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Problem Statement

Performance inefficiency: A major challenge in engineering projects

- Performance failures significantly affect the efficiency of investments in engineering projects across different industries:
  - Cost overruns
  - Schedule delays
  - Quality deficiencies
Many engineering projects cannot meet their performance goals.

1 out of 20 construction projects met both authorized cost and schedule goals

1 out of 10 large software development projects can be identified as successful
A paradigm shift in assessment of engineering projects based on the proper conceptualization of engineering projects is needed.
Complex engineering projects are systems-of-systems. The objective of this study is to propose a system-of-systems framework for the assessment of complex engineering projects.

Traits of SoS (Maier, 1998)
- Operational Independence
- Managerial Independence
- Emergent Properties
- Evolutionary Development
- Geographic Distribution

Design process
Production/construction process
Finance process
Procurement process
Safety process
An engineering project system-of-systems (EPSoS) framework is proposed based on two principles (DeLaurentis and Crossley, 2005): Base-level Abstraction and Multi-level Aggregation.
Three types of entities are abstracted at the base level.

**Human agent**
Entities who conduct production work, process information and make decisions

**Resource**
Entities that facilitate production work, information processing and decision making

**Information**
Knowledge or facts that affect dynamic behaviors of human agents
### Examples of attributes of base-level entities:

<table>
<thead>
<tr>
<th>Base-level entity types</th>
<th>Classification</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Agent</td>
<td>Production work agent</td>
<td>Productivity, attention allocation</td>
</tr>
<tr>
<td></td>
<td>Information processing agent</td>
<td>Response time</td>
</tr>
<tr>
<td></td>
<td>Decision making agent</td>
<td>Risk attitude</td>
</tr>
<tr>
<td>Resource</td>
<td>Material</td>
<td>Quantity, quality, cost</td>
</tr>
<tr>
<td></td>
<td>Equipment</td>
<td>Productivity, cost</td>
</tr>
<tr>
<td>Information</td>
<td>Existing information</td>
<td>Completeness, accuracy</td>
</tr>
<tr>
<td></td>
<td>Emergent information</td>
<td>Completeness, accuracy, recency</td>
</tr>
</tbody>
</table>
Four levels in engineering projects

Base level
- Activity1
- Activity2
- Activity3

Process level
- Design
- Procurement
- Production
- Finance

Activity level
- resilience
- agility
- vulnerability
- adaptive capacity

Project level
The application and effectiveness of the proposed EPSoS framework is shown in a complex construction project.

**Study 1**
How do the attributes and micro behaviors of base-level entities affect project performance?

**Study 2**
How to get a better understanding of project behaviors under uncertainty via emergent properties?
Case Description

- A complex construction project (Ioannou and Martinez, 1996)
- 1600-meter tunnel
- Varied ground conditions (Good, Medium, or Poor)
- New Austrian Tunneling Method (NATM)
- Adjusting design during the construction phase based on the changes of the ground condition
Study 1: Investigate the impacts of attributes and micro behaviors of base-level entities on project performance

**Step 1**: Abstract base-level entities and attributes

**Step 2**: Develop an agent-based model

**Step 3**: Conduct simulation experiments

**Step 4**: Analyze simulation results
### Application Example

#### Study 1: Base-level entities

**Step 1: Abstract base-level entities and attributes**

<table>
<thead>
<tr>
<th>Category</th>
<th>Base-level entities</th>
<th>Classification</th>
<th>Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Agent</td>
<td>Designer</td>
<td>Production/information processing/decision-making</td>
<td>response time, risk attitude</td>
</tr>
<tr>
<td></td>
<td>Workers</td>
<td>Production/information processing</td>
<td>Productivity, cost, response time</td>
</tr>
<tr>
<td>Resource</td>
<td>Excavator</td>
<td>Equipment</td>
<td>Productivity, cost</td>
</tr>
<tr>
<td></td>
<td>Support</td>
<td>Material</td>
<td>Quantity, quality, cost</td>
</tr>
<tr>
<td>Information</td>
<td>Historical data</td>
<td>Existing information</td>
<td>completeness, accuracy</td>
</tr>
<tr>
<td></td>
<td>Current ground condition</td>
<td>Emergent information</td>
<td>completeness, accuracy, recency</td>
</tr>
<tr>
<td></td>
<td>Step length</td>
<td>Emergent information</td>
<td>completeness, accuracy, recency</td>
</tr>
</tbody>
</table>
Application Example

Study 1: Base-level entities

Step 2: Develop an agent-based model

Class diagram

Sequence diagram
### Application Example

**Study 1: Base-level entities**

#### Step 3: Conduct simulation experiments

<table>
<thead>
<tr>
<th>Risk attitude</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk seeking</td>
<td>Design decisions are made for better outcomes with higher levels of uncertainty</td>
</tr>
<tr>
<td>Risk neutral</td>
<td>Design decisions are not affected by the degree of uncertainty</td>
</tr>
<tr>
<td>Risk averse</td>
<td>Design decisions are made for outcomes with lower levels of uncertainty</td>
</tr>
</tbody>
</table>

**Simulation experiment example:**
changing the risk-attitude of designer
Study 1: Base-level entities

Step 4: Analyze simulation results

- A risk-seeking designer improves project time, but increases the near-miss sections.
Study 2: Investigate emergent properties arising from interactions and interdependencies in projects

Application Example
Study 2: Emergent properties

- Step 1: Abstract project meta-network
- Step 2: Translate uncertainty
- Step 3: Assess vulnerability
- Step 4: Evaluate planning strategies
## Step 1: Abstract project meta-network

<table>
<thead>
<tr>
<th></th>
<th>Agent</th>
<th>Information</th>
<th>Resource</th>
<th>Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent</td>
<td>who works with and reports to whom</td>
<td>who knows what</td>
<td>who can use what resource</td>
<td>who is assigned to what activity</td>
</tr>
<tr>
<td>Information</td>
<td>what information is related to other information</td>
<td>what information is needed to use what resource</td>
<td>what information is needed for what activity</td>
<td></td>
</tr>
<tr>
<td>Resource</td>
<td>what resource is used for other resources</td>
<td></td>
<td>what resource is needed for what activity</td>
<td></td>
</tr>
<tr>
<td>Activity</td>
<td></td>
<td></td>
<td>what activity is related to other activities</td>
<td></td>
</tr>
</tbody>
</table>
### Step 2: Translate uncertainty

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Examples</th>
<th>Network Perturbation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent-related</td>
<td>- Staff turnover</td>
<td>![Agent Node]</td>
</tr>
<tr>
<td></td>
<td>- Dereliction of duty</td>
<td>![Agent Node]</td>
</tr>
<tr>
<td></td>
<td>- Safety accident or injury</td>
<td>![Agent Node]</td>
</tr>
<tr>
<td>Resource-related</td>
<td>- Defective materials</td>
<td>![Resource Node]</td>
</tr>
<tr>
<td></td>
<td>- Equipment breakdown</td>
<td>![Resource Node]</td>
</tr>
<tr>
<td></td>
<td>- Late delivery of material</td>
<td>![Resource Node]</td>
</tr>
<tr>
<td>Information-related</td>
<td>- Unclear scope/design</td>
<td>![Information Node]</td>
</tr>
<tr>
<td></td>
<td>- Limited access to required knowledge</td>
<td>![Information Node]</td>
</tr>
<tr>
<td></td>
<td>- Miscommunication</td>
<td>![Information Node]</td>
</tr>
</tbody>
</table>
Step 3: Assess Vulnerability (Carley and Reminga, 2004)

Network Efficiency
- the percentage of activities that can be completed by the agent assigned to them based on whether the agents have the requisite information and resources

Project Vulnerability
- the extent of the changes in network efficiency due to uncertainty-induced perturbations

Vulnerability assessment of project meta-networks
### Uncertain environment of the tunneling project

<table>
<thead>
<tr>
<th>Uncertain Events</th>
<th>Perturbation</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dereliction of duty</td>
<td>Agent-related</td>
<td>Medium</td>
</tr>
<tr>
<td>Staff turnover</td>
<td>Agent-related</td>
<td>Low</td>
</tr>
<tr>
<td>Inadequate information</td>
<td>Information-related</td>
<td>Medium</td>
</tr>
<tr>
<td>Equipment breakdown</td>
<td>Resource-related</td>
<td>Medium</td>
</tr>
<tr>
<td>Late delivery of material</td>
<td>Resource-related</td>
<td>High</td>
</tr>
<tr>
<td>Power system failure</td>
<td>Multiple resource-related</td>
<td>Medium</td>
</tr>
<tr>
<td>Severe weather</td>
<td>Agent and resource-related</td>
<td>Low</td>
</tr>
<tr>
<td>Economic fluctuation</td>
<td>Agent and resource-related</td>
<td>Low</td>
</tr>
</tbody>
</table>

**Boxplot of Project Organizational Vulnerability in the Base Scenario**

Mean: 0.4111
StDev: 0.1092
### Step 4: Evaluate planning strategies

#### Examples of planning strategy reflections in project meta-networks

<table>
<thead>
<tr>
<th>Task Assignment</th>
<th>Generalization of labor</th>
<th>Division of labor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Decision-making authority</strong></td>
<td>Centralized decision-making</td>
<td>Decentralized decision-making</td>
</tr>
<tr>
<td><strong>Resource management</strong></td>
<td>Redundancy</td>
<td>Non-redundancy</td>
</tr>
</tbody>
</table>

- **Agent Node**
- **Resource Node**
- **Information Node**
- **Activity Node**
Step 4: Evaluate planning strategies

Scenarios by combinations of planning strategies

<table>
<thead>
<tr>
<th>Planning Strategies</th>
<th>BS</th>
<th>S1</th>
<th>S2</th>
<th>S3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task assignment</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Generalization of labor</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Division of labor</td>
<td></td>
<td>√</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decision-making authority</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Centralized</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Decentralized</td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Resource management</td>
<td></td>
<td>√</td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Non-redundancy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Redundancy</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
</tbody>
</table>

Project meta-networks of the tunneling project under different planning scenarios without perturbations

Base Scenario BS

Comparative Scenario S1

Comparative Scenario S2

Comparative Scenario S3
### Application Example

**Study 2: Emergent properties**

#### Step 4: Evaluate planning strategies

- **Comparison of Project Organizational Vulnerability**
  - **Comparative Scenarios:**
    - Comparative Scenario 1
    - Comparative Scenario 2
    - Comparative Scenario 3
    - Base Scenario
  - **Vulnerability Analysis:**
    - **Project Organizational Vulnerability under Different Planning Strategies**
      - **95% CI for the Mean**
        - Base Scenario: 0.4111 ± 0.1092
        - Comparative Scenario 1: 0.343 ± 0.1186
        - Comparative Scenario 2: 0.4097 ± 0.1267
        - Comparative Scenario 3: 0.3611 ± 0.1235
  - **Effectiveness Calculation:**
    - **Effectiveness of planning strategies in mitigating project vulnerability compared to the base scenario**
      - **Division of Labor:** 16.57%
      - **Redundancy in Resource:** 12.16%
      - **Decentralized Decision-making:** 0.34%

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*Individual standard deviations were used to calculate the intervals.*

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**Effectiveness of planning strategies in mitigating project vulnerability compared to the base scenario**
The results from the application example show that the EPSoS framework is capable of facilitating investigation of: (1) micro behaviors of base-level entities and (2) project emergent properties using:

- **A proper level of abstraction**
  - Capture micro behaviors and interdependencies at the base-level

- **A bottom-up aggregation approach**
  - Capture emergent properties as macro behaviors at the project level

- **A dynamic perspective**
  - Consider the impacts of uncertainty and dynamic changes
Concluding Remarks

**Body of knowledge**
- A new theoretical lens for assessment of engineering projects
- First of its kind to assess the performance measures at the project level based on the micro-behaviors and interdependencies of project entities at the base level
- Exploration of emergent properties

**Body of practice**
- Design more resilient and less vulnerable engineering projects in pre-planning phase
- Develop contingency plan based on the expected performance loss and recovery
Reference


The research team at I-SoS Research Group focuses on solving the challenges pertaining to the sustainability and resilience of civil systems at the interface of the infrastructure, economy, environment and society based on System-of-Systems (SoS) analysis, computational simulation, and quantitative data analysis models.

http://www.isos-lab.com/
Thank You

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