Engineering Systems: Overview of Methodologies

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• Define **Engineering Systems** and how they can be classified and characterized

• Show a representative set of **problems** and **methods** and a sample of recent **results**

• Summarize the **progress that has been made in the last 5-10 years** in advancing the field of Engineering Systems

• List items for **future research**

• Discussion
A Class of Systems
Engineering systems are characterized by a high degree of technical and social complexity and they aim at fulfilling important functions in society.

Emerging Field of Research
Engineering systems research is problem-oriented, developing and employing multiple methodologies, and balances quantitative and qualitative arguments.

Domains
- Extended Enterprises
- Critical Infrastructures
- Energy and Sustainability
- Health Care Delivery

Approaches
- Humans and Technology
- Uncertainty and Dynamics
- Design and Implementation
- Networks and Flows
- Policy and Standards
Air Transportation
A typical Engineering System

Spatial Decomposition

Latent Demand

Passenger Flows

Flights / Aircraft flows

Infrastructure

System Performance and Other Issues

Transportation Demand
- Price of fuel ($/gal)
- Competition (car, train)
  -- Seasonal variations

Value to Society

Intermodal Transportation

Passenger Traffic
- RPMs, RPKs,
  - Passenger counts
  - Piggyback cargo (tons)

Highway and Rail Renewal

Airline Competition

Aircraft Traffic
- Flight counts
  - Airport operations

Bankruptcies

Emissions

Capacity Inadequacy

Pollution

Infrastructure
- Airport count
  - Airport capacity
    - Enroute capacity

Delays

Safety

Accidents

Where is “Engineering Systems” situated?

![Diagram showing the scale of Engineering Systems from different perspectives.](image-url)
### Functional Classification

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Matter</th>
<th>Energy</th>
<th>Information</th>
<th>Money</th>
<th>Humans Animals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Operand Process</strong></td>
<td><strong>Automotive Exhaust System</strong></td>
<td><strong>Oil and Gas Refinery</strong></td>
<td></td>
<td></td>
<td><strong>Mass General Hospital</strong></td>
</tr>
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<td><strong>Transform Process</strong></td>
<td><strong>Air Transport System</strong></td>
<td><strong>Radar System</strong></td>
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<td><strong>Air Transport System</strong></td>
</tr>
<tr>
<td><strong>Transport Distribute</strong></td>
<td><strong>Battery Systems</strong></td>
<td><strong>Magnetic Disc Drives</strong></td>
<td></td>
<td></td>
<td><strong>Commercial Real Estate</strong></td>
</tr>
<tr>
<td><strong>Store House</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>NYSE Stock Exchange</strong></td>
</tr>
<tr>
<td><strong>Exchange Trade</strong></td>
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<td></td>
<td></td>
<td></td>
<td><strong>U.S. Federal Reserve</strong></td>
</tr>
<tr>
<td><strong>Control Regulate</strong></td>
<td><strong>Climate Change Policy</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>Senior Driver Certification</strong></td>
</tr>
</tbody>
</table>

Adapted from Table 10

Sample Engineering Systems Problems, Methods and Results

- 1 Quantifying Rates of Technological Progress
- 2 Designing Systems for Technology Infusion
- 3 Assessing Driving Performance of Seniors
- 4 Predicting Impact of Policy on Climate Change
1 - Quantifying Technological Progress

Storing information [Mbits/cm³] – 20.8+/−1.6% p.a.

Storing Energy [Wh/kg] – 3.7+/−0.4% p.a.

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<th>Problem</th>
<th>Quantifying technological progress over long time periods (100 years+) independently of specific artifacts. Identifying fundamental limits.</th>
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<td>Result</td>
<td>Approach to study of technological change by examining the time dependence of Functional Performance Metrics (FPM). Interlinked “S”-curves.</td>
</tr>
<tr>
<td>Impact</td>
<td>Confirmation of continuous exponential progress for both information and energy technologies but at different rates. Received 2006 Elsevier Prize.</td>
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Design Structure Matrix (DSM)  
Multi-objective Optimization  
NPV Analysis  
Scenario Planning


**Problem**  
Quantify risks and opportunities of infusing new technologies into existing baseline or legacy systems and products

**Result**  
A framework for quantifying the potential benefits of a set of technology infusion concepts and weighing those against their technology invasiveness with respect to a host system using ΔDSM’s and fuzzy Pareto frontiers

**Impact**  
Applied to Arvin Meritor’s hydrogen-enhanced internal combustion engine (Plasmatron) product, currently being implemented at Xerox (iGen4 production printing system) and others, Best paper award 2007 in *Systems Engineering*
## 3- Assessing Driving Performance of Seniors

![AgeLab](image)

### Problem
Quantify the driving Performance of individuals under different cognitive task loading and demographic factors

### Result
A model for driver performance under off-nominal conditions including impairment by secondary tasks. Demonstrated that Young (19-23) and Older (51-66) drivers performed equally well but use different adaptation.

### Impact
Establish scientific connection between personal mobility and ageing. Impact on population through Hartford “campaign” to educate families and older drivers

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**Simulation**

**Human Experiments**

**Surveys**

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4 - Impact of Policy on Climate Change

Problem: Modeling the impact of different Greenhouse gas (GHG) stabilization policies on Earth’s surface temperature in the next century.

Result: Developed a model of Earth’s temperature evolution which is scientifically grounded both in Earth Science and Policy. Quantified probabilities of rise between 1-8 deg C.

Impact: Comparison of three major policies and characterization of their probability density functions. Communication about the severity of the threat using “roulette wheel” representation.

Research Methods Overview

“Ping-Pong”

Empirical Methods

- Grounded Theory
- Interviews
- Surveys
- Human Experiments
- “System” Experiments*
- Statistics
- Accident Investigations
- Sensor Networks

Induction

Theoretical Methods

- Object-Process Modeling (OPM)
- Abstract Algebra
- System Simulation
- Agent Based Modeling
- Network/Graph Theory
- System Optimization
- Real Options in Design
- System Dynamics
- Control Theory
- Scenario Planning
- NPV Analysis

Deduction

* e.g. “Green Islands” project in the Azores (MIT Portugal Program)
Progress since 1999

- Some emerging principles and methods for Engineering Systems analysis, design and management
  - Systems architecting (OPN/OPM)
  - Designing systems for changeability, safety, survivability ...
  - Emerging principles, e.g. Law of unintended consequences, Network coalescence versus aggregation, ...

- Impact on Real World
  - Resilient Enterprises (response to disruptions in manufacturing and logistics)
  - Flu Preparedness and Vaccine supply chains ... others

The number of credit units in Engineering Systems subjects at MIT has increased 4-fold in the last decade.

Source: Office of the Provost
Future Research in Engineering Systems

• Developing and refining a **unified language** for modeling complex engineering systems including their technological, social and natural components
  
  – Object-Process-Methodology, SysML, Network Science, Agent-based Modeling, Matrix Methods, System Dynamics

• **Multi-layer network** modeling
  
  – Recall Air Transportation Example. Most systems can be represented as interacting layers: social/organizational, technological, process-layer

• **Bayesian Learning in Policy Design** and Analysis
  
  – Treating policy as a control problem where not the control inputs (=actuator commands) are fixed, but the desired outcomes

• **Systems Architecture for Lifecycle** ("Illities")
  
  – Making causal connections between system form-function patterns (e.g. modularity) and quantifying their lifecycle properties explicitly, e.g. evolvability, safety, sustainability etc...
Questions?

Network plot of largest change network of 2579 associated change requests in sensor system design at Raytheon Integrated Defense Systems

Characterization of Engineering Systems Research Problems

- Feature intertwined “messy” complexity
  Understanding only technology or only social interactions is not enough

- Not “clean sheet” design, but need to deal with ...
  Existing topography, legacy infrastructure, policies, laws, demographics, ...

- Uncertainty is ubiquitous
  Demand for services, reliability of components, prices of commodities, ...

- Partially Designed – Partially Evolved
  No single stakeholder has full control over the system
### Problem Addressed
Understanding change propagation patterns on a large technical projects involving hardware, software and human operators

### Scientific Contribution
Developed procedure for data-mining of a large change request database (>40,000 changes) and analyzing change networks as well as classification of system components with a Change Propagation Index (CPI)

### Outcome, Impact
Applied to a large sensor system project at Raytheon IDS. Identified areas that are likely candidates for flexibility infusion

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Ensuring Industrial Systems Safety

Problem
Modeling accidents and ensuring safety in complex socio-technical systems where linear event models are insufficient

Result
Developed new methodology (STAMP) for analyzing systems safety from a control systems perspective, including the role of humans as operators, designers and managers

Impact
Application of STAMP to Columbia Accident investigation, industrial systems (BP), safety in health care, INCOSE conference best paper, ACM Newell Award

Beware of the Law of Unintended Consequences  
Dick Larson

• For those many who use Systems Dynamics as a modeling platform, we are often dealing with 2nd order and higher order systems. Policy or management changes that move the system in the direction desired in the short term may in the long term have just the reverse effect. There are numerous examples in both the public and private sectors. What is often required in the short term is 'short term pain' for 'long term gain.' (But people with short term appointments to positions of responsibility {e.g., politicians and many CEOs} will not be around to experience the future, positively or negatively. Thus, a mismatch between system response time and decision-making responsibility time.)

• The possible "fundamental" here might be stated:
  – "Second and higher order systems often have long-term responses to managerial or policy change that are the reverse of the short term changes. System managers need to be aware of this fact and also be held accountable for decisions that may outlast their tenure."
Patterns of Evolution in Complex Systems

- **Physical Systems** mainly grow through aggregation
  - Adding nodes and edges over time to the giant component
    - Preferential Attachment
    - Hub-Seeding
    - Hierarchy Interlinking etc...
  - Governed by physical laws
    - Conservation of mass etc...
    - Need for efficiency

- While **Social and Knowledge Systems** tend to grow by coalescence
  - Start with disconnected clusters which connect gradually over time
    - Network coalescence
    - Gradual formation of giant comp.
    - Weak links
  - Governed by human behaviors
    - Limited Rationality

Images: Airline Network, Internet, Wikipedia