RT 108 - An Analytic Workbench Perspective to Evolution of System of Systems Architectures

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### Motivation – Why we are doing RT-108

*From: “Systems of Systems Pain Points”, Dr. Judith Dahmann, INCOSE Webinar Series on Systems of Systems, 22-FEB, 2013*

<table>
<thead>
<tr>
<th>Pain Points</th>
<th>Question</th>
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</thead>
<tbody>
<tr>
<td><strong>SoS Authority</strong></td>
<td>What are effective collaboration patterns in systems of systems?</td>
</tr>
<tr>
<td><strong>Leadership</strong></td>
<td>What are the roles and characteristics of effective SoS leadership?</td>
</tr>
<tr>
<td><strong>Constituent Systems</strong></td>
<td>What are effective approaches to integrating constituent systems into a SoS?</td>
</tr>
<tr>
<td><strong>Autonomy, Interdependencies &amp; Emergence</strong></td>
<td>How can SE provide methods and tools for addressing the complexities of SoS interdependencies and emergent behaviors?</td>
</tr>
<tr>
<td><strong>Capabilities &amp; Requirements</strong></td>
<td>How can SE address SoS capabilities and requirements?</td>
</tr>
<tr>
<td><strong>Testing, Validation &amp; Learning</strong></td>
<td>How can SE approach the challenges of SoS testing, including incremental validation and continuous learning in SoS?</td>
</tr>
<tr>
<td><strong>SoS Principles</strong></td>
<td>What are the key SoS thinking principles, skills and supporting examples?</td>
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</tbody>
</table>

Survey identified seven ‘pain points’ raising a set of SoS SE questions
What are we trying to do?

- Current range of MPTs developed to support industry processes (e.g. Lean Six Sigma, SAS workbench)
- Seeking analog of such MPTs for SoS problems
- SoSE/SE problems need own set of tailored MPTs
- SERC RT 108 -SoS Analytic Workbench pursues this goal
RT-108 Analytic Workbench
Desired Characteristics

• Open
  — Accommodates SoS analytic methods (Purdue or others)

• Interoperability
  — Compatible w/ additional SoSE phases
  — ‘Domain agnostic’, cross platform

• Useable
  — (Scalability) ➔ computational scaling
  — (Ease of Use) Convert problem to inputs to methods and tools
SoS Analytic Workbench

Methods in Toolset:
- Bayesian Networks (BN)
- Robust Portfolio Optimization
- Approx. Dynamic Programming
- Stand-In Redundancy
- Functional/Developmental Dependency Networks

Input Data
(e.g. DoDAF OV, SV, PV declarations and other sources for SoS and system definition)
SoS Archetypal Analysis

Related classes of ‘Pain Point’ questions

Archetypal Analysis

Operational Analysis
Evaluating event-trigger based interactions between SoS elements in an architecture

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

Architecture Design (or Re-design)
Selection of collections of compatible systems to achieve optimal performance

Risk Assessment
Assessing potential consequences of architecture configurations (e.g. if a system goes down, what effect on overall SoS)

Mapping to Workbench Methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Operation Analysis</th>
<th>Data Driven</th>
<th>Architecture Design</th>
<th>Risk Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDNA/ODNA</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
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<tr>
<td>Bayesian Networks</td>
<td></td>
<td>X</td>
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<tr>
<td>Robust Portfolio Optim</td>
<td></td>
<td>X</td>
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<tr>
<td>Approx. Dynamic Program</td>
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<tr>
<td>Stand-In Redundancy</td>
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</tbody>
</table>
Inputs for Analysis

While each problem varies, a graph representation (node, links, weights, etc) is a useful basis.
A Very Compact Overview

SoS Optimization/decision support based

SoS Interdependency Analysis
Outreach Engagements

• Naval Surface Warfare Center Dahlgren Division (NSWCDD): Memorandum of Understanding (MOU) signed. Progressed to CRADA agreement.

• USAF Space Command (El Segundo, CA): Initial exchanges towards case studies in SoS architectural analysis and decision-making.


Demo Analytic Workbench to solicit feedback in developing MPTs.
Things we have learned so far

- Identified MPTs’ theory strengths and potential improvements for SoS analysis
- Potential use/value added of MPTs in collaborators’ problem context
- Declaration/format of data inputs (e.g. DoDAF/others) very important aspect of tool applicability
- Direction towards multi-stakeholder framework consistent with our current development
Near and Far Term Plans

- Mature AWB through collaborative exchanges towards demo tool set
- Planned deployment using HubZero technology
- Development of visual analytics driven interface for toolset (tradespace visualization)
- Incorporating group decision-making considerations into AWB toolset → how do I cooperate with other entities using tools?

Planning SoS Workshop summer 2014 at Purdue but with remote access provided...stay tuned for specifics
Questions and Discussion
Getting Ready

• Provide Doris with identification of who will be traveling to the meeting

• Make hotel reservations soon with the Radisson Hotel next to the USC campus

• Send PPT copies of your charts to boehm@usc.edu, jasanche@isc.edu by Friday, March 14

• Register, obtain information on driving directions, hotel, parking, campus map at URL:
  —TBD
Data driven methods to analyze and quantify interdependencies and cascading effects of risks through networks of systems.

**FDNA (developed by Garvey & Pinto, MITRE)**
Assess the effect of operational dependencies when partial failures (degraded operability) occur in operational networks (FDNA); *Purdue created stochastic version*

**DDNA (Purdue extension)**
Assess the effect of development dependencies when delays occur in development networks

- Directed acyclic networks
- Links are operational/developmental dependencies
- Nodes can be systems or capabilities

**Strength of Dependency (SOD):** $\alpha_{ij}$ is the fraction of the operability of node $N_j$ due to the dependency on node $N_i$. Ranges between 0 and 1.

**Criticality of Dependency (COD):** $\beta_{ij}$ is the maximum level of operability reachable by node $N_j$ when the operability of node $N_i$ is 0. Ranges 0-100.

Propagation of dependencies.
Data driven methods to analyze and quantify interdependencies and cascading effects of risks through networks of systems.

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**Propagation of dependencies.**
### Results from deterministic FDNA analysis (5-node case study)

#### Degradation in single systems

<table>
<thead>
<tr>
<th>Self-effectiveness</th>
<th>$\Delta O_1$</th>
<th>$\Delta O_2$</th>
<th>$\Delta O_3$</th>
<th>$\Delta O_4$</th>
<th>$\Delta O_5$</th>
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<td>-12.5</td>
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</table>

- High resilience
- Identification of most critical nodes (N1, N4)
- Positive critical dependency (node N4 "protects" node N5 from disruption in other nodes)
Behavior shows the complex impact of SOD, COD, multiple dependencies on the probability distribution, even if only two systems experience degraded self-effectiveness.

Results from stochastic FDNA analysis (5-node case study)

Degradation in systems 1 and 4. Self Effectiveness of each of them has independent uniform distribution

<table>
<thead>
<tr>
<th>System</th>
<th>$\mu(O)$</th>
<th>$\sigma(O)$</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>50</td>
<td>29.16</td>
</tr>
<tr>
<td>2</td>
<td>77.5</td>
<td>13.12</td>
</tr>
<tr>
<td>3</td>
<td>68.98</td>
<td>19.19</td>
</tr>
<tr>
<td>4</td>
<td>50</td>
<td>20.72</td>
</tr>
<tr>
<td>5</td>
<td>65.19</td>
<td>17.23</td>
</tr>
</tbody>
</table>
Complex behavior due to Strength and Criticality of Dependencies (SOD, COD), and multiple dependencies.

Differences from Bayesian approach for failure propagation:
  - Propagation is not probabilistic. It is a given function of Operability (O), Self-Effectiveness (SE), SOD, COD.
  - Partial failures are considered.
FDNA/DDNA – Applications

Cyber Security of Naval Warfare Scenario

- FDNA allows for analysis of cascading effects of cyber-attacks on communications links upon overall NWS SoS operability.

Solar Systems Exploration SoS

- The combined used of FDNA and DDNA allows us to quantify the partial capabilities that can be achieved during the development of the Solar Exploration SoS.
Robust Portfolio Optimization

- Treat SoS as ‘portfolio’ of systems
- Analyze operational ‘layers’ under uncertainty
- Model individual systems as ‘nodes’
  - Functional & Physical representation
- Rules for node connectivity
  - Compatibility between nodes
  - Bandwidth of linkages
  - Supply (Capability)
  - Demand (Requirements)
  - Relay capability
- Represent as mathematical programming problem
Decision support approach from financial engineering/operations research to identify ‘portfolios’ of systems by leveraging performance against risk under uncertainties

- Represent behaviors as connectivity constraints
- Formulate as mathematical programming problem
- Employ robust optimization techniques to deal with data uncertainty
- Computationally efficient tools to solve even large problems

Robustification to include data uncertainties
Mean-Variance Portfolio Approach

Objective

Maximize Performance Index

Portfolio Fraction

Portfolio Total Budget

Requirements Satisfaction

Constraints

Selection Rules (Compatibility)

Uncertainty in Covariance (Interdependencies)

\[
\max \left( \sum_q \left( \frac{S \cdot X_q^p - R \cdot X_q^p}{R} \right) \cdot \mathbf{w} \cdot X_q^p \right) - \lambda \left( X_q^p \right)^2 \cdot \sum_q X_q^p - \sum_q (C_q \cdot X_q^p)
\]

\[
X_q^p = \frac{X_q^p \cdot C_q}{\text{Budget}} \quad \text{(Portfolio Fractions)}
\]

\[
\sum_q C_q \cdot X_q^p + \epsilon = \text{Budget} \quad \text{(Budget Constraint)}
\]

\[
\sum_q S_{q-c} \cdot X_q^p \geq \sum_q S_{q-g} \cdot X_q^p \quad \text{(Satisfy All System Requirements)}
\]

\[
X_1^b + X_1^b + X_1^b = 1 \quad \text{(ASW System Compatibility)}
\]

\[
X_2^b + X_2^b = 1 \quad \text{(MCM System Compatibility)}
\]

\[
X_6^b + X_7^b = 1 \quad \text{(SUW System Compatibility)}
\]

\[
X_8^b + X_9^b + X^b = 1 \quad \text{(Package System Compatibility)}
\]

\[
\Sigma Y_{\mu} \leq \Sigma \leq \Sigma U_{\mu}
\]
Mean-Variance Portfolio: Robust Approach

Objective
Maximize Performance Index

Constraints
Portfolio Fraction
Portfolio Total Budget
Requirements Satisfaction
Selection Rules (Compatibility)

Robust Formulation
(Tutuncu & Koenig 2004)

Objective
\[ \max \{ \sum \frac{S_q - R_q}{R_q} \cdot W \cdot X_q^B - \lambda \{ \langle \Delta \rangle + \langle \Delta \Delta \rangle \} - \sum q \cdot (C_q \cdot X_q^B) \} \]

Capability
Risk
Cost

Constraints
\[ X_q^F = \frac{X_q^B \cdot C_q}{Budget} \] (Portfolio Fractions)
\[ \sum q \cdot C_q \cdot X_q^B + \varepsilon = Budget \] (Budget Constraint)
\[ \sum q \cdot S_q \cdot X_q^B = \sum q \cdot S_q \cdot X_q^B \] (Satisfy All System Requirements)
\[ X_1^F + X_1^B + X_1^F = 1 \] (ASW System Compatibility)
\[ X_1^F + X_1^B = 1 \] (MCM System Compatibility)
\[ X_1^F + X_1^B = 1 \] (SUW System Compatibility)
\[ X_1^F + X_1^B + X_1^B = 1 \] (Package System Compatibility)

Robust Formulation
\[ \begin{bmatrix} \Delta - \Delta X_q^F \\ X_q^F \end{bmatrix} \succeq 0 \] (Linear Matrix Inequality)
\[ X_q^F \in \{0, 1\} \] (binary)
Enabling tradespace exploration and identifying optimal ‘portfolios’ of systems (e.g. here in evaluating communications assets)

<table>
<thead>
<tr>
<th>Systems</th>
<th>Available System Packages</th>
<th>Gamma (Level of Conservatism)</th>
<th>0.01</th>
<th>0.21</th>
<th>0.41</th>
<th>0.61</th>
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</thead>
<tbody>
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<td>N-LOS Missiles</td>
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<tr>
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<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<td>System 3</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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</tr>
</tbody>
</table>

Portfolios of systems at prescribed conservatism

Trade SoS Performance for Conservatism in Communications

Communications Layer Analysis

SoS Performance Index

Gamma (Conservatism)

Performance Index

- Wiópan Range
- Detection Range
- Anti Mine
General Optimization Problem

**Objective**

Maximize Performance Index

\[
\max \left( \sum_{q} \left( \frac{S_{qc}^R}{R_c^q} \right) \right)
\]

s.t.

\[
\sum_{q} S_{qc}^B X_q^B \geq \sum_{q} S_{qR}^B X_q^B \quad \text{(Satisfy Requirements)}
\]

\[
\sum_{c} X_{cij} - X_{ij} M \leq 0
\]

\[
M \sum_{c} X_{cij} - X_{ij} \geq 0
\]

\[
\sum_{i} X_{cij} - \sum_{j} X_{cij} - X_{ij} X_j^B S_{ij} = 0
\]

\[
X_{cij} \leq \text{Limit}_{cij}
\]

\[
X_1^B + ... + X_n^B = D \quad \text{(System Compatibility)}
\]

(e.g. \(X_1^B + X_2^B + X_3^B = 1\))

\[
X_{cij} = 0 \quad i,j \in \{\text{incompatible set}\}
\]

\[
X_q^B \in \{0,1\} \quad \text{(binary)}
\]

**Constraints**

- Requirement Satisfaction
- Big-M Formulation (number of connections)
- Flow Balance Constraint
- Bandwidth Limit
- Node Connection Compatibility
Dealing with Uncertainty

• Entities
  — **System Capability**: Actual performance of system individually and as a whole SoS entity
  — **System Interdependence**: Interdependencies between systems and effects on translation of capability uncertainties

• Addressing data uncertainty in portfolio selection

  • Uncertainties in node (system) performance and connections (links)
    • Quantification of simulated phenomena (**e.g. cyber attack on comm. node**)
    • Capture variation in performance at each node (e.g. due to cyber-attacks) as **uncertainty sets**.
    • Variations/uncertainty bounds from ABM simulation or design choice.
Robust Operational Constraints

- Use Bertsimas-Sim approach to uncertain (data uncertainty) constraints
- Benefits: Linear Programming approach, constraint violation control with probabilistic guarantees, extends to discrete optimization

Constraint Rules for Connectivity & Operations

\[
\begin{align*}
[A] \{X_q\} & \leq \{b\} \\
\sum_i X^B_{cij} & \geq X^B_{ij} S_{rj} \\
\sum_i X^B_{cij} & \geq X^B_{ij} S_{rj} \\
X_1 + \ldots + X_n & = 0 \\
\sum_c X_{cij} - X^B_{ij} M & \leq 0 \\
M \sum_c X_{cij} - X^B_{ij} & \geq 0 \\
\sum_i X^B_{cij} - \sum_j X^B_{cij} - X^B_{ij} S_{rj} & = 0
\end{align*}
\]

Adjust conservatism $\Gamma_i$ term to control probability of constraint violation

Conservatism Added
(This can be converted to an LP == easy to solve even for large problems)
Multi-Metrics: Power & Comm. Layer Analysis

Build in robustness for communications and power layer simultaneously

Robustness to constraint violation of ‘requirements for communications and power generation capability being met’ → Tradespace analysis

Each point is a collection of systems

Probabilistic guarantees on constraint violation for multiple dimensions

Trade Comm. Conservatism Against other metrics (e.g. Power Layer)
Current extensions to portfolio approach:

- Work has so far utilized generated utilities/defined metrics in objective

- Employ approximate strategies in portfolio management based on:
  - Sampling via ABM simulation of operations
  - Value Function Approximations
  - Use simulation data to generate piece-wise linear representation of metrics (computationally tractable)
  - Adopt financial portfolio approaches (e.g. Conditional Value at Risk) to mitigate very complex risks.

*Concavity reflects rational preferences*
SoS Evolution Considerations

Stakeholder A
- System a1
- System a2

Stakeholder B
- System b1
- System b2

Stakeholder C
- System c1
- System c2

SE Engineer
- Decisions of Stakeholder A
  - Affect exogenous information
  - Affect Stakeholder B’s future approximation

SoS
Multi Time Scale Framework

- Extend portfolio based approaches to multi-period considerations
- Account for multi-stage and collaborative elements
- Util
Quantitatively assessing impact of compensating for a loss of performance in one or more constituent systems through re-tasking of remaining systems.

- Traditional reliability analysis tools not suitable for SoSs:
  - Heterogeneity, geographical distribution, interdependencies
  - Backup systems are costly and impractical

- Using stand-in redundancy, systems can:
  - Contribute to SoS-level capabilities in ideal case, and
  - “Stand-in” for failed functions during disruptions
**Illustrative example**

<table>
<thead>
<tr>
<th>Capability</th>
<th>Description</th>
<th>Systems Needed</th>
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</thead>
<tbody>
<tr>
<td>C1</td>
<td>Surveillance</td>
<td>S1</td>
</tr>
<tr>
<td>C2</td>
<td>Target identification</td>
<td>S1, S2</td>
</tr>
<tr>
<td>C3</td>
<td>Target elimination</td>
<td>S3, S4</td>
</tr>
</tbody>
</table>

**Features available on each system:**
- UAV1: High-definition camera
- UAV2: Basic camera + weapons
- UAV3: Basic camera + weapons

**Diagram:**
- S1: Satellite
- S2: UAV-1
  - "search"
- S3: UAV-3
  - "seek and destroy"
- S4: UAV-2
  - "seek and destroy"
- Ground Station
System Importance Measures

• Resilience metrics must be able to guide answers to the following:
  — Is the SoS resilience enough? Specifically, which part of the SoS is lacking in resilience?
  — What SoS features must be selected such that they balance the desired resilience with costs?

• A single metric to measure SoS resilience:
  — Will be challenging, if not impossible; could be misleading
  — Provides little information about “areas” in the SoS that need attention

• Family of System Importance Measures (SIMs) to capture different aspects of SoS resilience
  — Inspired by Component Importance Measures (CIMs) in reliability theory
  — Birnbaum importance, Risk achievement worth (RAW), Risk reduction worth (RRW), Improvement potential
System Importance Measures

- System Recoverability Importance
- System Disruption Importance
- System Down Time Importance
- System Performance Importance
System Importance Measures

• SIMs help determine which areas of the SoS have excess or inadequate resilience
  — Can use this information to identify systems that need more attention

• SIMs provide information to guide design decisions
  — For example, we used SIMs to compare two different resilience design choices:
    o Stand-by redundancy
    o Stand-in redundancy
  — Enabling stand-in redundancy for some systems may be a more cost-effective option to achieve almost same level of resilience as stand-by option