Advances towards a System of Systems Analytical Workbench

By
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Introduction

• Need → What people want out of systems of systems:
  — New capability ... but also: risk mitigation, robustness, resiliency in both developmental and operational domains
  — Tools to conceive, establish, and evolve SoS

• Response → Advancements brewing in many facets
  — Representation documentation: MBSE ... and towards MBSoS-SE
  — Interoperability of tools and systems: “Contracts” and meta-languages
  — Architecting and Decision-Making:
    o Our RT-108 (and prior) work has focused here; Answer questions like:
      Which SoS configurations?, Which metrics?, Which rules / incentives? Which evolution paths?
    o Combine M&S with decision-making (design) analytics – back to original MBSE (e.g., Wymore, A. Wayne. Model-based systems engineering. CRC, 1993.)

• Larger Context → Many synergies with other SERC and international endeavors
  o e.g., research in security, human systems, and enterprises
  o e.g., European Commission FP7 Efforts in SoS
    — Trans-Atlantic Research and Education Agenda in SoS (T-AREA-SoS); a Support Action
    — Several SoS Research Projects (DANSE, COMPASS, etc.)
Challenges- In Abstract …
SoS as complex endeavor

One notion of Complexity:
The amount of information necessary to describe regularities in the system effectively

Sources of Complexity
- Requirements & ops uncertainty
- Modeled & un-modeled interdependencies
  - Within and between levels of abstraction
- Dynamic connectivity & porous boundary
  - Nature of an open system
- Multiplicity of perspectives in participants
  - A root cause of interoperability issues

Aggregation
Challenges- In Particular ...


<table>
<thead>
<tr>
<th>Pain Points</th>
<th>Question</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SoS Authority</strong></td>
<td>What are effective collaboration patterns in systems of systems?</td>
</tr>
<tr>
<td>Leadership</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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</table>

Survey identified seven ‘pain points’ raising a set of SoS SE questions
Analytic Workbench: Target Capabilities

• Open
  — Accommodates insertion of new SoS analytic methods (from Purdue or others)

• Interoperability
  — Outcomes produced in form suitable for additional SoSE phases
  — ‘Domain agnostic’, cross platform operations
  — Address uncertainty in data/simulation outcomes

• Useable
  — (Scalability) ➔ reasonable scaling of computational need to problem sizes
  — (Ease of Use) ➔ Users can translate problem to inputs required by relevant methods and tools
RT-108: 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. DoDADF OV, SV, PV declarations and other sources for SoS architecture definition)
SoS AWB – Archetypal Analysis

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>FDNA/DDNA</th>
<th>Bayesian Networks</th>
<th>Robust Portfolio Optim</th>
<th>Approx. Dynamic Program</th>
<th>Stand-In Redundancy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation. Analysis</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>Data Driven</td>
<td>x</td>
<td>x</td>
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<td>x</td>
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<tr>
<td>Architecture Design</td>
<td></td>
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<td>x</td>
<td>x</td>
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<tr>
<td>Risk Assessment</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>
Analytic Workbench – Inputs for SoS Analysis

Data elements for analysis

<table>
<thead>
<tr>
<th>Methods</th>
<th>Required Input Data Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDNA/DDNA</td>
<td>COD, SOD, Inter-system connectivities</td>
</tr>
<tr>
<td>Bayesian Networks</td>
<td>Probability distributions of system capabilities</td>
</tr>
<tr>
<td>Robust Portfolio Optimization</td>
<td>Capabilities, development risk, Compatibilities, System cost</td>
</tr>
<tr>
<td>Approximate Dynamic Programming</td>
<td>Capabilities, development risk, Compatibilities, System cost, time horizon</td>
</tr>
<tr>
<td>Stand-In Redundancy</td>
<td>System capabilities, development risk, Inter-system compatibilities</td>
</tr>
</tbody>
</table>

Legend

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

Candidate System
- Capabilities
- Requirements

Distribution of Performance, Failure Rate
- Connectivity, COD, SOD

SoS Analytic Workbench
SoS Analytic Workbench

Analytic Workbench - Outputs of SoS Analysis & Verification

Workbench - Verification via ‘Truth Model’
(e.g. Agent Based Model)

Inputs to ‘Truth Model’ (e.g. system capabilities, connections) of ‘new architecture’

SoS Performance evaluation based on ‘new architecture’

Chosen SoS systems & connections

SoS new architecture
Bayesian Networks (BN)

BN: Analyzing Cascading Interdependencies

**Inputs:**
- Failure probabilities of constituent systems
- Conditional probabilities
- Architectures

**Bayesian Networks Model**
Assumption: Directional graph

**Outputs:**
- Criticality of systems
- Resilience patterns

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- Failure probabilities of constituent systems
- Conditional probabilities
- Architectures

**Outputs:**
- Criticality of systems
- Resilience patterns

Bayesian Networks (BN)

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Bayesian Networks (BN)

The systems that, once failed, produce low conditional resilience values are deemed critical systems.

The figure indicates that MCM LCS and ASW MH60S are most critical.

Best-case: when critical systems fail last.

Expected-case: when systems fail in order of system ‘failure probability’

Worst-case: when critical systems fail first.

Note: Architecture type and order of system failure affect SoS resilience.
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):** \( \pm_{ij} \) 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):** \( \gamma_{ij} \) 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.
DDNA results in a schedule of development (here reported as a Gantt chart)

Final development, which accounts for partial dependencies, requires a shorter time than that resulting from PERT

However, some system requires longer development (higher cost). Trade-off required
• Complex behavior due to Strength and Criticality of Dependencies (SOD, COD), and multiple dependencies

• Differences from Bayesian approach for failure propagation:
  o Propagation is not probabilistic. It is a given function of Operability (O), Self-Effectiveness (SE), SOD, COD
  o 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 use 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

Robust Operational Analysis for SoS
Robust Portfolio Optimization

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
Robust Portfolio Optimization

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>
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<tbody>
<tr>
<td></td>
<td></td>
<td>0.01</td>
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<tr>
<td>ASW</td>
<td>Variable Depth</td>
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<td></td>
<td>Multi Fcn Tow</td>
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<tr>
<td></td>
<td>Lightweight Tow</td>
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<tr>
<td>MCN</td>
<td>RAMCS II</td>
<td>-</td>
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<tr>
<td></td>
<td>ALMDS (MH-60)</td>
<td>x</td>
</tr>
<tr>
<td>SUW</td>
<td>N-LOS Missiles</td>
<td>x</td>
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<tr>
<td></td>
<td>Griffin Missiles</td>
<td>-</td>
</tr>
<tr>
<td>Seaframe</td>
<td>Package 1</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Package 2</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Package 3</td>
<td>x</td>
</tr>
<tr>
<td>Comm.</td>
<td>System 1</td>
<td>-</td>
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<tr>
<td></td>
<td>System 2</td>
<td>x</td>
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<td>System 3</td>
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<td></td>
<td>System 4</td>
<td>-</td>
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<tr>
<td></td>
<td>System 5</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>System 6</td>
<td>x</td>
</tr>
</tbody>
</table>

Portfolios of systems at prescribed conservatism

Trade SoS Performance for Conservatism in Communications

Communications Layer Analysis

SoS Performance Index vs. Probability of Communications Constraint Violation

- $\Gamma=0.21$
- $\Gamma=0.41$
- $\Gamma=0.61$

Decreasing $\Gamma$ (conservatism)
Current Ext. Portfolio Approach

Current efforts in extending 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

Monte-Carlo simulation based data of various ABM architecture
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
Outreach Engagements

Currently working with following collaborators on AWB development:

- **Naval Surface Warfare Center Dahlgren Division (NSWCDD):** Memorandum of Understanding (MOU) signed for collaborative work on development of AWB tools towards in analyzing interstitial spaces of SoSE engineering environments. Progressed to CRADA agreement.

- **USAF Space Command (El Segundo, CA):** Initial exchanges and exposure on potential use of AWB methods towards representative case studies in SoS architectural analysis and decision-making.

- **MSCI & (Army Research Labs) ARL:** Initial exchanges towards how AWB can be used towards supporting Army Always-On initiatives for 2014-2015 period.

General collaborations also involve a demonstration version of Analytic Workbench to solicit core feedback in developing MPTs for AWB.
Recent Dissemination Activities

- 3 journal article submissions and numerous conference papers/presentations:
  
  - Conference on System Engineering Research (CSER) 2014:
    7 abstract submitted / 7 abstract accepted
    - An Analytic Workbench Perspective to Assessing Impact of Disruptions in System of Systems Architectures
    - An Analytic Portfolio Approach to System of System Evolutions
    - Managing System of Systems Architecture Evolution using Approximate Dynamic Programming
    - Exploiting stand-in redundancy to improve resilience in a system-of-systems
    - Bandwidth Allocation in Tactical Data Networks
  
  - AIAA Space Conference 2013
    - "Maintenance, Recycling in Space: Functional Dependency Analysis of On-Orbit Servicing Satellites Team for Modular Spacecraft".
  
  - IAF International Astronautical Congress (IAC) 2013

- Webinars/Workshops
  - SoSCIE Webinar (10th October 2013) - A Portfolio Approach to System-of-Systems Acquisition and Architecture
  - SEI hosted workshop on SoS, Washington DC
  - EU-US Collaborative Strategic Research Agenda in Systems of Systems
  - ERS (Engineering Resilient Systems) Workshop Washington D.C.
  - INCOSE SoS Webinar Series
• Mature AWB through collaborative exchange with MSCI, NSWCDD, USAF Space Command towards deploying demo tool set

• Planned deployment for broader DoD-SE community using HubZero technology → tighter integration with data input definitions (e.g. DoDAF)

• 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?
Thank You
Development Dependency Network Analysis (DDNA)

- Development time (DT) of a node is computed according to its SE.
- Completion time is the maximum between one term not accounting for the dependency and one term evaluated through the SOD.

\[
DT_j = \text{MINIT}_j + (100 - SE_j) (\text{MAXIT}_j - \text{MINIT}_j)/100
\]

\[
CT_j = \max(BT_j + DT_j, CT_i + SOD_{ij} DT_j)
\]

- CT: Completion Time
- MINIT, MAXIT: Minimum and Maximum Development Time
- BT: Beginning Time
- SE: Self-Effectiveness
- SOD, COD: Strength, Criticality of Dependency
- B: Minimum Completion Time
- D: Completion time Corresponding to COD
Overview – Approach Supporting A

Stakeholder A
- System a1
- System a2

Stakeholder B
- System b1
- System b2

Stakeholder C
- System c1
- System c2

SoS

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

Decisions of Stakeholder A
Low level decisions are required for two reasons:

- Satisfy short time requirements
- Provide more accurate feedback and new information to high level decision makers to facilitate learning
Illustrative Example – Surface Warfare Module

**Notional Surface Warfare Problem**

*Objective:* maximize the total SoS capability over time  
*SoS Capability Index:* percentage of systems surviving after attack

**Strategic Level:**
*Time Scale:* annually (or longer)  
*Decision Variables:* whether to develop new systems (LCS, UAV, MH-60R) to support future littoral surface warfare

**Operational Level:**
*Time Scale:* seasonally (or shorter)  
*Decision Variables:* whether to put systems (LCS, UAV, MH-60R) in service or out of service

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**Surface Warfare (SUW) in Littoral Combat Ship Naval Warfare SoS**
Objective: maximize the expected sum of SoS capability at operational level after being attacked during each stage, with the constraints of budget on the investment of new systems at the beginning of each year

Decision Variables:
\( x_t = \) develop systems at the beginning of each year; \( y_{t,s} = \) put available systems in service

State Variables:
\( R_{tsa} = \) number of systems of type \( a \) at season \( s \) of year \( t \)
\( R_{ts} = [R_{ts,\text{new}}; R_{ts,\text{in}}; R_{ts,\text{out}}]_{9 \times 1} \)

Attribute of 'state':
\[
\begin{pmatrix}
\text{system type (LCS, UAV, MH-60R)} \\
\text{availability (0,1)} \\
\text{in use (0,1)}
\end{pmatrix}
\]

Transition Function:
new systems available: \( R_{t,s=1}^{\text{out}} = R_{t-1,s=4}^{\text{out}} + x_{t,s=1} \)
put in service: \( R_{t,s+1}^{\text{in}} = (R_{t,s}^{\text{in}} + y_{t,s})(1 - \hat{w}_{t,s+1}); \ R_{t,s+1}^{\text{out}} = R_{t,s}^{\text{out}} - y_{t,s} \)

Exogenous Information (uncertainty): \( \hat{w}_{t,s+1} = (p^c, p^s) \)
Probability of threats ocuring \( p^c : p^c = [0.6, 0.6, 0.6] \)
Probability of success attack \( p^s : p^s = [0.3, 0.5, 0.5] \)
Objective: maximize the expected sum of SoS capability at operational level after being attacked during each stage, with the constraints of budget on the investment of new systems at the beginning of each year

\[
\text{obj : max } E \left( \sum_{t=1}^{3} \sum_{s=1}^{4} c^p (R_{t,s}^{\text{in}} + y_{t,s}) (1 - \hat{w}_{t,s+1}) \right) \\
\text{st : } c^s x_{t} \leq B_{t} \quad (t=1..3) \quad \text{and} \quad y_{t,s} \leq R_{t,s}^{\text{out}} \quad (t=1..3, \ s=1..4)
\]

\[\Rightarrow\text{Can be solved by recursively computing the optimal value function:} \quad V(S) = \text{current contribution} + \text{future value}\]

What is the approximation of future value?
\[\Rightarrow\text{Currently assume it is a linear function of number of resources (LCS, UVA, MH-60R)}\]
\[\Rightarrow\text{Need estimation of future characteristics (including resources, effect of other stakeholders, etc)}\]

How to update the approximation?
\[\Rightarrow\text{Learning from new coming information}\]
\[\Rightarrow\text{Agent base Model will be incorporated to generate new information}\]
Introduction (1): Context at Purdue

  — Community of faculty from several schools (e.g.: AAE, IE, ME, Civil....)
  — NOT a new department, but authorized for special faculty hires in SoS (I was first, in 2004)
  — Multi-faceted domains: Transportation, Healthcare Delivery, Logistics, Defense, etc.
  — Recent CoE Strategic Plan creates Purdue Systems Institute, with SoS focus

• School of Aero& Astro Eng. (AAE): started Aerospace Systems area (2006)
  — Research and curriculum for Aerospace-oriented SoS
  — My home department
  — Distance Education MS degree available

• Center for Integrated Systems in Aerospace, CISA (2011)
  — Established in 2012 and dedicated to advancement of theories/methods and application domains
  — Spans 3 Colleges, including Cyber center (CERIAS) and Predictive Reliability (PCSI) at Purdue
  — Directed by yours truly (but is an Acknowledgement SoS, at most!)
  — NASA, FAA, Industry, and DoD-funded work in Aerospace-oriented systems and SoS

Systems Engineering education spans all of these organizations

e.g., Industrial Eng. & AAE led effort to establish SE and SoS graduate concentration
• Introduction and Context Setting

• Towards an Analytic Workbench for SoS Modeling
  — What is it?
  — Why is it needed?
  — What are some initial tools for it? Example applications.

• Outreach & Future
  — Current outreach efforts with DoD community
  — Future vision of Analytic Workbench development