CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

Resilience Methods and Applications

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CSYS 300 – COMPLEX SYSTEMS FUNDAMENTALS, METHODS & APPLICATIONS

Resilience Methods and Applications

Outline of Presentation

- Brief Biographical Note
- Where this Section Fits in the Structure of the Complex Systems Course
- Brief Survey of Methods and Application Areas
- The Infrastructure Resilience Analysis Method (IRAM)
- A Case Study
- Summary
- Question & Answer Session
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Resilience Methods and Applications

Brief Biographical Note on Eric Vugrin

Education:
- PhD in Mathematics from Virginia Tech
- Concentration in optimal control, distributed parameter systems, numerical analysis

SNL Work Experience
- 2008-current: infrastructure modeling and analysis, including
  - Characterization of economic criticality of chemical manufacturing facilities
  - CANARY water event detection software
  - Infrastructure resilience characterization and optimization
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Structure of the Course

- **Fundamentals of Complex Systems**
- **Methods**
  - Modeling Techniques
  - Approaches to Examining Complex Systems
- **Applications**
  - Examples of the use of complex systems fundamentals to solve problems
  - Learning how to use complex systems analysis tools

*Note: These approaches represent a simplified set of complex systems concepts chosen for the CSYS500 systems lectures. Please see the initial two lectures for additional detail and expanded references.*
Evolution of Security Philosophies

Physical Protection → Risk Analysis → Resilience

“Protection in isolation is a brittle strategy”
“Resilience is not a new idea.”

- Tom Corbet (2008)

1903: resilience defined in thermodynamic context
1973: C.S. Holling introduces resilience in an ecological context as complex systems property
  - Measures resilience by the magnitude of the disturbance that can be absorbed before the system redefines its structure

Frequency of “resilience” in print*

*Source: Park et al. 2013
Domains of Study

- Ecology (Holling 1973)
- Economic (Rose, Haimes)
- Disaster (Cutter)
- Seismic (MCEER)
- Engineering (Gunderson)
- Supply Chains (Fiksel)
- Cyber (Goldman)
- Human ecological conditions (Passell)
- Complex Systems (Park et al.)
- Nonproliferation (Pregenzer and Deland)
- Community (CARRI)
- Enterprise (Sheffi)
- Mental Health (Norris)

**Red font indicates areas with strong connection to complex systems**
Definitions: many options, no consensus

- Dozens of definitions exist
- Common concepts included in definitions include
  - Withstand changes from external force
  - Absorb impact
  - Adaptation
  - Rate of recovery
- Literature highlights two major definition types
  - Ecological resilience: measured by magnitude of disturbance required to move system to new “stability domain”
  - Engineering resilience: ability to return to a steady state following a disturbance

“The term ‘resilience’ means the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.”

-Resilience definition from PPD-21
## Analysis Methods: 2 Major Categories

<table>
<thead>
<tr>
<th>Attribute-Focused</th>
<th>Performance-Focused</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Central question:</strong> “What makes the system resilient?”</td>
<td><strong>Central question:</strong> “How resilient is the system?”</td>
</tr>
<tr>
<td>Analyzes system attributes to ID strengths/weaknesses</td>
<td>Analyzes system outputs via quantitative metrics</td>
</tr>
<tr>
<td>Qualitative or semi-quantitative</td>
<td></td>
</tr>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Pros</strong></td>
</tr>
<tr>
<td>Limited data requirements</td>
<td>Less subjective/more objective</td>
</tr>
<tr>
<td>Direct link to attribute focused definitions</td>
<td>Metrics make cross-system comparison easier</td>
</tr>
<tr>
<td><strong>Limitations</strong></td>
<td><strong>Limitations</strong></td>
</tr>
<tr>
<td>Inherent subjectivity makes cross-system comparison difficult and questioned</td>
<td>Does not explain “Why?”</td>
</tr>
<tr>
<td></td>
<td>Interpretation of unitless quantities</td>
</tr>
<tr>
<td></td>
<td>Can be model-specific</td>
</tr>
<tr>
<td></td>
<td>Less direct connection to definitions</td>
</tr>
</tbody>
</table>
Infrastructure Resilience Analysis Methodology (IRAM)

- IRAM is a “hybrid” methodology focusing on both performance-metrics and attribute analysis
- IRAM consists of 4 primary components
  - Definition: measurement focus sets up metrics
  - Metrics: include both performance and resources
  - Attribute analysis: explains quantitative results and IDs improvement options
  - Process: formalizes application of the IRAM
- Though initially developed for infrastructure systems, the IRAM is generally applicable to complex systems
Questions to Address

- How resilient is the current system?
- What are costs/impacts associated resilience and disruptions?
- What system features limit resilience and how can they be improved?
- Which recovery strategies enhance (optimize) the system resilience?
  - What are the resource requirements and costs associated with those strategies?
- In an uncertain environment, how can one effectively (optimally) invest in resilience?
“Given the occurrence of a particular, disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to reduce efficiently both the magnitude and duration of the deviation from targeted system performance levels.”

-Vugrin et al., 2010

- Context matters
  - Disturbance type
  - System structure
  - Resources

- Performance
  - Magnitude and duration
  - Target level

- Efficiency is “tip of the hat” to importance of resources
Metrics: Systemic Impact (SI)

\[ SI = \int_{t_0}^{t_f} \left( \sum_j q_j(t) \left[ TSP_j(t) - SP_j(t) \right] \right) dt. \]

- **Notes:**
  - SI is cumulative impact on performance
  - TSP can vary over time
  - Allows multiple performance metrics
  - Similar formulations for discrete time
Metrics: Total Recovery Effort (TRE)

- **Notes:**
  - TRE represents cumulative resource expenditure
  - Allows multiple resource categories
  - Similar formulations for discrete time

\[
TRE = \int_{t_0}^{t_f} \left\{ \sum_k r_k(t) [R E_k(t)] \right\} dt
\]
Metrics: Two Indices

\[
RDR(d, RE, SP(t_0)) = \frac{SI + \alpha \times TRE}{\text{Norm}}
\]

\[
\text{Norm} = \int_t^f \left\{ \sum_j q_j(t) |TSP_j(t)| \right\} dt
\]

- \textit{RDR} = “recovery dependent resilience” index
  - Measures cumulative “cost” of disruption
  - Explicitly depends upon recovery actions
- \textit{Norm} quantifies magnitude of system and allows comparison of different sized systems
- \( \alpha \) = weighting factor between performance and resources
- Most useful for comparison

As RDR increases, resilience decreases.
Metrics: Two Indices

\[ OR(d, SP(t0)) = \min_{RE} \frac{SI + \alpha \times TRE}{Norm} \]

- \( OR = \) “optimal resilience” index
  - Minimum cumulative “cost” across all feasible recovery options
- Likely requires model
- Optimal recovery option may not exist or be unique
## Attribute Analysis: 3 Capacities

<table>
<thead>
<tr>
<th></th>
<th>Absorptive Capacity</th>
<th>Adaptive Capacity</th>
<th>Restorative Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Directly Impacts</strong></td>
<td>Systemic Impact</td>
<td>Primarily Systemic Impact, but also TRE</td>
<td>Total Recovery Effort</td>
</tr>
<tr>
<td><strong>Distinguishing features</strong></td>
<td>Automatic manifestation after disruption</td>
<td>Reorganization and change from standard operating procedures</td>
<td>System repair</td>
</tr>
<tr>
<td><strong>Temporal Sequencing</strong></td>
<td>First line of defense</td>
<td>Second line of defense</td>
<td>Final line of defense</td>
</tr>
<tr>
<td><strong>Post-disruption event required</strong></td>
<td>Automatic/little effort</td>
<td>Increased effort</td>
<td>Greatest effort</td>
</tr>
<tr>
<td><strong>Duration of changes</strong></td>
<td>Permanent</td>
<td>Temporary</td>
<td>Permanent</td>
</tr>
<tr>
<td><strong>Resilience enhancement feature examples</strong></td>
<td>Stored inventory; robustness; redundancy; segregation</td>
<td>Substitution; rerouting; conservation; reorganization; ingenuity</td>
<td>Advance warning and monitoring systems; pre-positioning; reciprocal aid agreements</td>
</tr>
</tbody>
</table>
Process

1. Define System(s)
2. Define Scenario(s)
3. Define Metrics
4. Obtain Data
5. Calculate Resilience Costs
6. Perform Attribute Analysis
Example Study: Rail Networks

- Fundamental question: what is the optimal recovery sequence that maximizes resilience of the rail carriers to a flooding event, given that
  - Recovery resources are limited;
  - Multiple recovery modes are available;
  - Multiple restoration sequences are available.

- Focus of study on measurement and optimization, so we will skip the attribute analysis.
Steps 1 and 2: ID system and hazards

- **System:** US freight rail system
- **Scenario:**
  - 4 rail bridges on northern Mississippi out due to flooding
  - 3 bridges unaffected
  - East-West rail traffic significantly affected
  - Chicago is the largest east-west interchange point
  - Traffic between Chicago and Kansas City, Omaha and Denver expected to be disrupted
Steps 1 and 2: ID system and hazards

- Adaptation option (rerouting): delay times and increased distances increase operating expenses
- Recovery options: 3 modes to repair bridge
  - Normal mode is most cost effective repair mode
  - Emergency mode: most expensive but additional costs may be justified to avoid large system impacts
  - Staged mode: allows restoration of partial capacity
  - Assumption: 3 “resource units” may be spent at any given time

<table>
<thead>
<tr>
<th>Mode</th>
<th>Duration</th>
<th>Cost</th>
<th>Capacity Restored</th>
<th>Resource Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>15 days</td>
<td>$5M</td>
<td>100%</td>
<td>1</td>
</tr>
<tr>
<td>Emergency</td>
<td>10 days</td>
<td>$10M</td>
<td>100%</td>
<td>2</td>
</tr>
<tr>
<td>Staged</td>
<td>9 days</td>
<td>$3M</td>
<td>50%</td>
<td>1</td>
</tr>
</tbody>
</table>
Step 3: ID Metrics

- System performance (SP) = daily revenue from carload movement in Iowa, Illinois, Nebraska, Kansas and Missouri
  - TSP = “nominal” daily revenue from carload movement
  - SI = lost revenue from carloads not moved

- TRE: cost of rerouting plus recovery activities
  - Additional operating cost from increased time
  - Additional operating cost from increased distance
  - Bridge repair costs
Step 3: ID Metrics

<table>
<thead>
<tr>
<th>Category</th>
<th>Variable</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additional car-miles</td>
<td>ACM</td>
<td>$1.50/car-mile</td>
</tr>
<tr>
<td>Additional Transit Time</td>
<td>ATT</td>
<td>$38/car-day</td>
</tr>
<tr>
<td>Carloads not moved</td>
<td>CNM</td>
<td>$1770/load</td>
</tr>
<tr>
<td>Bridge Repairs</td>
<td>BR</td>
<td>TBD</td>
</tr>
</tbody>
</table>

\[ SI = \sum_t \left[ 1770 \, CNM \, (t) \right] \]

\[ TRE = \sum_t \left[ 1.5 \, ACM \, (t) + \frac{38}{24} \, ATT \, (t) \right] + BR \]
Step 4: Obtain Data (Simulation Tool)

Basis for model: Rail Network Analysis System (R-NAS)

- Static, nonlinear optimization model developed by NISAC for consequence analysis
- R-NAS solves for network flows under the assumption that car-miles are minimized
- Distances and congestion “delay functions” determine travel times and distances

Model was adapted to add dynamics or recovery

- Network flows change as repairs are completed
- Costs to the rail carriers decrease as repairs completed
- Systemic impact measured from initiation of disruption to return to baseline conditions
Step 4: Obtain Data (Optimization Model)

- Optimization resembles Multimodal Resource Constrained Project Planning (MRCPP) problem
- Bilevel optimization problem
  - Outer loop: optimize recovery sequence that minimizes resilience costs with resource constraints
  - Inner loop: optimize flows for specified network state

Simulated annealing (SA) algorithm (Boctor 1996) solves outer loop problem and searches space of feasible recovery sequences
  - For a given recovery sequence, R-NAS solves inner loop optimization and reports resilience costs
  - SA algorithm analyzes R-NAS output and identifies “optimal” recovery sequence
  - Algorithm modifications developed to enhance computational efficiency
Step 4: Obtain Data (Results: 4 bridges out)

<table>
<thead>
<tr>
<th>Commodity Group</th>
<th>Additional Car-Miles</th>
<th>% Change</th>
<th>Additional Car-Hours</th>
<th>% Change</th>
<th>Not Moved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>169929</td>
<td>2.9</td>
<td>294479</td>
<td>97.2</td>
<td>58</td>
</tr>
<tr>
<td>Grain</td>
<td>-26182</td>
<td>-2</td>
<td>6892</td>
<td>3.2</td>
<td>700</td>
</tr>
<tr>
<td>Chemicals</td>
<td>28220</td>
<td>1.6</td>
<td>14234</td>
<td>3.3</td>
<td>819</td>
</tr>
<tr>
<td>Intermodal</td>
<td>213801</td>
<td>15.4</td>
<td>31928</td>
<td>48</td>
<td>1146</td>
</tr>
<tr>
<td>Motor Veh</td>
<td>45550</td>
<td>3.2</td>
<td>61109</td>
<td>87.1</td>
<td>355</td>
</tr>
<tr>
<td>Other</td>
<td>88613</td>
<td>1.6</td>
<td>15616</td>
<td>1</td>
<td>2539</td>
</tr>
<tr>
<td>Total</td>
<td>519931</td>
<td>3</td>
<td>424258</td>
<td>15.9</td>
<td>5617</td>
</tr>
</tbody>
</table>

- Daily lost revenue (CNM) = $9.9 M/day
  - # of cars moved decreases by > 1/3
- Daily ACM= $830k
- Daily ATT= $700k
  - Average additional car-hours increase: 16%
  - Nearly double for coal and motor vehicles
Step 5: Calculate Resilience Costs

Recovery sequence for nominal case, no cooperation

- Bridge Repair
  - Clinton - Normal Mode
  - Hannibal - Normal Mode
  - Ft. Madison - Normal Mode
  - Burlington - Normal Mode

- SI = $176 M

Daily CNM Cost

Days

Days

$10M
Step 5: Calculate Resilience Costs

Recovery sequence for nominal case, no cooperation

<table>
<thead>
<tr>
<th>Location</th>
<th>Normal Mode</th>
<th>Bridge Repairs Costs</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Burlington</td>
<td>Normal Mode $5M</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>Ft. Madison</td>
<td>Normal Mode $5M</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td>Hannibal</td>
<td>Normal Mode $5M</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clinton</td>
<td>Normal Mode $5M</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total = $28M

TRE = $48M
Step 5: Calculate Resilience Costs

Optimal recovery sequence, i.e., pool resources

- Clinton- (a)
- Ft. Madison- (b)
- Burlington- Normal Mode
- Clinton- (b)
- Ft. Madison- (a)
- Hannibal- Normal Mode

Bridge Repair

$10M Daily CNM Cost

SI = $96 M

Cars not moved decreases to < 1k/day
Step 5: Calculate Resilience Costs

Recovery sequence for nominal case, no cooperation

<table>
<thead>
<tr>
<th>Bridge Repair Costs</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinton- (a) $3M</td>
<td>9</td>
</tr>
<tr>
<td>Ft. Madison- (a) $3M</td>
<td>15</td>
</tr>
<tr>
<td>Burlington- Normal Mode $5M</td>
<td>18</td>
</tr>
<tr>
<td>Ft. Madison- (b) $3M</td>
<td>24</td>
</tr>
<tr>
<td>Clinton- (b) $3M</td>
<td>30</td>
</tr>
<tr>
<td>Hannibal- Normal Mode $5M</td>
<td></td>
</tr>
</tbody>
</table>

$1.5M Daily ATT+ ACM Cost

Total =$21M

TRE =$43M
Comparing Two Strategies

<table>
<thead>
<tr>
<th></th>
<th>Days To Complete Recovery</th>
<th>Systemic Impact</th>
<th>Total Recovery Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooperative Approach</td>
<td>24</td>
<td>$96M</td>
<td>$43m</td>
</tr>
<tr>
<td>Non-cooperative Approach</td>
<td>30</td>
<td>$176M</td>
<td>$48M</td>
</tr>
</tbody>
</table>

- **Cooperative approach**
  - Decreases time to recovery by 6 days
  - Decreases SI by $80M (45%)
  - Decreases TRE by $5M (10%)
  - Decreases total resilience costs by $85M (38%)
Summary

- Resilience is not a new concept
  - Lots of work, but little consensus
- Resilience has recently emerged as a key national and homeland security priority
  - It doesn’t seem to be going anywhere, yet
- For these two reasons, Sandia ought to be involved in the “formalization” of resilience analysis
  - Science, tools, policy, etc.
- The IRAM represents an attempt to do so for infrastructures
Future Opportunities

- **Span the “bang”**
  - Resilience is about more than response
  - Investment and design decisions matter

- **Get uncertain**
  - Initial research performed into hazard/scenario uncertainty
  - Other sources of uncertainty matter and need to be considered

- **Deal with the “human in the loop”**
  - Need better tools/methods to understand resilience of integrated engineered and human systems
IRAM Resources

Critical Infrastructure Security and Resilience
Biringer, Vugrin, and Warren (2013)

CASOS Website:
Papers of Note


QUESTION & ANSWERS

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