncertainty:
  - Actual performance/requirements of individual systems
  - Interoperability of systems affected by cascading effects of uncertain performance of constituent nodes



- Addressing uncertainty in SoS architectures
  - Robust methods to consider system level uncertainties and potential effects
  - Allows for selection of 'robust' portfolios - SoS performance degrades minimally within defined system level uncertainties.



Evolution of Portfolio Work

- Early work (NPS) focus on addressing cost, SoS performance and development risk
  - What optimal collections of systems (current and yet-to-be introduced) balance these metrics?
  - How to address complexity - large decision-making with large number of systems.

- SERC research extends to include
  - More detailed modeling of system interdependencies as archetypal rules
  - Addresses computational tractability with alternative formulation

Robust Portfolio Case Study: Simple NWS

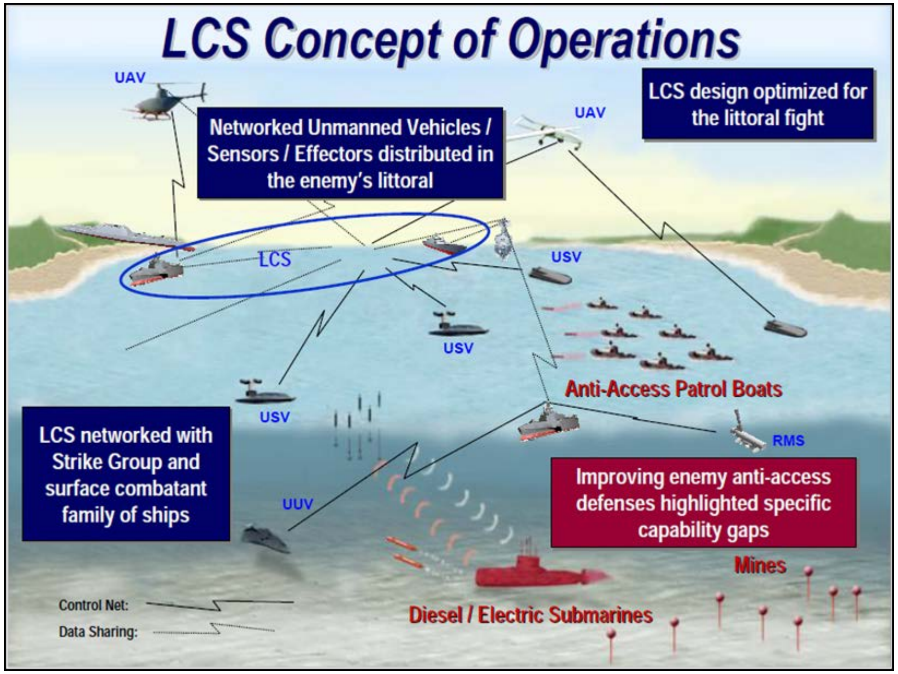


Image from: Presentation slides by RDML Vic Guillory of OPNAV at Mine Warfare Association Conference (titled "Littoral Combat Ship", 08-May-07)

Table 2: System interdependency and development risk (covariance)

	Variable Depth	Multi Fcn Tow	Lightweight tow	RAMCS II	ALMDS (MH-60)	N-LOS Missiles	Griffin Missiles	Package System 1	Package System 2	Package System 3
Variable Depth	0.1	0	0	0	0	0	0	0	0	0
Multi Fcn Tow	0	0.6	0	0	0	0	0	0.1	0.1	0
Lightweight tow	0	0	0.2	0	0	0	0	0.3	0	0.2
RAMCS II	0	0	0	0.3	0.1	0	0	0	0.2	0
ALMDS (MH-60)	0	0	0	0.1	0.1	0	0	0	0	0.3
N-LOS Missiles	0	0	0	0	0	0.5	0.2	0	0.1	0
Griffin Missiles	0	0	0	0	0	0.2	0.3	0	0	0
Package System 1	0	0.1	0.3	0	0	0	0	0.5	0	0
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

Table 1: Individual system information

Package		System Capabilities: Weapon Strike Range	Threat Detection Range	Anti Mine Detection Speed	Comm. Capacity	Air/Sea State Capacity	System Req.: Air/Sea State	Comm.	Develop. Time (Years)	Acq. Cost ($)
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 & Combat Management	Package System 1	0	0	0	400	4	0	0	3	3000000
	Package System 2	0	0	0	300	4	0	0	4	4000000
	Package System 3	0	0	0	250	3	0	0	5	5000000

Robust Mean-Variance Portfolio Optimization

Objective

Maximize Performance Index

Capability | Risk | Cost

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

Constraints

Portfolio Fraction

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

Portfolio Total Budget

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

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)

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

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

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

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

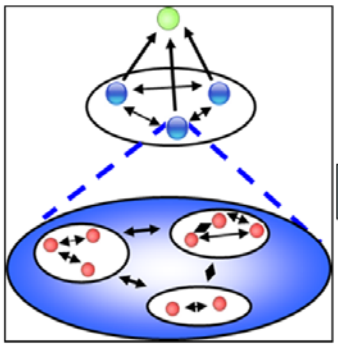
Robust Formulation (Tutuncu & Koenig 2004)

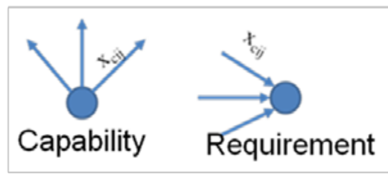
$$\begin{bmatrix}\overline{\Lambda}-\underline{\Lambda} & X_q^F\\ X_q^{F}{}' & 1\end{bmatrix}\succeq 0\ \text{(Linear Matrix Inequality)}$$

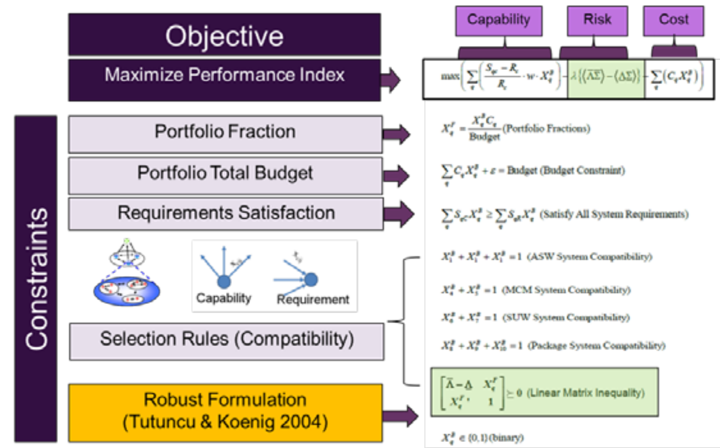
$$X_q^B\in\{0,1\}\text{(binary)}$$

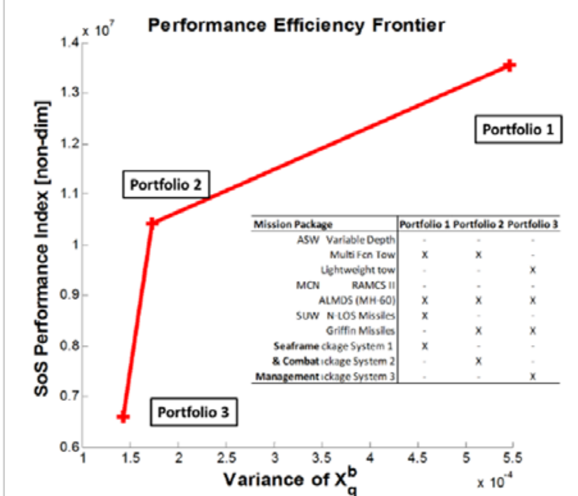
Robust Mean Variance Portfolio Optimization

Decision support approach from financial engineering/operations .
Balancing ‘rewards’ of acquisition with interconnected ‘risks’ of development time

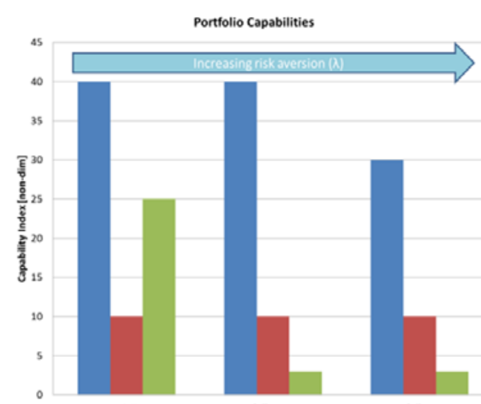


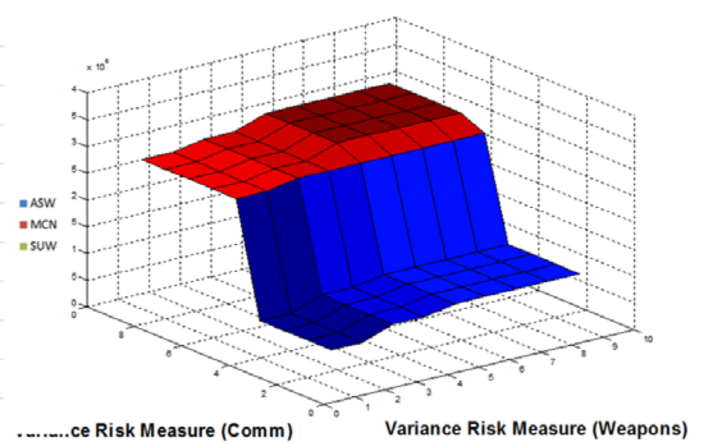






Mission Package		Portfolio 1	Portfolio 2	Portfolio 3
ASW	Variable Depth	-	-	-
	Multi Fcn Tow	X	X	-
	Lightweight tow	-	-	X
MCN	RAMCS II	-	-	-
	ALMDS (MH-60)	X	X	X
SUW	N-LOS Missiles	X	-	-
	Griffin Missiles	-	X	X
Seaframe	ckage System 1	X	-	-
& Combat	ckage System 2	-	X	-
Management	ckage System 3	-	-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





General Optimization: Uncertain Constraints

Capability | Risk | Cost

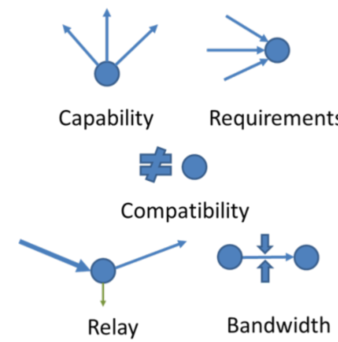
$$\max \left(\sum_q \left(\frac{S_{qc} - R_c}{R_c} \cdot w \cdot X_q^B \right) - \lambda \left(X_q^F \right)^T \Sigma_{ij} X_q^F - \sum_q \left(C_q X_q^B \right) \right)$$

Objective

Constraints

$$[A]\{X_q\} \leq \{b\}$$

Uncertainties in **[A]** reflect uncertainties in the **operational** aspects of capability/requirement



$$\sum s_{qC} X_q^B + \max\left\{ \hat{s}_{qC} y_j + \left(\Gamma_i - \lfloor \Gamma_i \rfloor \hat{s}_{it_i} y_t \right) \right\} \leq b_i$$

Adjust conservatism Γ_i term to control probability of **constraint violation** (Bertsimas-Sim method)

- **Connectivity between systems**

  e.g. Network connectivity between systems

- **Flow Balance conservation**

  e.g. flow of power throughout a network

NWS Case – Uncertainty in constraints

		SoS Performance Index Related			Capabilities		Requirements		Uncertain
Package		Weapon Range	Detect. Range	Anti Mine	Comm. Capability	Power Capability	Power Require.	Comm. Require.	Uncertainty Set
ASW	Variable Depth	0	50	0	0	0	100	200	0
	Multi Fcn Tow	0	40	0	0	0	90	120	0
	Lightweight tow	0	30	0	0	0	75	100	0
MCN	RAMCS II	0	0	10	0	0	70	120	0
	ALMDS (MH-60)	0	0	20	0	0	90	150	0
SUW	N-LOS Missiles	25	0	0	0	0	0	250	0
	Griffin Missiles	3	0	0	0	0	0	100	0
Seaframe	Package 1	0	0	0	0	300	0	0	10
	Package 2	0	0	0	0	450	0	0	70
	Package 3	0	0	0	0	500	0	0	100
Comm.	System 1	0	40	0	180	0	100	0	30
	System 2	0	200	0	200	0	120	0	35
	System 3	0	0	0	240	0	140	0	45
	System 4	0	0	0	300	0	160	0	55
	System 5	0	0	0	360	0	180	0	60
	System 6	0	0	0	380	0	200	0	80

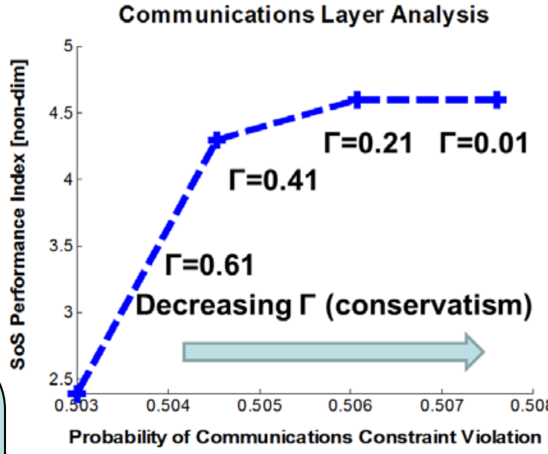
NWS Communications Layer Analysis

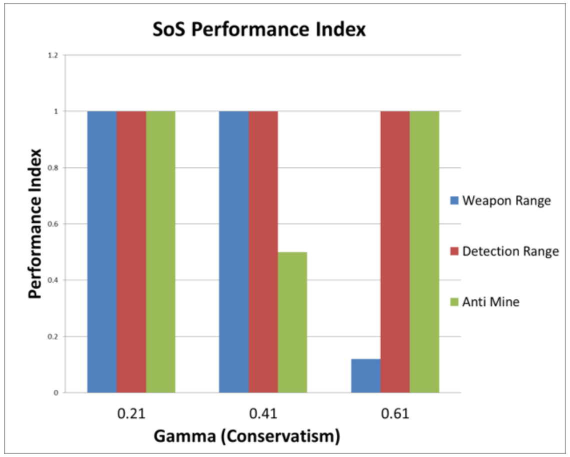
- Build robustness for communications layer subject to defined uncertainties in performance

Systems	Available System Packages	Gamma (Level of Conservatism) 0.01	0.21	0.41	0.61
ASW	Variable Depth	-	-	-	-
	Multi Fcn Tow	x	x	x	x
	Lightweight Tow	-	-	-	-
MCN	RAMCS II	-	-	-	-
	ALMDS (MH-60)	x	x	-	-
SUW	N-LOS Missiles	x	x	x	-
	Griffin Missiles	-	-	-	x
Seaframe	Package 1	-	-	-	-
	Package 2	-	-	-	-
	Package 3	x	x	x	x
Comm.	System 1	-	-	-	-
	System 2	x	x	x	x
	System 3	-	-	-	-
	System 4	-	-	-	x
	System 5	-	-	-	-
	System 6	x	x	x	-

Portfolios of systems at prescribed conservatism

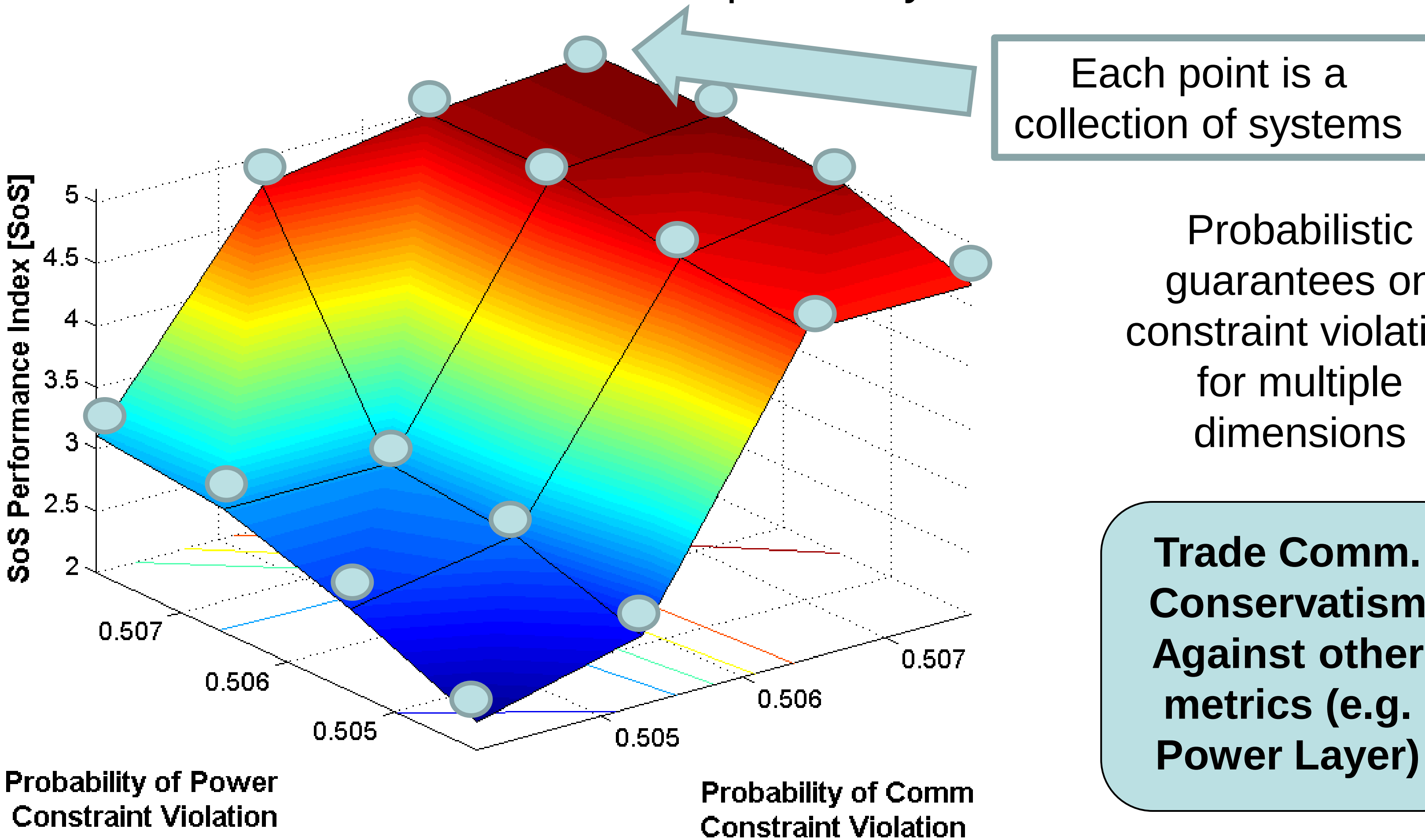
Trade SoS Performance for Comm. Conservatism (uncertainties in communications grid)





Multi-Metrics: Power & Comm. Layer Analysis

- Extend to address multiple constraints in tradespace analysis
- Robustness of communications and power layer constraints



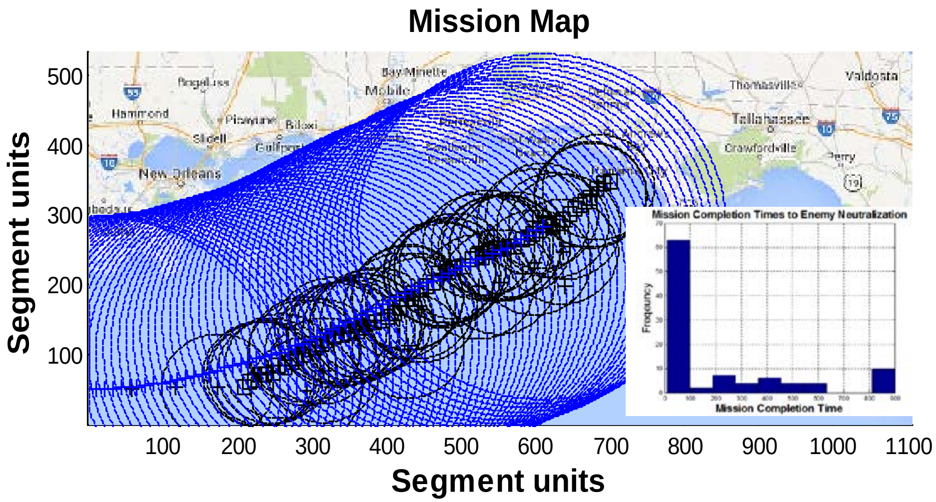
Probabilistic guarantees on constraint violation for multiple dimensions

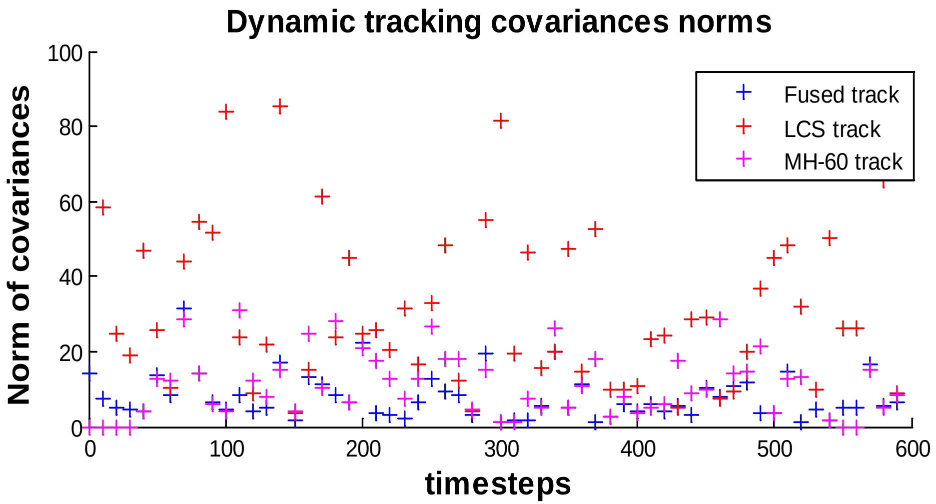
Trade Comm. Conservatism Against other metrics (e.g. Power Layer)

Portfolio: Current Efforts to link to ABM

Agent Based Simulation (ABM) of Naval Scenario(s)

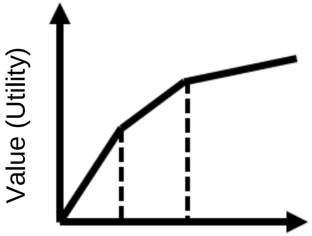
- 'Detect-Track-Engage' Scenario
  - Different combinations of mission scenarios, assets and conditions result in varied performance
- Complex scenario interactions in ABM:
  - Shared radar info between LCS and MH-60 counterpart
  - Successful engagement dependent on quality of track, range of radar, weapon range, etc.
  - Target weave reduces probability of engagement
  - MH-60 refueling rules based on simulated design





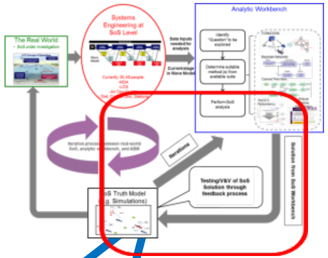
Portfolio Approach using ABM Simulation

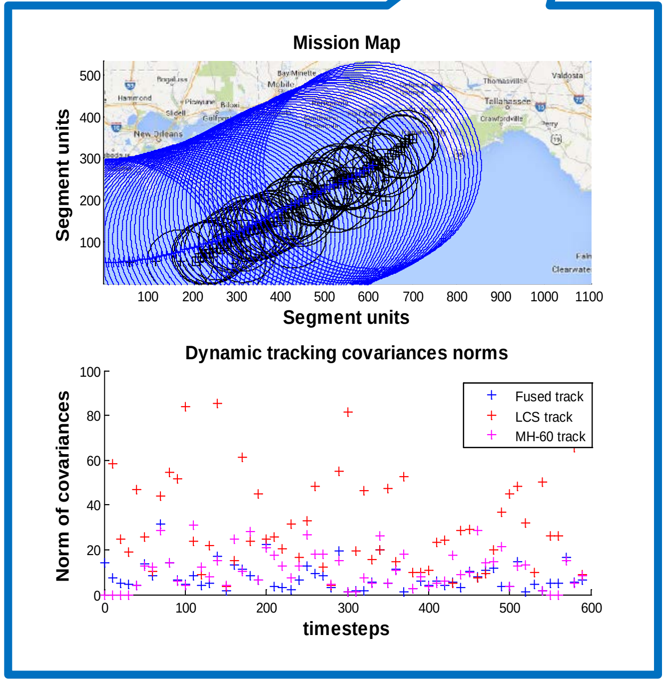
- Work has so far utilized generated utilities/defined metrics in objective
- Employ approximate strategies in portfolio management based on:
  - Monte Carlo sampling via ABM simulation of operations
  - Value Function Approximations
- Use simulation data to generate piece-wise linear representation of metrics (computationally tractable)



Monte-Carlo simulation based data of various ABM architecture

*Concavity reflects rational preferences





Summary and Conclusions

- SoS architectures – complex, needs tools to address high-dimensions of problem esp under uncertainty.

- Robust portfolio method potential
  - Reduces high-dimensions and complexity of tradespace using algorithmic innovations
  - Addresses risk, cost, uncertainty between interconnected entities
  - Identify collections of 'portfolios' → decision still with practitioner

- Future Work
  - Extend to include simulation based information
  - Analytic Workbench: further feedback/insight from SoS community
  - Extend to multi-period portfolio case with demo

Acknowledgements

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- SoSECIE community

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