Complexity and Systems Engineering

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Agenda

- Systems engineering today
- Complexity in science
- Complexity spectra
- Complexity in systems engineering
- Types and measures
SE and Complexity

◆“in the 1960s... engineers, scientists, and managers... had found the systems approach effective in responding to physical and organizational complexity...”

◆“What has led to...systems engineering as a separate function in organized creative technology? ...increasing system complexity...”
  – A. Hall, A Methodology for Systems Engineering (1962)
**Systems Engineering Is?**

**Org Charts**
- Titles

**Twelve SE Roles**
- Requirements
- Designer
- Analyst
- V&V
- Logistics
- Glue

**Cust. Interface**
- Tech Manager
- Info Manager
- Process
- Coordinator
- Classified Ads

**Information Technology SE**
- Software and computer system development done with an eye to the larger system

**SE Principles & Heuristics**
- Know the problem, the customer, and the consumer.
- Use effectiveness criteria based on needs to make systems decisions. ...

**Three Types of Implementation**
- **Type 1**
  - Discovery
  - Unprecedented Problems
  - Unprecedented Solutions
- **Type 2**
  - Program SE
  - Unprecedented Solutions
- **Type 3**
  - Approach

**The SE Vee (Life Cycle)**
- Define Needs and Operational Concept
- Define System Requirements
- Design System
- Implement System
- Verify System
- Integrate System
- Validate System

**The SE Engine**
(Mil-Std-499B)

**SE of Complex Systems (CxSE)**
- We don’t have good patterns yet
- Heuristics, based on research
- Principles, based on experience as extended by research
Systems have evolved
Army SOS

C2 CONSTELLATION

JOINT INTERAGENCY MULTINATION INTEROPERABLE

CURRENT FORCE INTEROPERABLE

Network Enabled
Battle Command

Enhanced Soldier Protection

Dynamic, Uninterrupted C4 Architecture

Service Based Architecture
One to Many Interfaces

LANDWARNET

Survivability
Reliability
Networked Lethality
Networked BC
Net-Ready
Sustainability
Transportability

Logistics & Medical in a high
OPTEMPO, non-contiguous battlespace

Source: Monica Farah-Stapleton, IEEE SOS conference, 2006
Used with permission
Definition of Complex System

◆ A system not describable by a single rule. Structure exists on many scales whose characteristics are not reducible to only one level of description. A system exhibiting unexpected features not contained within its specification. (http://www.calresco.org/glossary.htm)

◆ 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. (Adapted from Braha et al. eds., 2006)
The Complexity Quagmire

Dynamics

Display

of

interesting

Modeling

of

of

Networks

Markets

Complex Adaptive Systems

Small Worlds

Scale-Free Networks

Power Law Distributions

Order

Chaos

Complexity =

Edge of Chaos

Display

via

Study

Grow

Described

Describe

Display

Have

Are

Are

Lead to

Third Millennium Systems

Balance Growth Connections
A View of the Spectrum

Order
Stability
Short-Term Order
Long-Term Order

Oscillation
Complexity
Short-Term Order
Long-Term Order

Chaos
Disorder
Short-Term Disorder
Long-Term Disorder

Source: http://www.personal.psu.edu/ref7/apparatus/2005%20competition/flores.htm

Source: http://background-wallpaper.110mb.com/background-wallpaper-fractals2.php
Complexity and Systems Engineering

Ordered systems

Decomposable Systems

Complex systems
### Spectra -1

<table>
<thead>
<tr>
<th>Less Complex</th>
<th>More Complex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closed systems</td>
<td>Open systems</td>
</tr>
<tr>
<td>Clockwork systems</td>
<td>Swarm systems</td>
</tr>
<tr>
<td>Organized</td>
<td>Self-organizing</td>
</tr>
<tr>
<td>Weakly integrated systems</td>
<td>Highly integrated systems</td>
</tr>
<tr>
<td>Central control</td>
<td>Decentralized control</td>
</tr>
<tr>
<td>Single agents/pairs of agents</td>
<td>Infinites of agents</td>
</tr>
<tr>
<td>Technical</td>
<td>Socio-political</td>
</tr>
<tr>
<td>Less Complex</td>
<td>More Complex</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-----------------------</td>
</tr>
<tr>
<td>Understandable</td>
<td>Difficult to understand</td>
</tr>
<tr>
<td>Predictable</td>
<td>Unpredictable</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>Chaos</td>
</tr>
<tr>
<td>Stable</td>
<td>Unstable</td>
</tr>
<tr>
<td>Linear</td>
<td>Nonlinear</td>
</tr>
<tr>
<td>Loose coupling</td>
<td>Tight coupling</td>
</tr>
<tr>
<td>Controllability</td>
<td>Adaptability</td>
</tr>
<tr>
<td>Less Complex</td>
<td>More Complex</td>
</tr>
<tr>
<td>------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td>Strict hierarchies</td>
<td>Networks</td>
</tr>
<tr>
<td>Tactical behavior</td>
<td>Strategic behavior</td>
</tr>
<tr>
<td>Simple behavior</td>
<td>Emergent behavior</td>
</tr>
<tr>
<td>Clear cause and effect</td>
<td>Unclear cause/effect</td>
</tr>
<tr>
<td>Single scale</td>
<td>Multi-scale</td>
</tr>
<tr>
<td>Reductionism works</td>
<td>Holism required</td>
</tr>
</tbody>
</table>
What’s the difference?

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

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

- Political
Complexity Contributors and Results

Technical Characteristics/
System Characteristics/
Objective Complexity

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

Cognitive Characteristics/
Subjective Complexity

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

- Planning, and monitoring to ensure compliance
- Control
- Hierarchy and modularization
- Decomposition (Reductionism)
- Order...predicting and avoiding chaotic regimes
- Gaussian distributions
- Trade Studies
- Requirements
- Architecture, Stable intermediates
- Vanquish complexity

Many pieces
Emergent
Nonlinear
Adaptive
Chaotic
Hierarchy and modularization
Decomposition (Reductionism)
Order...predicting and avoiding chaotic regimes
Gaussian distributions
Trade Studies
Requirements
Architecture, Stable intermediates
Vanquish complexity
How SE Could Better Address Complexity

- Planned co-evolution with environment
- Understand decentralized control
- Use modularity and hierarchy along with networks
- Decomposition (Reductionism) where appropriate
- Intensive modeling and simulation
- Predicting ordered and chaotic regimes in technological systems and development systems
- Managing the boundaries of safe state spaces
- Power-law distributions as well as Gaussian
- Trade Studies, Requirements, Architecture, Stable intermediates
- Invoke social sciences
- Manage complexity as risk
Dissertation Topic

◆Correlation of Measures of Complexity for Systems Engineering with Measures of Program Success

● Goal: determine a small set of complexity measures that predict program success
  ➔ Or none at all!

● Measure complexity
  ➔ First: know what it is!

● Define “for systems engineering”

● Measure program success
What Is Measured?

**Configuration Complexity** - Number of levels of components nested within a boundary or environment

**Complicatedness/Functional Complexity**
Number of different elementary components through specific interactions

**Subjective Complexity** Based on human perception; related to observers’ own thinking

**Statistical Complexity** Statistical measures of structure or pattern

**Algorithmic/Deterministic Complexity** Based on information theory, use mathematical computation to measure the algorithmic content of data

**Interface Complexity.** An interface of a component in isolation

**Complicatedness/Functional Complex-ity**
Number of different elementary components through specific interactions

**Product complexity.** Number of subsystems of a physical deliverable of the project, their interrelationships

**Dynamic Organizational complexity.**
Pattern and rate of change in organizational environment, such as business processes, organizational structures

**Inter-Component Complexity.** Interactions of components at the system level

**Implementation Complexity.** Complexity of creating and implementing components beyond interface complexity, such as program code

Ref: Young, Farr, Valerdi: Role of Complexities in SE Cost Estimating Processes CSER 2010
“Atomic Pieces” of Complexity Representation

System Dynamics

Networks

McCabe Complexity

Vertices

Edges

Nodes

Links

Stock

Flow

Stock

Software

Modules

Messages

Connections

People

Social Networking

Subsystems or Elements

Interfaces

Systems Engineering

System Analysis

Entities

Relationships

Model = Things + Relationships
Theoretical types of complexity

Objective complexity

- Things (Systems, products)
- Development processes
- Environment

Subjective complexity

- Cognitive complexity

Structural complexity

- Structural complexity: Size
- Structural complexity: Connectivity
- Structural complexity: Inhomogeneity

Dynamic complexity

- Dynamic complexity: short term
- Dynamic complexity: long term

Socio-political complexity

- Difficulty, problems, confusion, risk, control, prediction, uncertainty

Environment subtypes

- Subtypes

Theoretical types of complexity

- Size
- Connectivity
- Inhomogeneity
- Short term
- Long term
- Socio-political complexity

Balance Growth Connections
All these things change over time

There is information (data) about all these things
All these things change over time

There is information (data) about all these things
Complexity Measures

◆ Winnowing down measures to a surveyable set
◆ Seek correlation
◆ Looking for historical programs to interview
◆ Need both successful and unsuccessful programs (late, very overrun, cancelled)
Survey Questions for Dissertation

◆ Goal: Determine which complexity measures matter

◆ Asked 50 projects:
  ● How complex was it? (~30 measures, 5 bins)
  ● How successful was it? (cost, schedule, performance/quality)
  ● Your role and contact information
  ● Program name not required

◆ Link to questions
  ● http://www.surveymonkey.com/s/SEComplexitySuccessSurvey
5. What was the cost of the project
b) over the life of the project?

- $< 100K
- $100K - $1M
- $1M - $10M
- $10M - $100M
- > $100M

Notes

6. "This project was bigger than the typical project that this organization had pursued up to that time."

Do you agree with this statement?

- Strongly Agree (much bigger)
- Agree (bigger)
- Neutral (about typical size)
- Disagree (a bit smaller)
- Strongly Disagree (much smaller)

Notes
### Measures in survey

<table>
<thead>
<tr>
<th>Project</th>
<th>System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost, annually and total</td>
<td>Subsystems</td>
</tr>
<tr>
<td>Relative size</td>
<td>No. Requirements</td>
</tr>
<tr>
<td>Duration of project</td>
<td>No. Requirements, Difficult</td>
</tr>
<tr>
<td>Replanned?</td>
<td>Architecture precedence</td>
</tr>
<tr>
<td>Use PERT, Risk Mgt, Agile, Lean, Double Loop, Set</td>
<td>Requirements conflict</td>
</tr>
<tr>
<td>Change packages in limbo</td>
<td>Requirements/cost/schedule conflict</td>
</tr>
<tr>
<td>Task dependencies</td>
<td>Technology maturity</td>
</tr>
<tr>
<td>Project control</td>
<td>System evolution</td>
</tr>
<tr>
<td>Staff skills</td>
<td>Contractors</td>
</tr>
<tr>
<td># Decision makers</td>
<td>Ease of meeting user/sponsor expectations</td>
</tr>
<tr>
<td># Government organizations</td>
<td># Sponsors</td>
</tr>
<tr>
<td># Contractor organizations</td>
<td>Stakeholder conflict</td>
</tr>
<tr>
<td>Fog of conflicting data and cognitive overload</td>
<td>Change in stakeholder needs</td>
</tr>
<tr>
<td>Estimates were good</td>
<td>ESE Profiler</td>
</tr>
<tr>
<td>Short-term vs Long-term focus</td>
<td></td>
</tr>
</tbody>
</table>

| Success, general | |
| Delivered a product | |
| Cost rel. to plan | |
| Schedule rel. to plan | |
| Performance rel. to plan | |
Backup slides
Complexity Types from SE Literature I

◆ Requirements and problem space
  ● Conflict
  ● How many people would you have to get into a room to understand the whole problem?

◆ Technical feasibility
  ● Match of needs to plan

◆ Skills
  ● Domain knowledge
  ● Gap between know and need to know
  ● How long to come up to speed?
Complexity Types from SE Literature II

◆ Technology Maturity
  ● Technology and interfaces
  ● TRLs
  ● Computer and language

◆ Socio-Political subcategories
  ● Organizational instability
  ● Organizational structure
  ● Stakeholder cohesion
  ● Management task
  ● Testing
Existing Measure for SocioPolitical

Enterprise Systems Engineering Profiler™ of MITRE

◆ Traditional program domain
  ● Well-bounded problem
  ● Predictable behavior
  ● Stable environment

◆ Transitional domain
  ● Systems engineering across boundaries
  ● Influence vs. authority

◆ Messy frontier
  ● Political engineering (power, control…)
  ● High risk, potentially high reward
  ● Foster cooperative behavior