A Perspective on Decision-Making Research in System of Systems Context

System of Systems Engineering Collaborators Information Exchange (SoSECIE)

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Motivations/observations

- We all make decisions – some good, some bad:
  - Braess Paradox - individual vs. social incentive equilibriums
  - Centralized vs. decentralized – overloaded information – cannot make rational decisions
  - “Mumbai cobras and mismatched incentives”
  - Defense acquisitions – jet fuel trails in the sky
  - My airline experience – the “irrational” traveller
    - Revenue management
SoS – the KEY Questions

- US DoD SE/SoSE guidelines
- Transportation, Healthcare, Defense, Software Engineering etc.
- An international endeavor (beyond U.S. DoD, NSF), e.g. European Commission FP7 Efforts in SoS
- Several Major SoS Research Projects
- IBM 4 trillion dollar challenge to deal with SoS level problems

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

Modeling and simulation

- **Air Transportation**
  - Crossley, Mane – Simultaneous design of aircraft and operations in SoS context
  - DeLaurentis, Kotegawa – Improved predictive modeling of terminal area forecasts due to SoS interaction
  - NASA ACES, FACET - Simulators

- **Defense Acquisition, SE/SoSE**
  - Defense Acquisition Guide (DAG), Wave Model,
  - Garett et al - Interstitials of BMDS as a SoS
  - SERC – Acheson cooperative, non-cooperative dynamics of SoS meta-architecture
  - DARPA –SoS maritime application for networks

Image Sources from main websites of each effort : available on request
Decision Analysis and control

**Software /Systems Engineering/Decision Support**
- DANSE – technical approaches for SoS Engineering
- COMPASS – MBSE techniques for developing and maintaining SoS
- Various works from: JPL, CMU-SEI, USC, MIT, Purdue

**Control Systems as a System of Systems**
- Distributed/Decentralized/Consensus Control
- Smart grid systems, UAV/drone application (military, agriculture)
- VoIP, Communication Network Protocols and Routing.

**Book Publications:**
A Decision Theoretic perspective

SoS stakeholders may be cooperative or non-cooperative decision-makers

Maximization of individual utility affected by:

• **Data to Information**
  - Too much data to determine value of choices
  - Too many options to quantify value of choices
  - Data privacy/segmentation

• **Rules of Autonomic Engagement**
  - Constraints on how to talk to another stakeholder
  - Information flow based on constraints

• **Perceived Fairness**
  - Good allocation for whole is not fair to individual (price of fairness)
  - Changes individual behavior/participation (gaming behavior)

• **Network structure**
  - Structure of information flow across network
  - Game/Incentive based on structure of network for resource flow
Modeling for decision making

Agent Interactions and Theories
- Adaptive Markets Hypothesis (Lo)
- Reconcile modern financial economics with behavioral models to explain market dynamics (e.g.) -
- Rationality/Irrationality
- Loss Aversion
- Overconfidence
- Overreaction
- Cultural Theory
- Risk regulation driven theory – explain how certain stakeholder groups make alliance and shift equilibrium.

Modeling Framework(s)
- Agent Based Model (ABM)
- System Dynamics
- Various Stochastic Processes
Mechanism design & learning preferences

- **Mechanism Design**: involves the design of institutions and how these affect the outcomes of (stakeholder) interactions. Also known as “reverse game theory”. (e.g. – Auctions using Vickery Clarke-Groves Mechanisms)

- **Game Theory**: the study of mathematical models of conflict and cooperation between intelligent rational decision-makers

- **Network Science** – nature of connections between stakeholders/systems

- **Learning Preferences** – statistical/data mining to find stakeholder preferences

  - We often apply these to the product/service not to organization

Prior Research (Mechanism Design)

The Idea: Can we treat policy selection as a ‘game’ and design game accordingly?

Our Work: Early mechanism design framework for policy selection in acquisitions-use of empirical data in policy generation work

Prior Efforts:

• Dagli et.al – Agent simulation of iterations: planning, implementation, analysis phases in wave model, in preparation for sequential tasks for each epoch.

• Sheard survey driven analysis on complexity, cognitive overload, difficulty of system development.


A Bayesian Perspective to McNew Survey

- McNew uses behavior archetypes to structure survey
- 65 program managers surveyed to confirm these ‘behaviors’ on program
- If present, confirm cost, schedule growth, root cause
- Use Bayes to determine

\[ P(\text{outcomes} \mid \text{root cause}) \& P(\text{root cause}) \]
Mechanism Design

• Also known as ‘reverse game theory’ – invent the game,. Applied in auctions, communications networks.

• Frequently applied in auction theory (how does auctioneer maximize revenue) though mostly in single item auctions.

• Individual Rationality: Buyers do not achieve negative utility with truthful bids,

• Budget Feasibility: Buyers are constrained by resource budgets in bidding, and,

• Incentive Compatibility: Bidders fare best (optimal utility) when truthfully disclosing information.
A Simple Application to McNew Data

Policy generation scenario

**Given:**

- Bayesian Analysis of McNew data
- Cost implications
- Potential gain by using policy ($x_i$)
- Uncertainty in correlated gains for policies ($x_i$)

**Question:**
What policies should I effect at various levels of policy robustness, satisfying some mechanism conditions?

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- R1: Govt failed to define requirements
- R2: Contractor failed to understand risk
- R3: Requirements changed to accommodate additional users
- R4: Contractor struggled integrating technologies
- R5: Contractor failed to assign sufficient personnel

**Behavior**
- Cost Growth
- Schedule Growth

**Root Cause**
- Happy path testing
A Simple Example Application

- Tradespace analysis, policy control
- Objective view of policy effects given current available state

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Conservatism ($\Gamma$) 0.1 0.3 0.9

P(Constraint Viol) 0.64 0.61 0.52
Optimal Selection of Organizational Structuring for Complex System Development and Acquisition*

- **Conway’s Law**
  
  “..product designs tend to reflect the structure of an organization in which they are conceived..” **

- **Organizational Structure**
  - Connections between groups
  - Volume, type, function, form of information
  - Incentives between groups, individuals

- **Complex Product Structure**
  - Physical, Functional boundaries
  - Multidisciplinary Boundaries


Can we reconcile them to better organize a team AND the end product?

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Some prior research

- **MacCormack et al** – Conway’s law is a notable effect – examined software system layout and showed degree of coupling and propagation costs

- **Honda et al** – comparison of information passing strategies in system-level modeling

- **Ulrich** - how degree of product’s novelty affects 5 areas of managerial importance
  - Product change, variety, component standardization, performance, development management

- **Sinha & de Weck** – explore how the degree of a new product’s novelty affects the structure of an organization.

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Concept Application

Multiple Stakeholders

- Stakeholder 1 Utility Model
  - Profit vs. Risk

- Stakeholder 2 Utility Model
  - Profit vs. Risk

- Stakeholder 3 Utility Model
  - Utilities: Profit vs. Risk vs. Personal

“Retail” Rebalance Portfolio

Product A

Product B

Organization Structure

“Product” Structure
Summary and forward thoughts

Current SoS research mostly focus on:

- Implicit value to stakeholder(s)
- Modeling complex interdependencies/dynamics of SoS
- Acknowledges a coupled effect between organization and product structure

For **operational** and **managerial** independence questions, need to address:

- Developments in MPTs to improve the collaborative/competitive decision-making elements across stakeholders in a SoS.
- The SoS level impact of changing preferences and behaviors
- Policy generation through quantitative, decision-theoretic approach.
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