A Complexity Primer for Systems Engineers

November 2015

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Agenda

- Brief overview of Complex Systems WG
- Complexity Primer for Systems Engineers
Complex Systems (CxS) WG Overview

- Organized in 2006 from Systems Science WG
- Co-chairs: Dr. Jimmie McEver, JHU/APL
  Mr. Michael Watson, NASA/MSFC
- 46 INCOSE members participated in discussions at IW 2015

https://connect.incose.org/WorkingGroups/ComplexSystems/
Purpose and Objectives

- The purpose of the Complex Systems Working Group is to enhance the ability of the systems engineering community to deal with complexity.
- The CxS Working Group works at the intersection of complex systems sciences and SE, focusing on systems beyond those for which traditional systems engineering approaches and methods were developed.
- Complex Systems Working Group objectives
  - Communicate the complexity characteristics to systems engineering practitioners
  - Provide knowledge and expertise on complex systems in support of other INCOSE working groups working in their systems engineering areas
  - Facilitate the identification of tools and techniques to apply in the engineering of complex systems
  - Provide a map of the current, diverse literature on complex systems to those interested in gaining an understanding of complexity.
- Although analysis is important, the goal is to make a difference in synthesis (creation of new systems).
Candidate Activities

- Expand on Mat French MBSE in Complexity Contexts work begun in 2014
- Expand on selected Primer topics; evolve into wiki to facilitate evolution and access; develop annotated complexity bibliography
- Work with US Government partners to identify WG initiatives to help address current systems challenges (digital engineering, engineering resilient systems, open architecture based approaches for engineering complex systems)
- Identify relationships and strengthen interactions with other INCOSE WGs (and with complexity groups in other organizations)
- Workshop or other joint meeting with AIAA Complex Aerospace Systems Exchange organizers
- Maturity Model for the Complex SE capability of an organization or endeavor
- Organize webinars to discuss WG initiatives and topics of interest
A Primer on Complexity for Systems Engineers

- The INCOSE Complex Systems Working Group has drafted a primer to introduce complexity concepts and approaches to practicing systems engineers
- Members of the primer development team
  - Sarah Sheard
  - Eric Honour
  - Jimmie McEver
  - Dorothy McKinney
  - Alex Ryan
  - Stephen Cook
  - Duane Hybertson
  - Joseph Krupa
  - Paul Ondrus
  - Robert Scheurer
  - Janet Singer
  - Joshua Sparber
  - Brian White
Motivation: The Implications of Complexity

- Systems engineering has evolved to improve our ability to deal with scale and interdependency though the life cycle of engineered systems.

- Systems are becoming increasingly dynamic and interdependent, with growing emphasis on adaptiveness.

- BUT, complexity places new demands on systems engineers that require more than extensions of “classical” SE practice.
Classes of Systems Problems: Kurtz and Snowden’s Cynefin Framework

Cynefin domains

Complex systems, characterized by interdependence, self-organization, and emergence – new tools and approaches are needed.

Chaotic systems can only be reacted to; can attempt to transform into another domain.

Massively-complicated systems present challenges of scale and interface accounting – extensions of traditional methods/tools can help.

Simple and complicated systems are straightforward to deal with using traditional systems engineering / mgmt approaches.

What do we mean by complexity?

• No easy, agreed-upon definition
• We often call something complex when we cannot fully understand its structure or behavior: it is uncertain, unpredictable, complicated, or just plain difficult (see Sillitto (2009): Subjective Complexity)
• Concepts that seem essential
  – Emergence: Features/behavior associated with the holistic system that are more than aggregations of component properties
  – Multi-scale behavior: System not describable by a single rule, structure exists on many scales, characteristics are not reducible to only one level of description.
  – A system with self-organization, analogous to natural systems, that grows without explicit control, and is driven by multiple locally operating, socio-technical processes, usually involving adaptation
Complex vs Complicated

Complex system

Traffic jams exhibit:
• **Self-organization** and **Emergence** – local actors and decisions interact to create larger patterns
• **Memory** – even after an obstacle is removed the jam can persist for hours
• **Counter-intuitive outcomes** – e.g., Braess’ Paradox – adding capacity to the network can degrade network performance

Complicated system

Modern transit vehicles exhibit:
• **Large numbers of interacting systems** – fuel, electrical, engine, transmission, safety, etc.
• **Aggregate** properties, but not emergence – e.g., range, top speed…
  • Unexpected outcomes still possible, but origin is different
  • Transit systems may be complex

The opposite of “complex” is “decomposable”, not “simple”
## Hallmarks and Implications of Complexity

<table>
<thead>
<tr>
<th>Hallmarks of complexity</th>
<th>Impact on Decision Maker</th>
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<tbody>
<tr>
<td>Interdependence</td>
<td>Cannot treat by decomposition</td>
</tr>
<tr>
<td>Nonlinearities</td>
<td>Extrapolation of current conditions → error</td>
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<tr>
<td>Open boundaries</td>
<td>Cannot focus only on processes inside boundary</td>
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<tr>
<td>Multi-scalarity</td>
<td>Have to address all relevant scales</td>
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<tr>
<td>Causal &amp; influence networks</td>
<td>Challenge: develop ‘requisite’ conceptual model within time and information resource constraints</td>
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<tr>
<td>Emergence</td>
<td>Unknown risks and unrecognised opportunities</td>
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<tr>
<td>Complex goals</td>
<td>Goals may change, be unrealistic, vague</td>
</tr>
<tr>
<td>Adaptation &amp; innovation</td>
<td>‘Rules’ change, interventions stimulate adaptation</td>
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<tr>
<td>Opaqueness</td>
<td>Many possible hypotheses about causal paths, insufficient evidence to discriminate</td>
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Sources of Complexity

• System
  – Large number of components, many intricate interdependencies
  – Adaptive components, interactions
  – Interfaces with human users or other complex entities
  – Evolving technology

• Environment
  – Operational environment
    • Problem you’re trying to solve changes
    • Conditions under which you’re trying to solve a problem change
    • Way that you elect to solve the problem changes
  – System environment
    • Changes to elements of the larger SoS

• Design/management
  – Large number of people and organizations involved
System Complexity as SE Challenges

System Characteristics (Objective Complexity)

- Many pieces
- Nonlinear
- Chaotic
- Emergent
- Self-Organized
- Tightly coupled
- Decentralized
- Open
- Multi-Scale
- Adaptive

Cognitive Characteristics (Subjective Complexity)

- Uncertain
- Difficult to understand
- Unclear cause and effect
- Unpredictable
- Unstable
- Uncontrollable
- Unrepairable, unmaintainable
- Takes too long to build
- Costly

Sarah Sheard, Complexity and Systems Engineering, 2011. Used with permission
Complexity and Systems Development

• You need complexity to respond to complexity
  – Provides degrees of freedom to needed to deal with/work in complex, volatile and uncertain environments
• But developing and using complex systems have their own challenges
  – Less ability to plan and predict
  – Problems/systems not neatly decomposable – interdependencies between subsystems grow beyond ability to deal with them in traditional ways
  – Uncomfortable phenomena arise, such as normal accidents, black swans, catastrophic fragility

Ashby’s Law of Requisite Variety

A model system or controller can only model or control something to the extent that it has sufficient internal variety to represent it.
Candidate approaches: Selected Guiding Principles

Think like a gardener, not a watchmaker

- Grow, don’t build
- Focus on the ecosystem
  - Extensible substrate
  - Rules and feedback for adaptation
- Influence and intervene vice design and control

Take an adaptive stance

- Enable and improve adaptation capabilities
  - Observe system behavior
  - ID and create variation
  - Selecting the best versions
  - Amplify the fit of the selected versions
Candidate approaches: Selected Guiding Principles

Think at multiple levels and from multiple perspectives

- Systems may create different value at different levels and from different perspectives
- Need to look at systems and requirement from diverse perspectives

- System behavior may be fundamentally different at different levels
- The decomposed problem is a different problem
Candidate approaches: Selected Guiding Principles

- Combine courage with humility
- Use free order
- Identify and use patterns
- See through new eyes
- Collaborate
- Achieve balance
- Learn from problems
- Meta-cognition

- Focus on desired regions of the outcome space rather than specifying detailed outcomes
- Understand what motivates autonomous agents
- Maintain adaptive feedback loops
- Integrate problems
## Candidate approaches: SE Methods

### Environmental Complexity

<table>
<thead>
<tr>
<th>Environment susceptible to unpredictable but high-consequence events and/or recursive complexity</th>
<th>Requirements Elicitation and Derivation</th>
<th>Trade Studies</th>
<th>Solution Architecture and Design</th>
<th>Development Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use power laws to characterize relevant phenomena</td>
<td>Make dimensions of agility key trade-space attributes</td>
<td>Design for resilience to “beyond-design-envelope” events to provide robustness and timely recovery to a minimally functional state.</td>
<td>Resilience analysis</td>
<td></td>
</tr>
<tr>
<td>Focus elicitation on agility vice optimizing to particular assumptions</td>
<td>Use trades to ID aspects of the problem space that will drive the system architecture</td>
<td></td>
<td>Enterprise development: study how enterprises or societies survive catastrophes.</td>
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### Candidate approaches: SE Methods

**System/Solution Complexity**

<table>
<thead>
<tr>
<th>Complexity in System Design &amp; Development (General)</th>
<th>Requirements Elicitation and Derivation</th>
<th>Trade Studies</th>
<th>Solution Architecture and Design</th>
<th>Development Process</th>
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</table>
| Use multi-scale modeling (linking macro- and micro-level models), including exploratory analysis and agent-based modeling, and experimentation: | • To generate insight into the implications of derived requirements  
• As the basis for trade studies and to inform trade-off decisions | Emphasize selection of robust and adaptive elements and structures over optimizing to meet current requirements | Use Systems-of-Systems methodologies to synchronize constituent systems; incentivize collaboration.  
Ensure prototyping and experimentation are used. |
Applicability of Generalized Analytic Methods: The Cook Matrix

- Lists and briefly describes modeling and analysis methods from a wide range of disciplines
- Candidate approaches to consider in modeling complex systems problems

<table>
<thead>
<tr>
<th>Analyze</th>
<th>Diagnose</th>
<th>Model</th>
<th>Synthesize</th>
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</thead>
<tbody>
<tr>
<td>Data Mining</td>
<td>Algorithmic Complexity</td>
<td>Uncertainty Modeling</td>
<td>Design Structure Matrix</td>
</tr>
<tr>
<td>Splines</td>
<td>Monte Carlo Methods</td>
<td>Virtual Immersive Modeling</td>
<td>Architectural Frameworks</td>
</tr>
<tr>
<td>Fuzzy Logic</td>
<td>Thermodynamic Depth</td>
<td>Functional / Behavioral Models</td>
<td>Simulated Annealing</td>
</tr>
<tr>
<td>Neural Networks</td>
<td>Fractal Dimension</td>
<td>Feedback Control Models</td>
<td>Artificial Immune System</td>
</tr>
<tr>
<td>Classification &amp; Regression Trees</td>
<td>Information Theory</td>
<td>Dissipative Systems</td>
<td>Particle Swarm Optimization</td>
</tr>
<tr>
<td>Kernel Machines</td>
<td>Statistical Complexity</td>
<td>Game Theory</td>
<td>Genetic Algorithms</td>
</tr>
<tr>
<td>Nonlinear Time Series Analysis</td>
<td>Graph Theory</td>
<td>Cellular Automata</td>
<td>Multi-Agent Systems</td>
</tr>
<tr>
<td>Markov Chains</td>
<td>Functional Information</td>
<td>System Dynamics</td>
<td>Adaptive Networks</td>
</tr>
<tr>
<td>Power Law Statistics</td>
<td>Multi-scale Complexity</td>
<td>Dynamical Systems</td>
<td></td>
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<tr>
<td>Social Network Analysis</td>
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<td>Network Models</td>
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<td></td>
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<td>Agent Based Models</td>
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<td>Multi-Scale Models</td>
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</table>
Candidate approaches: Analytic tools for the Complex SE Toolkit?

• Some are emerging for “massively complicated” SE
  – MBSE tools and methods
  – Emerging thinking on T&E in large test spaces

• For complex SE, some exist – but are not designed for or aligned with SE community

• Complex SE (or CxSE) requires more than just tools
  – Not a “run the tool, get the answer” problem
  – Requires understanding of the nature of complexity and how to deal with volatility and deep uncertainty
    • Mindset, experience (and education)
      – Tools needed are those that will enable this understanding

• A key role of the systems engineer is to facilitate this understanding across his/her stakeholder communities
Next Steps (for the Primer and the WG)

- Present Primer for INCOSE technical review
- Continue to socialize primer as a resource for INCOSE members
- Expand on selected Primer topics; evolve into wiki to facilitate evolution and access; develop annotated complexity bibliography
  - Construct Concept Map for complex systems knowledge
- Leverage primer (and other) approaches to address (or at least generate new insight into) community “hard problems”
  - Cybersecurity
  - Evolutionary Acquisition
  - Systems of systems
- Engage with other working groups to identify intersection topics we can work together