TOWARDS RESILIENT TRANSPORTATION SYSTEMS – THE ROLE OF ANALYTICAL TOOLS

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ROUNDTABLE ON TRANSPORT SYSTEM RESILIENCE
INTERNATIONAL TRANSPORT FORUM (ITF)
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

PARIS HEADQUARTERS| 15 SEPTEMBER 2023
Tools support resilience enhancement across applications

- Intermodal freight
- Rail scheduling recovery
- Roadways
- Airport taxi/runways
- CIBSS
- Evolving conditions
- Global port network
- Coupled traffic-power
- Socio-technical systems
- Transit
- Resilient topologies
- Traffic systems
- Port digital twin
- Disruption recovery
- SLR & climate change
- Cyberattack
- Arctic resilience
- Future systems

Tools support resilience enhancement across applications.
Multi-hazard resilience & infrastructure systems

Natural (with or without notice): hurricane, EQ, fire,…
Malicious attack: coordinated, targeted, physical vs. cyber
Technical/accidental: design or implementations, human errors, aging materials, failed parts, production mistakes, organizational challenges,…
Specific: derailment in rail or shoaling in maritime system,…
Immediate or slow: tsunami vs. climate change

US Department of Homeland Security

Inherent
Inherent capability to absorb or cushion effects of disruption via its topological and operational attributes

Adaptive
Potential cost-effective, immediate actions that can be taken to preserve or restore system’s ability to perform its intended function in disruption’s aftermath

OECD
Ability to absorb and recover from shocks while adapting and transforming to face long-term stresses, change and uncertainty
Action framework

- **Retrofit**: Hardening system elements diminishes level of damage.
- **Expansion**: Increasing connectivity/redundancy or capacity.
- **Coping capacity**: Innate capability to resist disruption through material strength and built-in redundancy and excess.
- **Response**: Pre-positioning resources for post-event recovery support.
- **Resource availability**: Restoring system performance.

RESILIENCE VIA ACTION
**Initial conceptualization**

- **Objective**
  - Maximize Expected Throughput overall Scenarios

- **Total Flow along Paths** < Demand

- **Link Capacities**

- **Budget Constraint on Recovery Actions**

  Can be decomposed by realization x independent deterministic NP-hard programs (P(x))

  **Exact solution:**
  - Benders decomposition, column generation and Monte Carlo simulation with spatial and temporal dependencies for generating scenarios

- **Binary and Integrality Constraints**
IM nodal facility

Port of Świnoujście, Poland

Nodes
- Quays
- Storage areas
- Intersection (road/rail)
- Demand origins and destinations
- Marshalling areas
- Parking areas
- Rail sidings

Ares
- Physical road links
- Physical rail links
- Waterways
- Storage yards and warehouse
- Gantry cranes
- Mobile cranes
- Conveyer belts
- Yard movements

Base flows
Earthquake
Flooding

Terrorism (bomb)
Terrorism (hinterland (coord/arson access) - chem storage)

Physical infrastructure & processes

Recovery activities directed to sub-components of IM facility
Computational experiments
- 10,000 random realizations of disruptions

Network
- 10 O-D pairs, 164 arcs, 390 paths
- 1261 recovery actions with total =$76.6 million

Recovery budget: $0-$100,000

- **Point resilience**

<table>
<thead>
<tr>
<th>Budget ($)</th>
<th>Resilience level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>77%*</td>
</tr>
<tr>
<td>10,000</td>
<td>87%</td>
</tr>
<tr>
<td>50,000</td>
<td>97%</td>
</tr>
<tr>
<td>100,000</td>
<td>99%</td>
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</tbody>
</table>

- Increase in resilience due solely to recovery actions

Stabilization after ~2k realizations
Digital twin in place of mathematical model

- Replace complex operational constraints by digital twin
- Ordinary operational uncertainties & in recovery performance

Recovery actions: alternative QC/AGV power options

Resilience as a function of Berth-on-Arrival (BoA) enabled post-event through recovery actions

Partial shutdown – power loss

Simulation output

Actual system

Digital twin

Data input
Resilience with preparedness – 2 stages

1\textsuperscript{st} Stage Objective: Max Exp Throughput over Scenarios & # Preparedness Activities Constraint

2\textsuperscript{nd} Stage Objective: Max Throughput by Scenario

Total Flow along Paths < Demand

Budget Constraint on Prep. & Rec. Actions

Nonlinear, two-stage SP

- Integer L-shaped decomposition
  - *Laporte & Louveaux 1993*
  - Bilinearity (1st & 2nd stage variables) eliminated through stage-wise decomposition

Recovery Activity Number Constraint

Binary and Integrality Constraints
Airport runways & taxiways
With preparedness

<table>
<thead>
<tr>
<th>Damage types to be repaired</th>
<th>Repaired Internally</th>
<th>Repaired externally</th>
<th>Weather-dependent multiplier for repair duration and costs</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Equipment set requirement</td>
<td>Duration (hr)</td>
<td>Cost ($)</td>
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<tr>
<td>Alligator cracking</td>
<td>1,2,4,8,10,15,16</td>
<td>5</td>
<td>2510</td>
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<tr>
<td>Block cracking</td>
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<td>736</td>
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<td>Transverse cracking</td>
<td>2,11,12</td>
<td>2</td>
<td>736</td>
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<td>Jet Blast</td>
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<td>1912</td>
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<tr>
<td>Raveling</td>
<td>2,4,5,8,9,10,15</td>
<td>4</td>
<td>1912</td>
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<tr>
<td>Rutting</td>
<td>2,4,5,8,9,10,15</td>
<td>4</td>
<td>1912</td>
</tr>
<tr>
<td>Array of small potholes</td>
<td>1,2,4,5,6,16</td>
<td>3</td>
<td>1407</td>
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<tr>
<td>A single crater</td>
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<td>4374</td>
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<td>Slippery surface</td>
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<td>Bleeding</td>
<td>2,4,5,6,13,17</td>
<td>3</td>
<td>1665</td>
</tr>
</tbody>
</table>
❖ Optimal budget allocation on ext/int resources

❖ Resilience indifference curves

❖ Probability runway configuration selected
- Affected users may rethink routes
- Decentralized response of users
  - Bi-level structure
    - UL: 3-stage SP – determine investments
    - LL: response of users: partial UE
    - Solution at Stackelberg equilibrium

\begin{itemize}
  \item \textbf{Disaster phases & decision tree}
\end{itemize}
Traffic and power networks interdependence

Minimize travel delay subject to:
User equilibrium constraints
❖ Whose resilience is it anyway?
Unmet demand in power when prioritize roadways

Average unmet power demand:
- 6.3%
- 50%
- 12.5%

Average unmet power demand:
- 12.5%
- 50%
- 0%
Transit-communications & diverse populations
A user’s perspective

Reliability extension
- Diverse pop’s – socio-tech system
- Dependency graph
  - Fault-tree extension
  - w/ multivalued logic functions
- Interacting pop’s experiences differ
- Induced coupling of technical systems
- Resilience wrt LOS
- Baseline has uncertainty & is user-dependent
Critical infrastructure-based societal systems
Simulation-optimization

Objective function

- Expected cost
- Unmet demand
- Waiting time
- Access and transfer time

Expected waiting time metamodel

First stage constraint sets
- Linearization of objective function
  - Waiting time estimation
  - Travel time component
- At most one preparedness/mitigation action per network element permitted

Second stage constraint sets
- State variables of infrastructure networks corresponding to mitigation/recovery actions and damage state
  - Damage is not realized if mitigation actions are taken in first stage
  - Link power, water, transportation network states and functionality and effects of response options
  - Link supporting lifeline functionality to health care facility operational capacity (service rate, # patients discharged,...)

Third stage constraint sets
- State variables of infrastructure networks corresponding to mitigation/recovery actions and damage state
  - Links recovery actions of second stage to functionality in third stage
  - Links supporting lifeline function to health care facility operational capacity (service rate, # patients discharged,...)
- Budget constraints

Infrastructure element | Preparedness action option to prevent damage or utility loss, cost (in units)
--- | ---
Power line | Strengthening poles with guy wires, 1
| Relocating/constructing new lines, 5
| Undergrounding of existing overheating lines, 5
Health Care Facility | Onsite power generator, 5
| Onsite water storage, 10
Water treatment plant | Retrofitting, 30
| Onsite generator, 5
Power feeder | Elevating/relocating power feeder, 10
| Water pump, 5
Water pipeline | Relocating/constructing new lines, 5
| Retrofit, 5

Decision
- Mitigation decision for infrastructures $\beta_{dp}$ and preparedness actions for loss of power, $\beta_{pp}$, and water, $\beta_{pw}$, at the health care facilities

Information revealed
- Disaster type, damage state to infrastructure nodes $\psi_{p}(\xi^1)$ and, and patient demand $D_{d}(\xi^2)$
- Repair and recovery actions to infrastructure, $\gamma_{dr}^{damage}(\xi^3)$, and links, $\gamma_{l}^{damage}(\xi^3)$, and transfer plans

Decisions
- Capacity of health care facilities $\psi_{d}(\xi^1)$ after 24 hrs, Patient discharge (service) rate $\mu_{d}(\xi^2)$
- Repair and recovery actions to infrastructure, $\gamma_{dr}^{damage}(\xi^3)$, and links, $\gamma_{l}^{damage}(\xi^3)$, and transfer plans
Disruptions Cascading in Intermodal Network
◆ Formulate multi-port protective investment problem
  
  a) Simultaneous consideration of multiple SMPECs, each modeling an individual port and its market
  
  b) Together - Stochastic Equilibrium Problem with Equilibrium Constraints (EPEC) – accounts for common market

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**SINGLE-LEVEL SMPEC: PORT 1**

Maximize port 1 Expected Throughput* subject to:
Upper-level Constraints

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**SINGLE-LEVEL SMPEC: PORT i**

Maximize port i Expected Throughput* subject to:
Upper-level Constraints

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**Diagonalization**

Initialize investment decisions for all ports: $n = 1, x_{1p}^n = x_{1p}^0, x_{2p}^n = x_{2p}^0, x_{j-1,p}^n = x_{j-1,p}^0$

Solve SMPEC_1
Max Port Throughput subject to:
Fixed $x_{i}^0$ for all $i \neq 1$
Budget Constraint
Scenario 1: KKT conditions Optimal $f_{w1}(1), y_{w1}(1)$
Scenario 4: KKT conditions Optimal $f_{w1}(1), y_{w1}(1)$

Solve SMPEC_2
Max Port Throughput subject to:
Fixed $x_{i}^0$ for all $i \neq 2$
Budget Constraint
Scenario 1: KKT conditions Optimal $f_{w1}(1), y_{w1}(1)$
Scenario 4: KKT conditions Optimal $f_{w1}(1), y_{w1}(1)$

Solve SMPEC_j
Max Port Throughput subject to:
Fixed $x_{i}^0$ for all $i \neq j$
Budget Constraint
Scenario 1: KKT conditions Optimal $f_{w1}(1), y_{w1}(1)$
Scenario 4: KKT conditions Optimal $f_{w1}(1), y_{w1}(1)$

If convergence achieved, set equilibrium investment decisions: $x_{1p}^n$
1. **No investment:** Reduces to lower level
2. **Restricted game:** Investments in own facilities permitted
3. **Unrestricted game:** Investments in all ports permitted
4. **Semi-restricted game:** Only a portion of ports willing to invest in another port
5. **System perspective:** Single, centralized budget
6. **Coalitions:** Limited & semi-restricted with shared capacity

*Whose resilience?*

**System** (total OD demand served)

**Port** (port throughput/profit)

**Shippers** (cost)
Implications of port-related workforce shortages on global maritime performance

- Linear, square and exponential port handling rates
- Solution by Benders decomposition and column generation

Path-based MILP

- How does shortage in one region affect other regions?
- What shortage levels can be absorbed?
- Design alliance strategy to reduce risk exposure
Prioritizing critical facilities

RESTORING CRITICAL SERVICES

water (35), power (39), transport (35), hospitals (2)

Two-Stage Stochastic Program in Rolling Horizon

\[ \text{Max } Z = \left( \sum_a c_{fa} + \sum_t \sum_r s_{fr} + \sum_o \sum_f \sigma_{of} \right) + \sum_t \left( \sum_g c_{fgt} + \sum_o \sum_s s_{ost} \right) + \sum_a \sum_f s_{fa} \]

Maximize expected time critical services function in post-disaster

- Restoration Outcomes
  \[ \sum_i \sigma_i \leq 1, \ldots \]
  \[ \sum_i \sigma_{it}(s) \leq 1, \ldots \]

- Path Availability
  \[ a_i \leq \sum_{n} I_{in, p_{in}}, \forall i \ldots \]

- Lifeline Component Damage States
  \[ s_{ai}(s) = \frac{d_i(s)}{n} + \sum_{x=0}^{t-1} \sigma_{it}(s), \forall i \ldots \]

- Critical Societal Services Dependencies
  \[ c_{f} \leq \frac{1}{2} \left( \sum_{k=0}^{t-1} s_{ik} + \sum_{o} s_{of} \right), \forall o \]

- Inter- & Within Lifeline Dependencies Network
  \[ s_{ij} \leq \sum_{j} I_{ij}, s_{ai}, \forall i, j \ldots \]

- Binary and Integrality

- 2-stage approximation

- Rolling horizon

- Start the Algorithm
  - \( t = 0 \)
  - Crews located at Depot

- Observe an element
  - Observed to be down
  - + parallel processing

- Rolling horizon
  - Scenario Reduction
    - Main Framework
      - \( t = 0 \)
      - Apply Scenario Reduction
        - Reduced Scenario Sets
      - PH Algorithm
        - Element Restoration Schedule
      - Update Scenario Set and Crew Location
    - Termination Criteria Met?
      - End of Planning Horizon
      - No More Elements to Restore
        - Yes
          - End the Algorithm

- Progressive Hedging
  - Solve each scenario dependent problem with zero penalty \( \sigma_{i}(s), \ldots \)
    - \( k = 0, w_k = 0 \)
  - Update Penalty term
    - \( w = \rho(\sigma_i(s) - \bar{\sigma}_i) + w \ldots \)
  - Calculate average for each variable
    - \( \bar{\sigma}_i, \ldots \)
  - If \( |\sigma_i(s) - \bar{\sigma}_i| < \epsilon \), \ldots \) Terminate
    - Else \( k = k + 1 \)
  - Re-solve with penalty term
    - \( z + \sum_i (\sum_{i} \sigma_i + \ldots) + \frac{\epsilon}{2} ||\sigma_i(s) - \bar{\sigma}_i||^2 + \ldots \)
Hospital services restored earlier if prioritized

Hospital resilience

**With** hospitals: 26

**Without** hospitals: 28

Full-system resilience

**With** hospitals: 89

**Without** hospitals: 86

Resilience: expected time to hospital recovery over all scenarios

Prioritizing hospitals

- quicker restoration of road links that support access to hospitals & lifeline elements
Resilience

Hospital
- **People** incorporated: 13
- **No people** incorporated: 33

Fueling station
- **People** incorporated: 11
- **No people** incorporated: 35
Hazard events
- Sudden impact, one-time events
- Take immediate adaptive actions
  - Recovery
  - Response
  - Restoration
- Measurements of continuity of operations/rebound

Climate change
- Slow process that changes environment
  - probabilistic SLR levels over long horizon
- Added recurrent or episodic events
  - w/ increasingly harmful disruption occurrences
- Threatens long-term sustainability of infrastructure
- Requires multi-temporal approach
  - decadal investments with daily impacts
- Long-term protective investment planning for safeguarding performance
Investing in transport infrastructure for climate change

Goal: minimize long-term costs for roadway network prone to flooding

- **Upper level** (government): multi-stage SP- determines investments (location, timing, extent) and post-event recovery actions to minimize direct (repairs) + indirect costs (disruption to users)
  
  DVs: seawall location/height, height for raising link, drainage improvement, rebuilding link

- **Lower level** (system users): travel times from UE traffic formulation
  
  DVs: traffic flows during flooding events

**Bi-level, Stochastic Model Structure**

- **Upper level**
  
  Minimize objective function
  
  \[
  \min \sum_v \sum_a \bar{b}_{v,a} \gamma_{v,a} + i^1 E_{\xi^1} [Q^1 (\xi^1)]
  \]

  Subject to constraints
  
  - Capacity: reduction due to SLR, reduction due to flooding events, impacted by destruction and rebuild capacity caps
  - Travel Time: BPR function
  - Allowable range for investment decisions

- **Lower level**
  
  Minimize objective function
  
  \[
  \min \sum_a \int_0^{x_{f,a}(\omega)} \left( t_a + m_a \frac{v}{c_{f,a}(\omega)} \right) ^{n_a} dv
  \]

  Subject to
  
  - Demand
  - Path and Link Flows

  Minimizing expected future costs given x achieved
Planning for a stochastic future

(i) Long-term costs of no-investment?
(ii) How optimal investment decisions change with different future SLR and flooding event scenarios?
(iii) How system performs if investments are made for one future scenario but a different scenario is realized?
(iv) What is value of hedging against multiple possible futures?
(v) How much improvement in investment effectiveness is gained through accurate prediction?

Comparing no-investment scenario & investment-allowed

- Cost of inaction > cost of preparedness justifies investment

54% reduction in added costs due to the implementation of protective investments

Washington, D.C. Area


Flood exceedance probability

Sea level rise estimates

Planning for a stochastic future

(i) Long-term costs of no-investment?
(ii) How optimal investment decisions change with different future SLR and flooding event scenarios?
(iii) How system performs if investments are made for one future scenario but a different scenario is realized?
(iv) What is value of hedging against multiple possible futures?
(v) How much improvement in investment effectiveness is gained through accurate prediction?
A real options approach to transportation infrastructure protection investment timing

Real Options Approach

Compute value of waiting and learning more
Irreversible investment decisions
Ongoing uncertainty

1) Scenario Generation  2) NPV Calculation  3) Decision-Making

Monte Carlo Simulation

\[
\begin{align*}
\Phi_{\tau, \omega} &= \max \left\{ \pi_{\tau, \omega}, \frac{\mathbb{E}[\Phi_{\tau+1, \omega}]}{(1+\rho)\Delta t} \right\} \\
&= \max \left\{ \pi_{\tau, \omega}, \frac{f_{\tau, \omega}^{\pi \ell}(\mathbf{0}_1, \ldots, \mathbf{0}_n)}{(1+\rho)\Delta t} \right\}
\end{align*}
\]

\(\Phi_{\tau, \omega} \) = Impact of SLR and Storm Surge Flooding
Subject to 36 sets of constraints

3 Step Approach
These tools provide examples of how mathematical modeling and algorithms can support decision-making on investments to bolster continuity of operations & resilience in transportation systems, lifelines and services transportation systems support.
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Thanks!

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