TOWARDS RESILIENT TRANSPORTATION SYSTEMS – THE ROLE OF ANALYTICAL TOOLS

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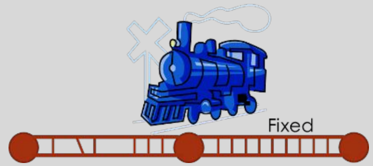
ROUNDTABLE ON TRANSPORT SYSTEM RESILIENCE
INTERNATIONAL TRANSPORT FORUM (ITF)
ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

PARIS HEADQUARTERS| 15 SEPTEMBER 2023

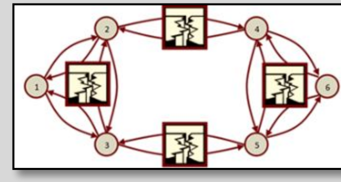
TOOLS & APPLICATIONS

❖ Tools support resilience enhancement across applications

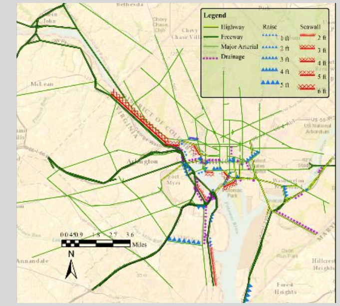
Intermodal freight



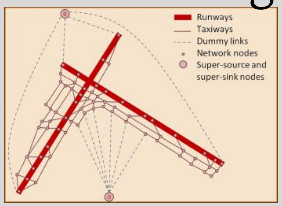
Rail scheduling recovery



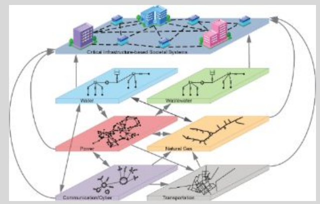
Roadways



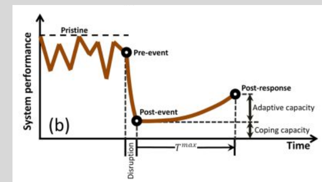
SLR & climate change



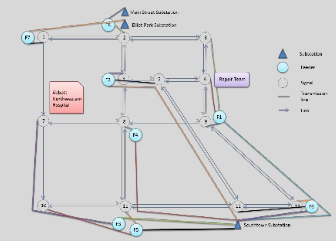
Airport taxi/runways



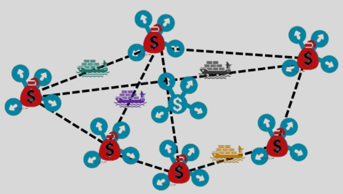
CIBSS



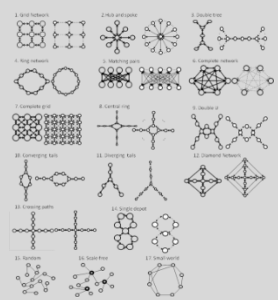
Evolving conditions



Coupled traffic-power

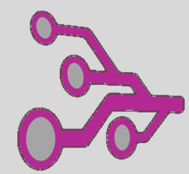


Global port network

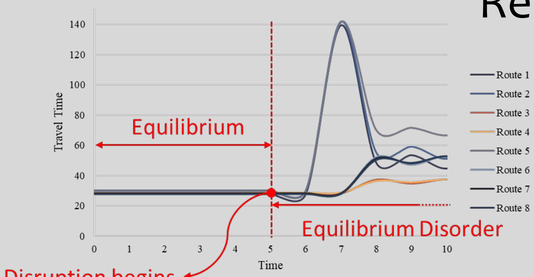


Resilient topologies

Socio-technical systems
Transit



Cyberattack



Traffic systems
disruption recovery

Port digital twin

Photo by Cpt Ralph Pundt
Arctic resilience

qrowd-project.edu
Future systems

RESILIENCE & HAZARDS

❖ Multi-hazard resilience & infrastructure systems

Hazards

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

Resilience Definitions

US Department of Homeland Security

Inherent

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

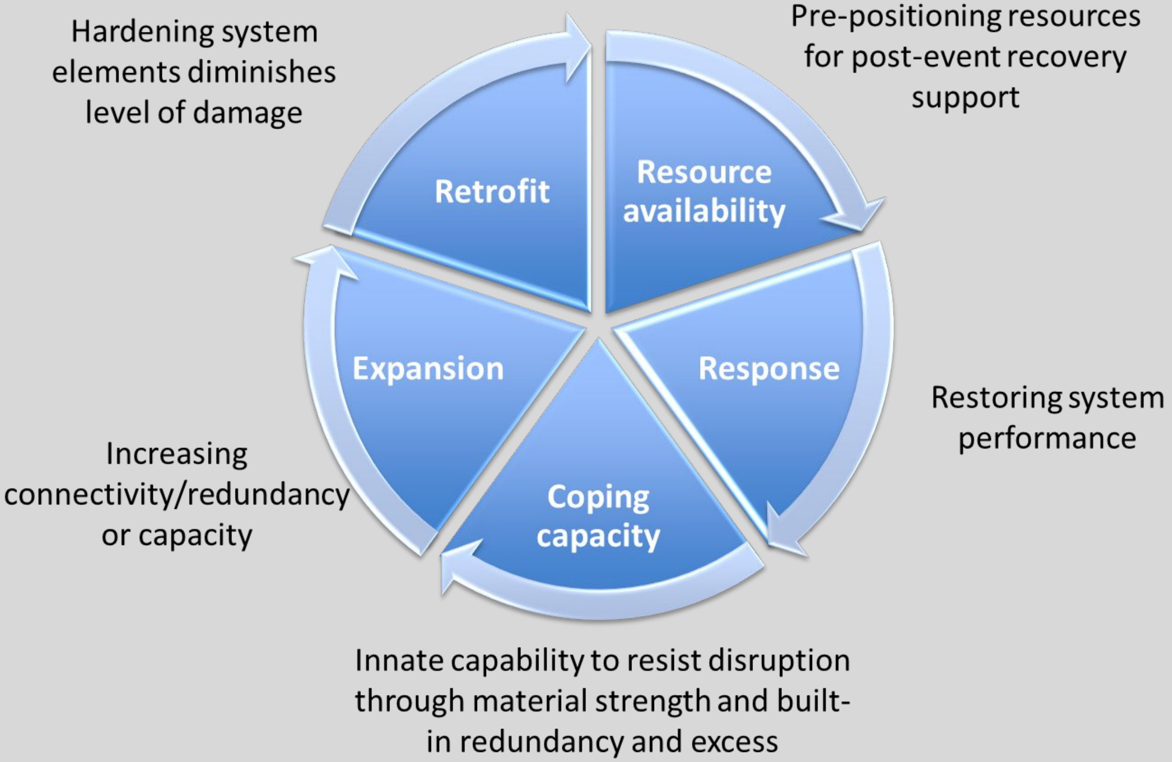
Adaptive

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



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:

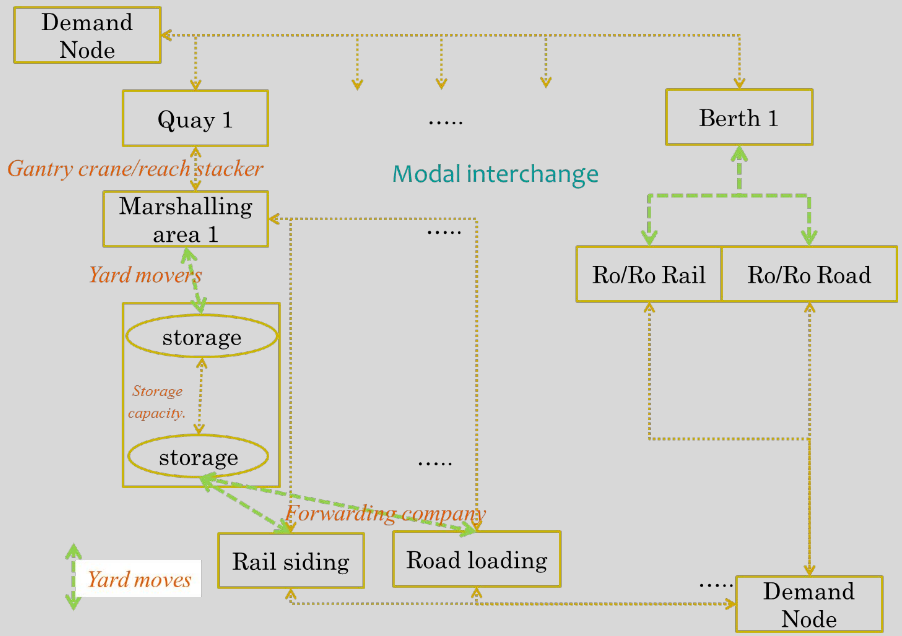
Benders decomposition, column generation and Monte Carlo simulation with spatial and temporal dependencies for generating scenarios

Binary and Integrality Constraints

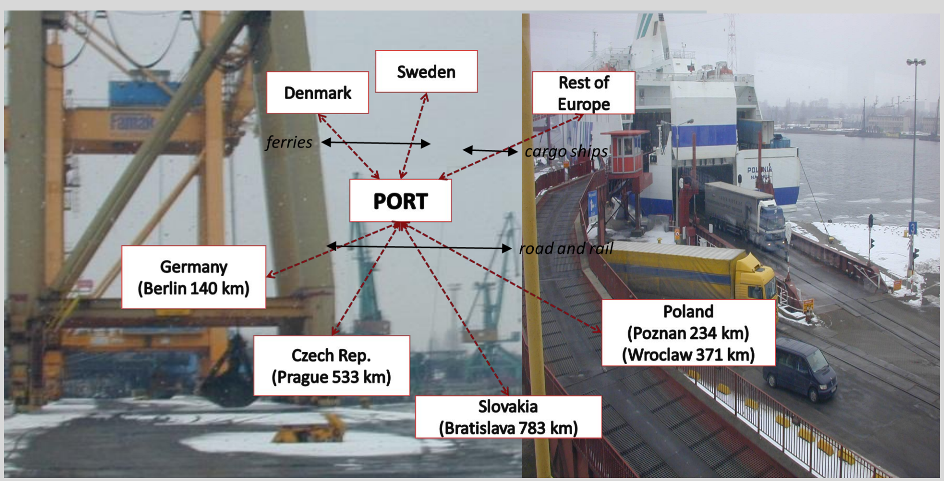
PORTS & TERMINALS

❖ IM nodal facility

Port of Świnoujście, Poland

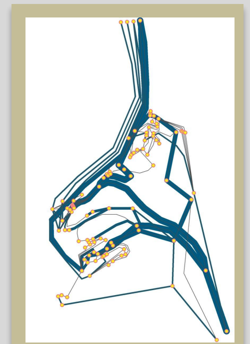


Recovery activities directed to sub-components of IM facility



Physical infrastructure & processes

Nodes	Arcs
Quays	Physical road links
Storage areas	Physical rail links
Intersection (road/rail)	Waterways
Demand origins and destinations	Storage yards and warehouse
Marshalling areas	Gantry cranes
Parking areas	Mobile cranes
Rail sidings	Conveyer belts
	Yard movements



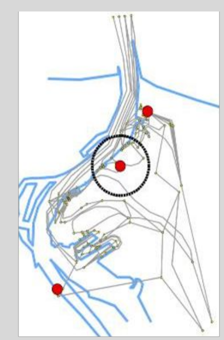
Base flows

Earthquake

Flooding

Terrorism (bomb)

Terrorism (hinterland access)



Terrorism (coord/arson - chem storage)

PORTS - OUTPUTS

Computational experiments

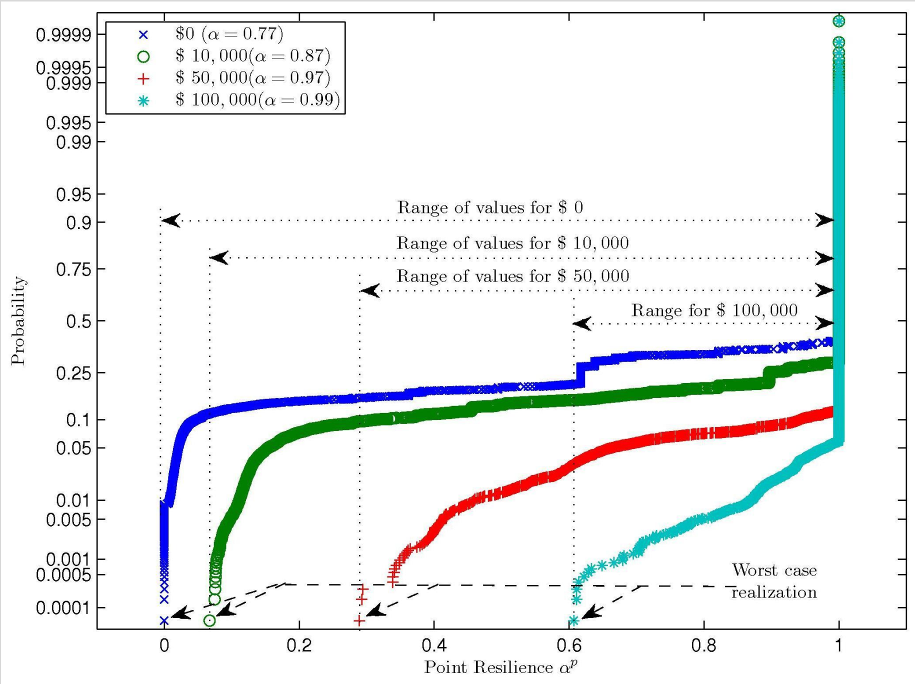
- 10,000 random realizations of disruptions

Network

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

Recovery budget: $0-$100,000

❖ Point resilience



Budget ($)	Resilience level
0	77%*
10,000	87%
50,000	97%
100,000	99%

❖ Increase in resilience due so to recovery actions

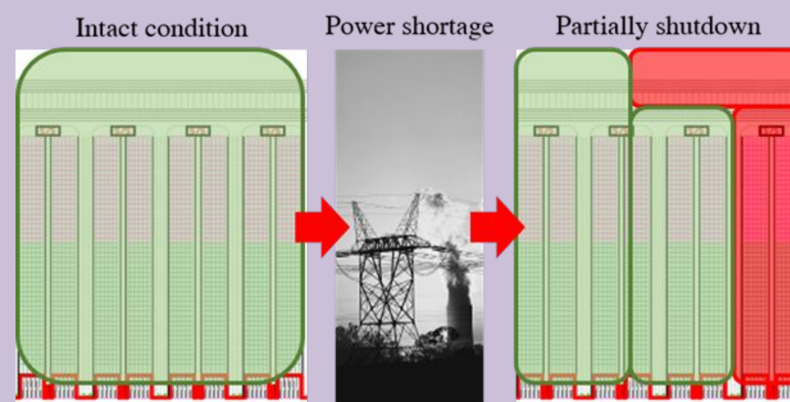
Stabilization after ~2k realizations

REVISITING THE PORT

❖ Digital twin in place of mathematical model

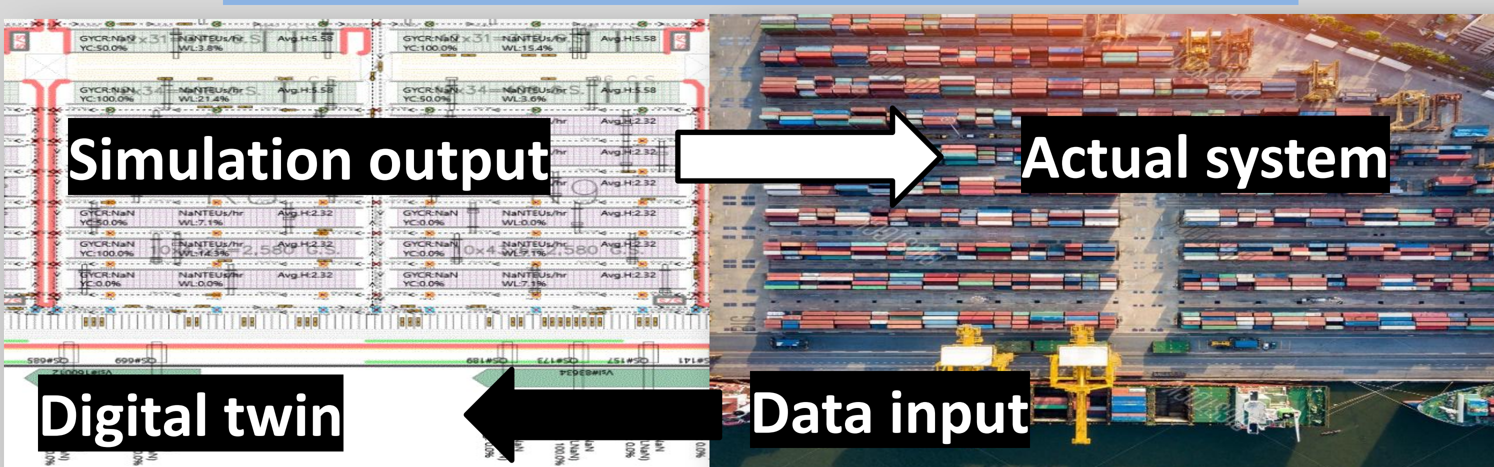
- Replace complex operational constraints by digital twin
- Ordinary operational uncertainties & in recovery performance

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



Partial shutdown – power loss

Recovery actions: alternative QC/AGV power options



PRE-EVENT ACTIONS

❖ Resilience with preparedness – 2 stages

1st Stage Objective: Max Exp Throughput over Scenarios & # Preparedness Activities Constraint

2nd Stage Objective: Max Throughput by Scenario

Total Flow along Paths < Demand

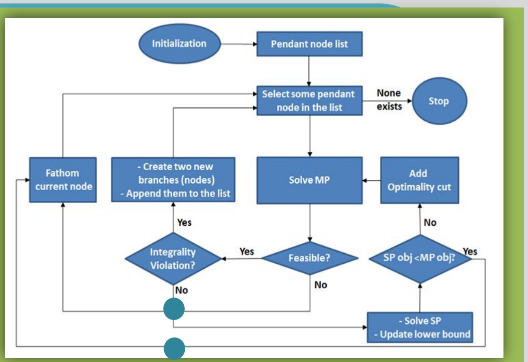
Budget Constraint on Prep. & Rec. Actions

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

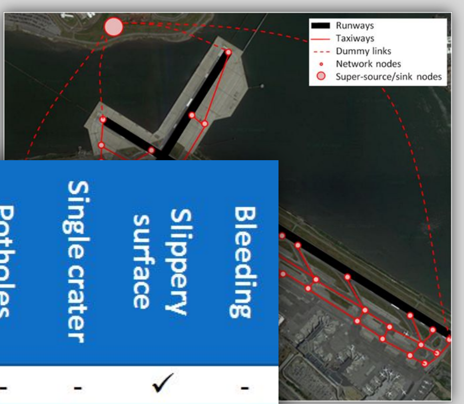
AIRPORT RUNWAYS

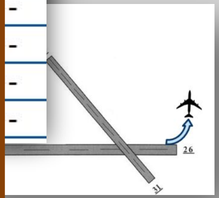
❖ Airport runways & taxiways

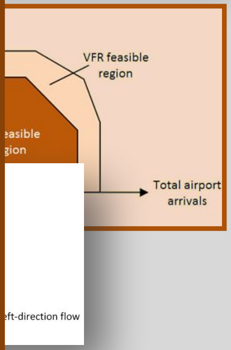
With preparedness

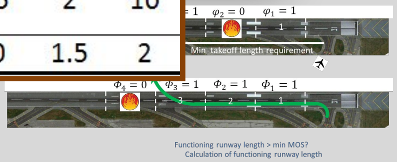
Disaster events		Alligator cracking	Block cracking	Transverse cracking	Jet Blast	Raveling	Rutting	Potholes	Single crater	Slippery surface	Bleeding
Extreme climatic or geologic event	Flood	-	-	-	-	-	-	-	-	✓	-
	Snow/ice	-	✓	✓	-	-	-	-	-	✓	-
	Very hot	-	-	-	-	-	✓	-	-	-	✓

Damage types to be repaired	Repaired Internally			Repaired externally		Weather-dependent multiplier for repair duration and costs					
	Equipment set requirement	Duration (hr)	Cost ($)	Duration (hr)	Cost ($)	1	2	3	4	5	6
Alligator cracking	1,2,4,8,10,15,16	5	2510	9	4267	1	10	1	10	1.5	2
Block cracking	2,11,12	2	736	6	1251.2	1	10	1	10	1	10
Transverse cracking	2,11,12	2	736	6	1251.2	1	10	1	10	1	10
Jet Blast	2,4,5,8,9,10,15	4	1912	8	3250.4	1	10	1	10	1.5	2
Raveling	2,4,5,8,9,10,15	4	1912	8	3250.4	1	10	1	10	1.5	2
Rutting	2,4,5,8,9,10,15	4	1912	8	3250.4	1	10	1	10	1.5	2
Array of small potholes	1,2,4,5,6,16	3	1407	7	2391.9	1	10	1	10	1.5	2
A single crater	1,2,3,4,5,6,7,15,16, 17,19	6	4374	10	7435.8	1	10	1	10	1.5	2
Slippery surface	2,4,14,15,18	1	461	5	783.7	1	1.5	1	1.5	2	10
Bleeding	2,4,5,6,13,17	3	1665	7	2830.5	1	10	1	10	1.5	2



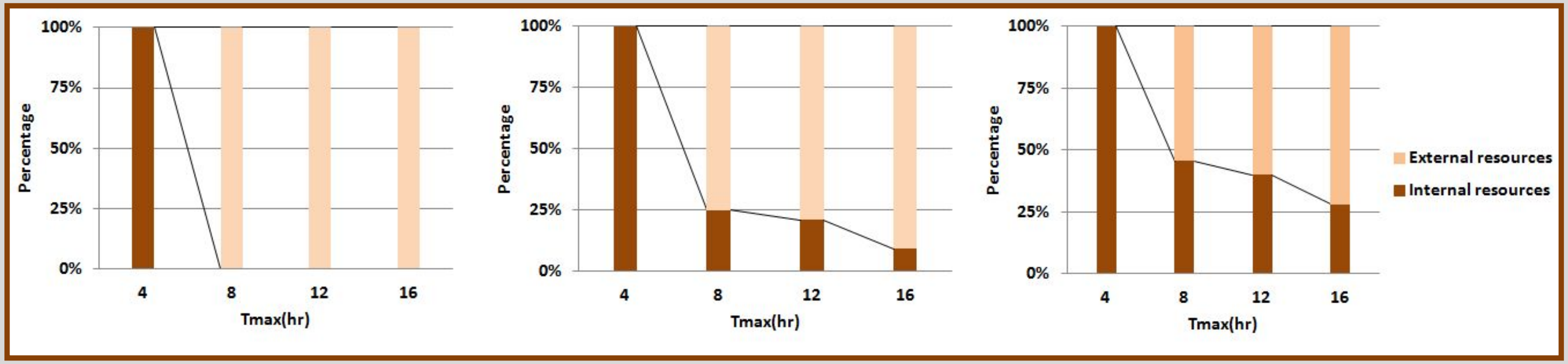




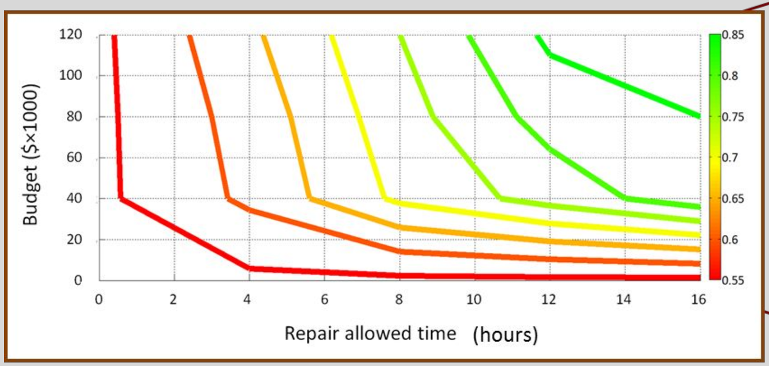


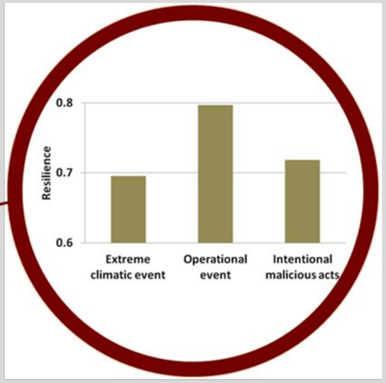
AIRPORT OUTPUT

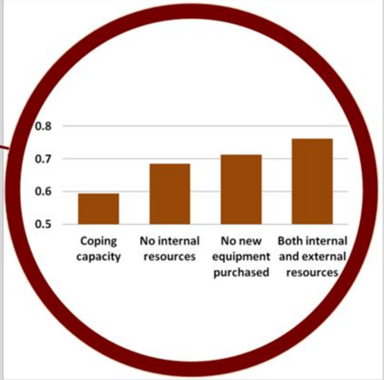
❖ Optimal budget allocation on ext/int resources



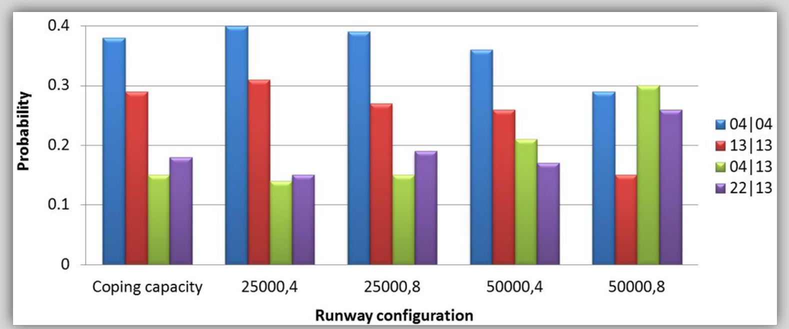
❖ Resilience indifference curves





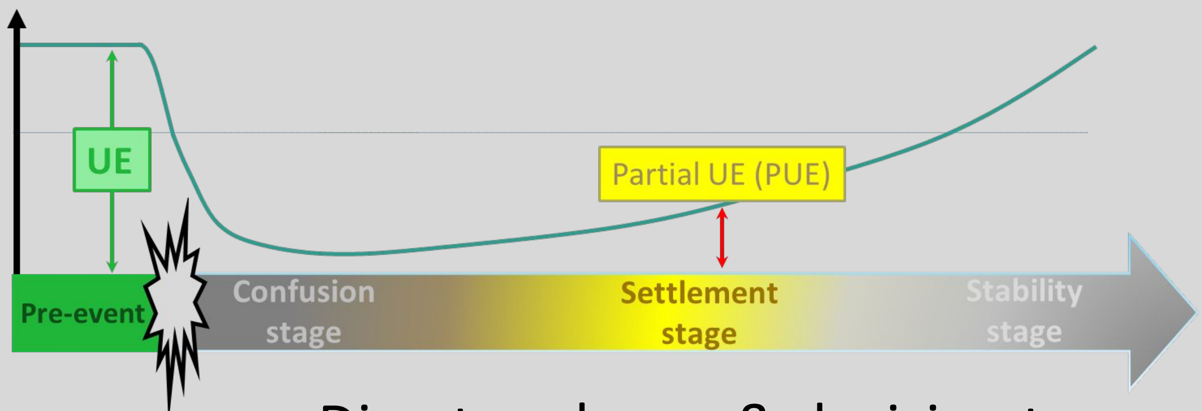


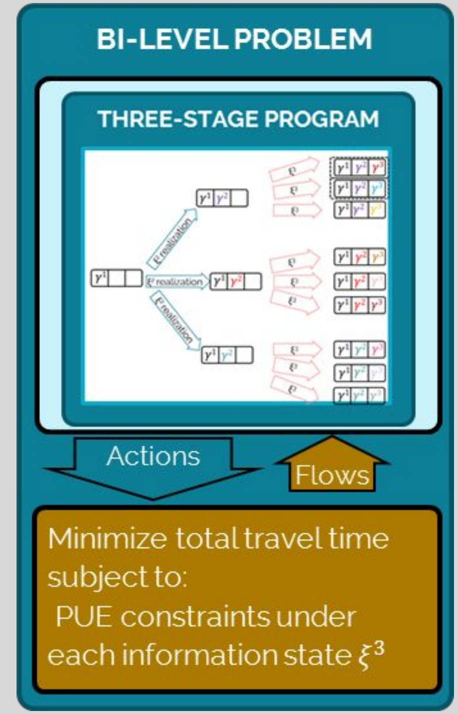
❖ Probability runway configuration selected



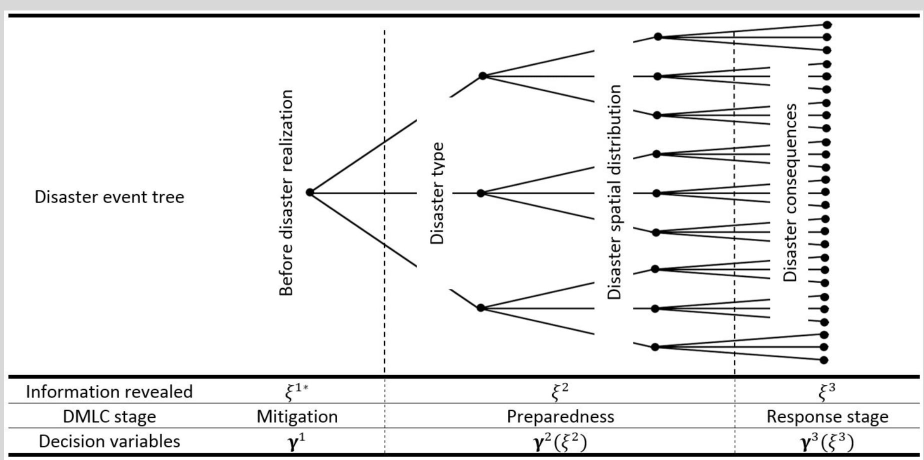
ROADWAY RESILIENCE

- ❖ 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

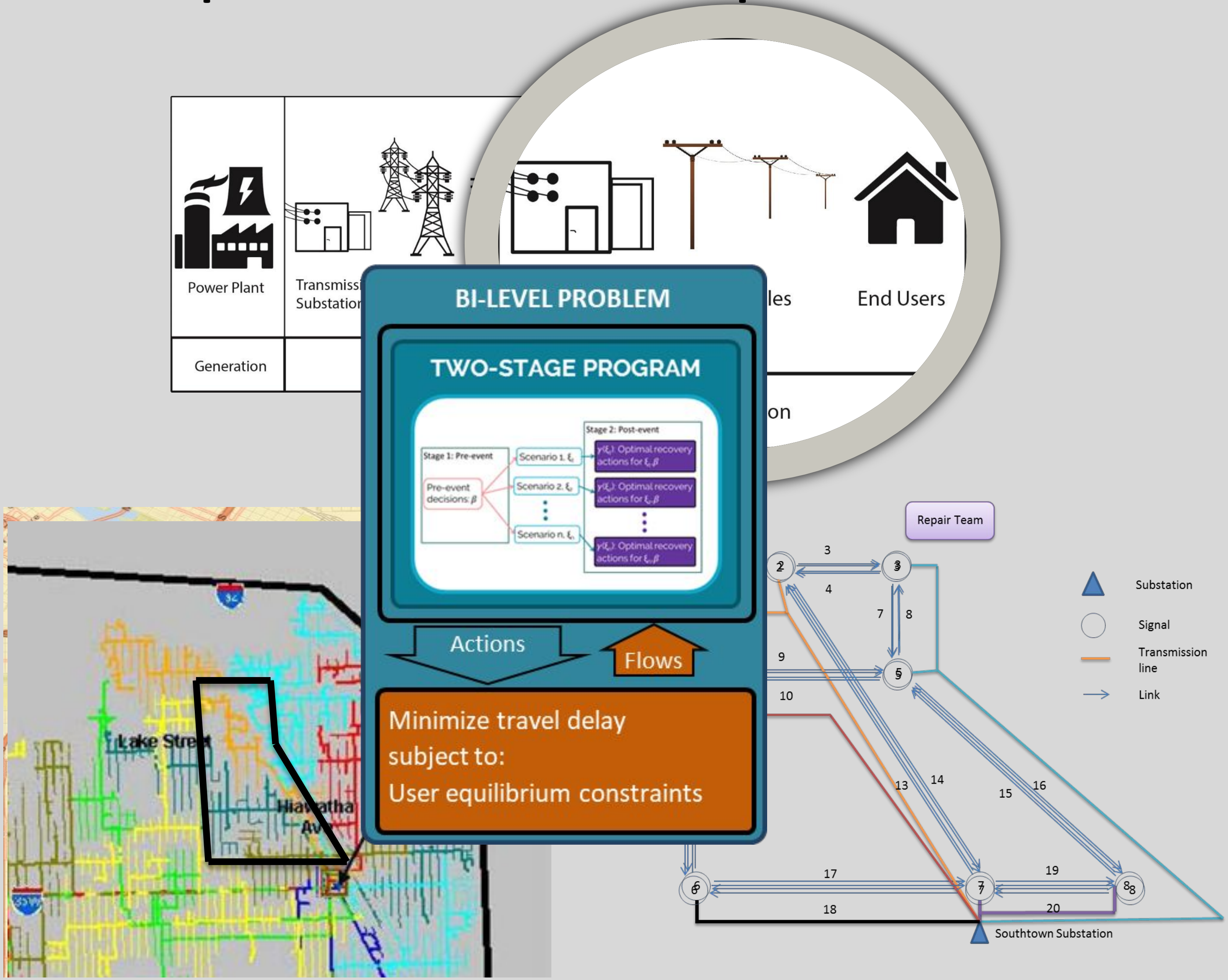




❖Disaster phases & decision tree



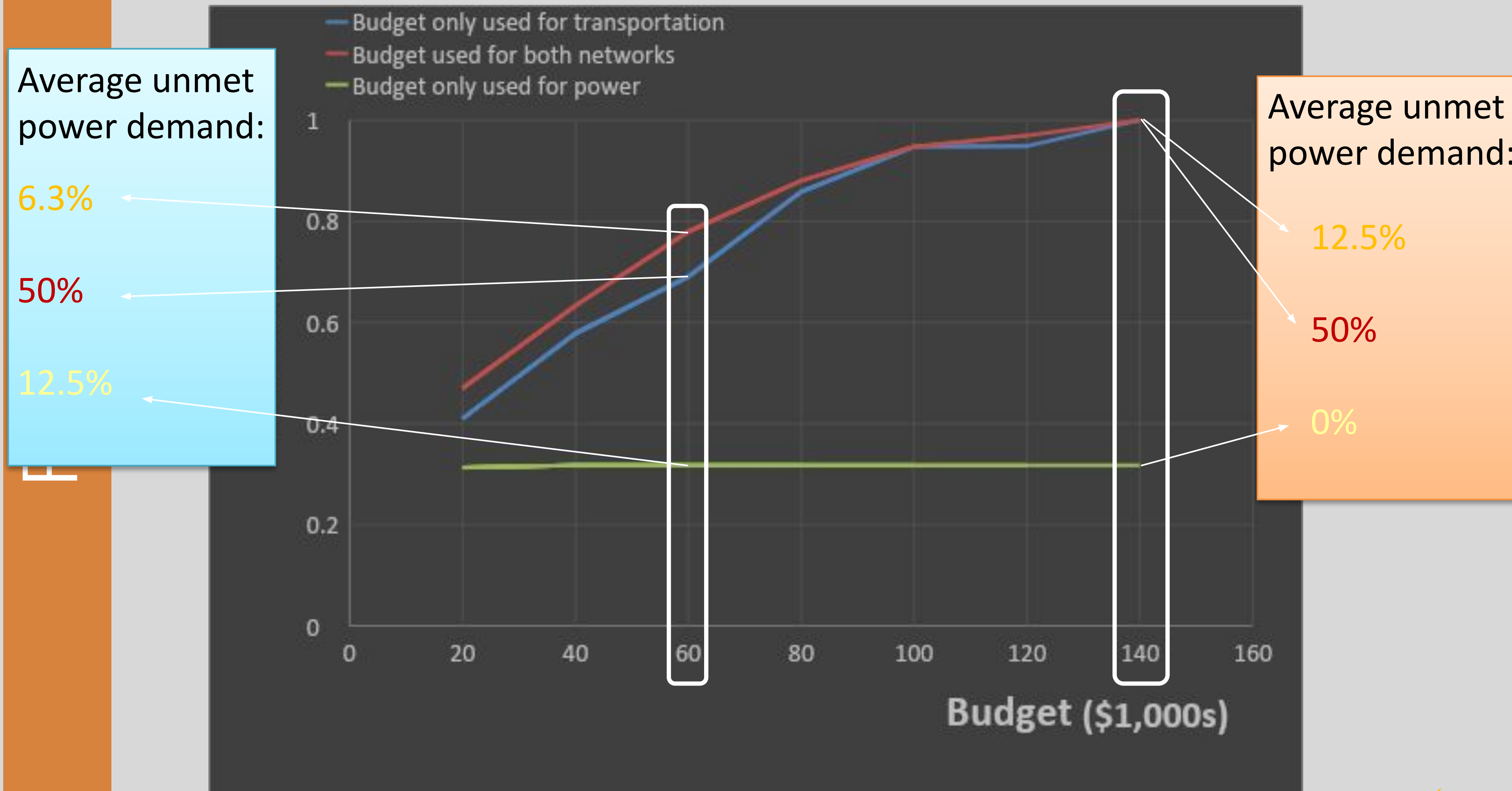
Traffic and power networks interdependence



GEORGE MASON UNIVERSITY

❖ Whose resilience is it anyway?

Unmet demand in power when prioritize roadways

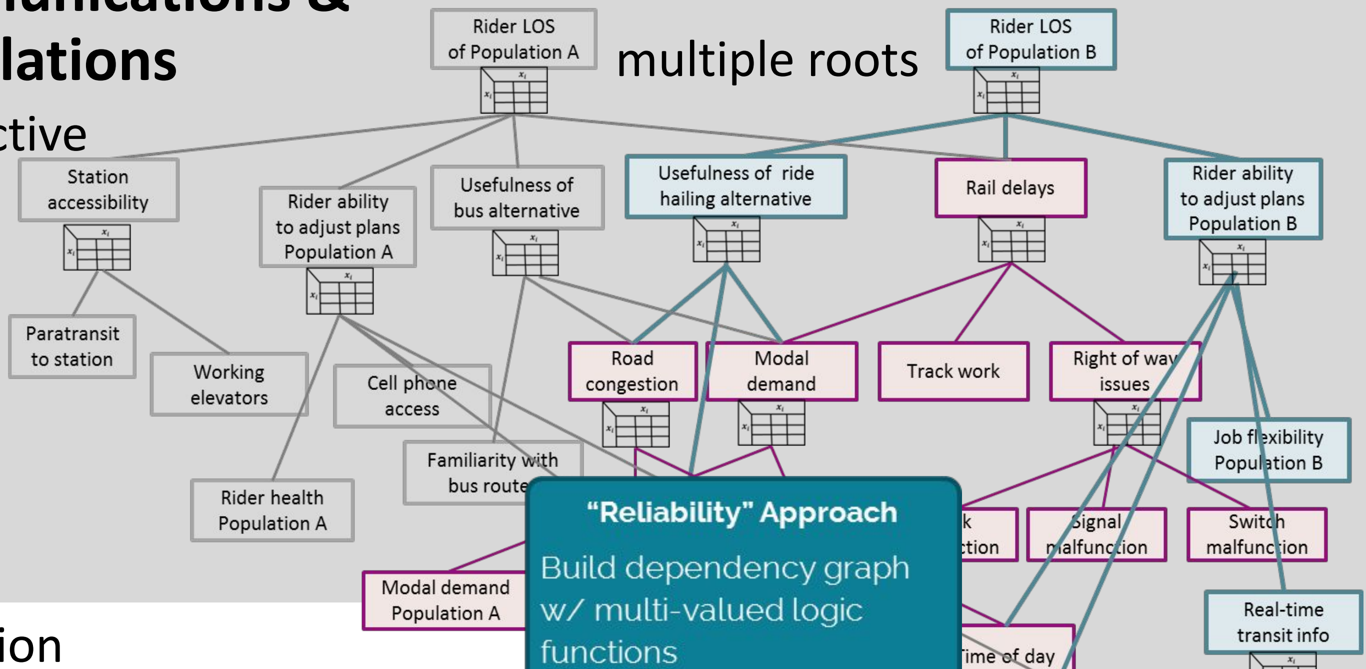


SOCIO-TECHNICAL

Transit-communications & diverse populations

A user's perspective

multiple roots



it, elevators

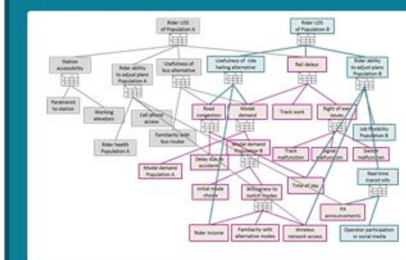
miliar w/ ridehaling apps

Reliability extension

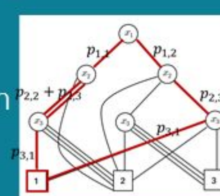
- Diverse pop's – socio-tech system
- Dependency graph
  - Fault-tree extension
  - w/ multivalue logic functions
- Interacting pop's experiences differ
- Induced coupling of technical systems
- Resilience wrt LOS
- Baseline has uncertainty & is user-dependent

"Reliability" Approach

Build dependency graph w/ multi-valued logic functions



Build multi-valued decision diagram (MVDD), recursive function composition



Efficiently compute path probabilities

SERVICES & LIFELINES

❖ Critical infrastructure-based societal systems

Simulation-optimization

Objective function

Expected cost → **Unmet demand** + **Waiting time** + **Access and transfer time**

Expected waiting time metamodel

Initial patient assignment to hospitals

First stage constraint sets

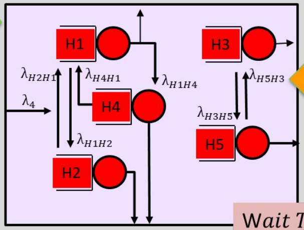
- Linearization of objective function
  - Waiting time estimation
  - Travel time component
- At most one preparedness/mitigation action per network element permitted

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



Patient transfers between hospitals

Metamodel

$Wait\ Time_e(\xi^s) = 42.657(u_e(\xi^s)/\bar{u}_e) - 10.194$ $(R^2 = 0.99)$

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
Road	Retrofit, 5

Disaster is unknown | Disaster strikes | 24 hrs. after disaster strikes

0 — **Stage1** — Event — **Stage2** — Event+24 — **Stage3**

Stage1

Decisions
Mitigation decision for infrastructures $\beta_{e,p}^{damage}$, and preparedness actions for loss of power, $\beta_{e,p}^{power}$,and water, $\beta_{e,p}^{water}$, at the health care facilities

Stage2

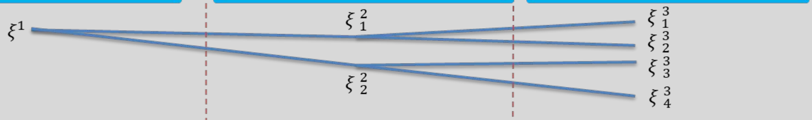
Information revealed
Disaster type, damage state to infrastructure nodes $\varphi_e(\xi^2)$)and links $\varphi_l(\xi^2)$, and patient demand $D_e(\xi^2)$)

Decisions
Repair and recovery actions to infrastructure, $\gamma_{e,r}^{damage}(\xi^2)$, and links, $\gamma_{l,r}^{damage}(\xi^2)$, and transfer plans

Stage3

Information revealed
Capacity of health care facilities $\hat{u}_e(\xi^3)$after 24 hrs, Patient discharge (service) rate $\mu_e(\xi^3)$

Decisions
Repair and recovery actions to infrastructure, $\gamma_{e,r}^{damage}(\xi^3)$, links, $\gamma_{l,r}^{damage}(\xi^3)$, and transfer plans



PORT CO-OPETITION

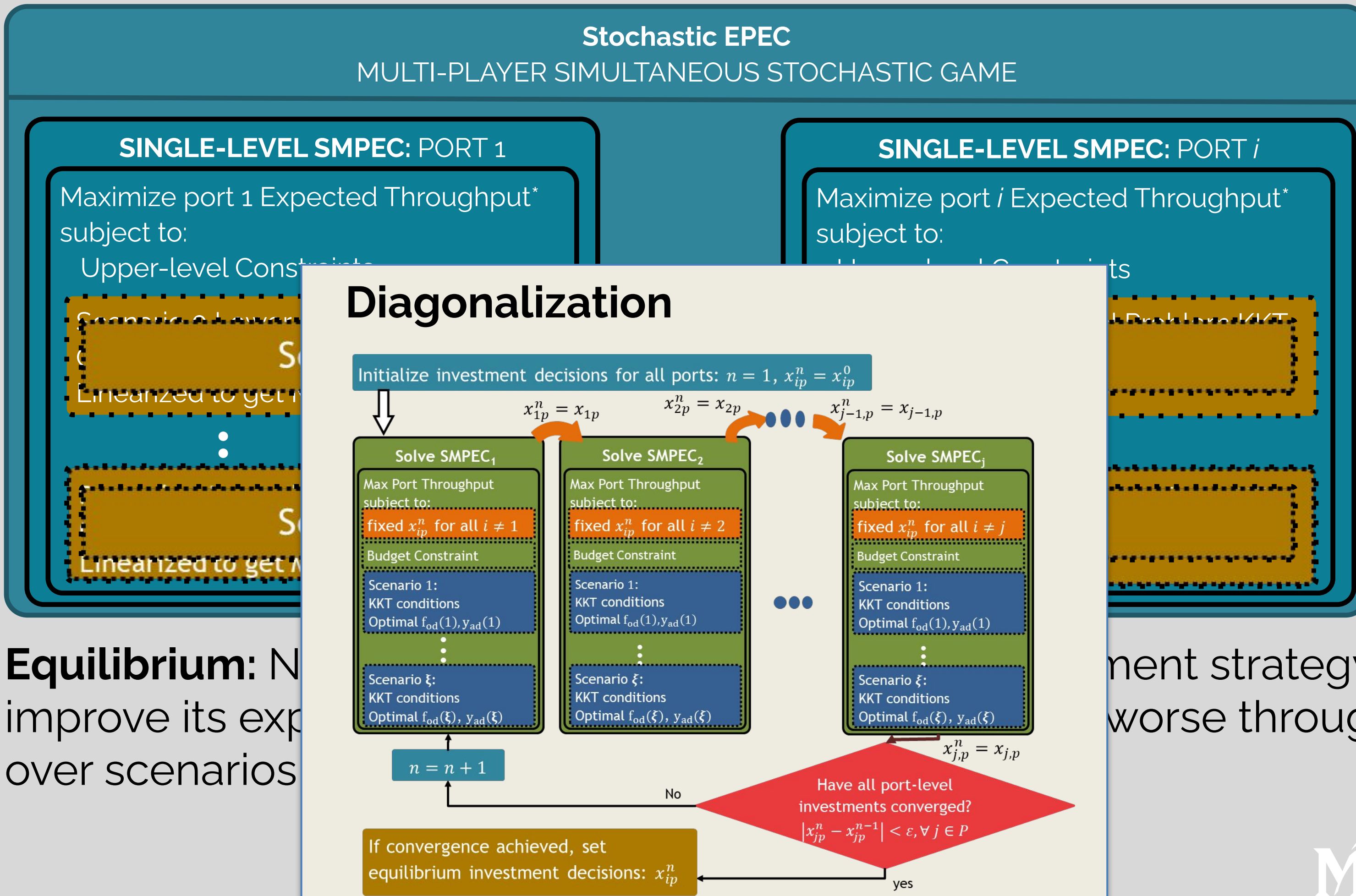
Disruptions Cascading in Intermodal Network

MULTI-PORT EPEC

❖ Formulate multi-port protective investment problem

a) Simultaneous consideration of multiple SMPECs, each modeling an individual port and its market

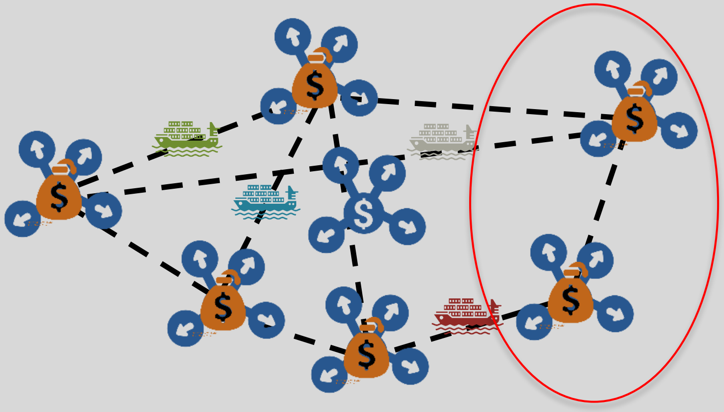
b) Together - Stochastic Equilibrium Problem with Equilibrium Constraints (EPEC) – accounts for common market



Equilibrium: N … ment strategy and improve its exp … worse throughput over scenarios

CO-OPETITION

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)

WORKFORCE EFFECTS

- **Implications of port-related workforce shortages on global maritime performance**
  - Linear, square and exponential port handling rates
  - Solution by Benders decomposition and column generation

Problem $P(r_p)$ (given r_p, $\forall p \in P$)

$$\text{Minimize} \sum_{v \in V} \sum_{\phi \in \Phi} c_\phi^v \cdot f_\phi^v + \sum_{od \in OD} \sum_{s_{od} \in S_{od}} \left(c_s(od) \cdot z_s(od)\right) + \omega \cdot \sum_{od \in OD} u_{od}$$

subject to

$$\sum_{s_{od} \in S_{od}} z_s(od) = D_{od} - u_{od}, \forall od \in OD$$

$$\sum_{od \in OD} \sum_{s_{od} \in S\left(l_\phi^v(i,j)\right)} z_s(od) \le y_\phi^v(i,j), \forall v \in V, \phi \in \Phi, l_\phi^v(i,j) \in L(\phi)$$

$$\sum_{l_\phi^v(i',j') \in L(\phi)} \zeta_{kl\phi} \cdot y_\phi^v(i',j') \le cap_v \cdot f_\phi^v, \forall v \in V, \phi \in \Phi, k_\phi^v(i,j) \in K(\phi)$$

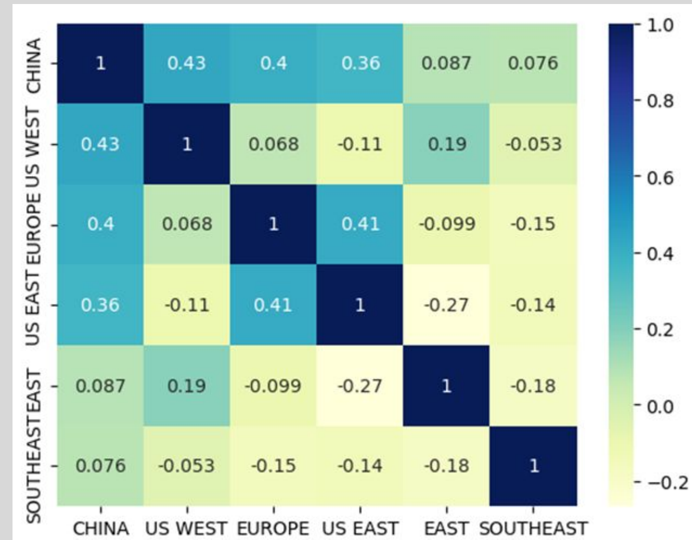
$$f_\phi^v \le cap_\phi^v, \forall v \in V, \phi \in \Phi$$

$$\sum_{v \in V} \sum_{\phi \in \Phi} \sum_{l_\phi^v(i,p), l_\phi^v(p,j) \in L(\phi)} \left(y_\phi^v(i,p) + y_\phi^v(p,j)\right) \le cap(r_p), \forall p \in P$$

$$f_\phi^v \in \mathbb{Z}_+ \quad \forall v \in V, \phi \in \Phi$$

$$z_s(od), y_\phi^v(i,j), u_{od} \in \mathbb{R}_+, \forall s_{od} \in S_{od}, v \in V, \phi \in \Phi, l_\phi^v(i,j) \in L(\phi), od \in OD$$

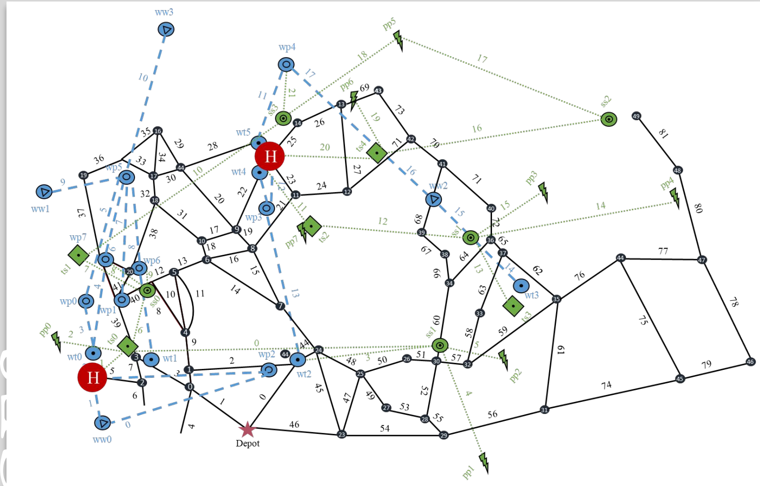
Path-based MILP



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

RESTORING CRITICAL

❖Prioritizing critical facilities



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

Two-Stage Stochastic Program in Rolling Horizon

$$Max\ Z = \left(\sum_{\emptyset} cf_{\emptyset} + \sum_{l} s\mu_{l} + \sum_{o} s\beta_{o}\right) + \sum_{s} p_{s}.\left(\sum_{t}\sum_{\emptyset} cf_{\emptyset t}(s) + \sum_{t}\sum_{l} s\mu_{lt}(s) + \sum_{t}\sum_{o} s\beta_{ot}(s)\right)$$

Maximize expected time critical services function in post-disaster

Restoration Outcomes

$\sum_{i} \sigma_i \leq 1, \dots$

$\sum_{t} \sigma_{it}(s) \leq 1, \dots$

Path Availability

$\sigma_i \leq \sum_{\alpha} I_{in}.p_{n\alpha}, \forall i \quad , \dots$

\# constraint sets 85

Lifeline Component Damage States

$s\sigma_{it}(s) = d_i(s) + \sum_{t'=0}^{t-1} \sigma_{it'}(s), \forall i, \dots$

Inter- & Within Lifeline Dependencies Network

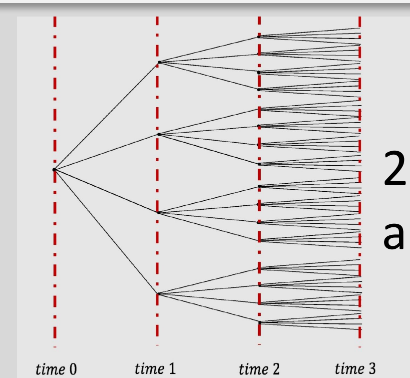
$s\gamma_j \leq \sum_{j} I_{ij}.s\sigma_i, \forall j \ , \dots$

Critical Societal Services Dependencies

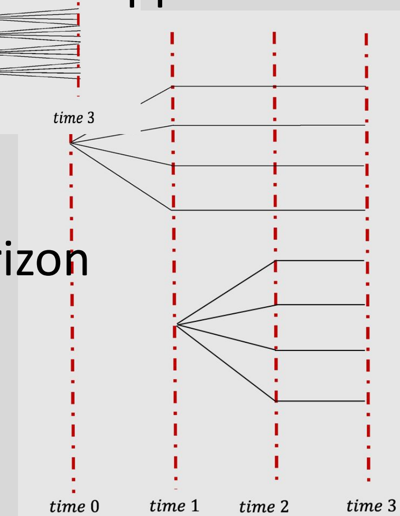
$cf_{\phi} \leq \frac{1}{2}\left(\sum_{l} I_{l\phi}.\ s\mu_l + \sum_{o} I_{o\phi}.\ s\beta_o\right), \forall \emptyset$

...

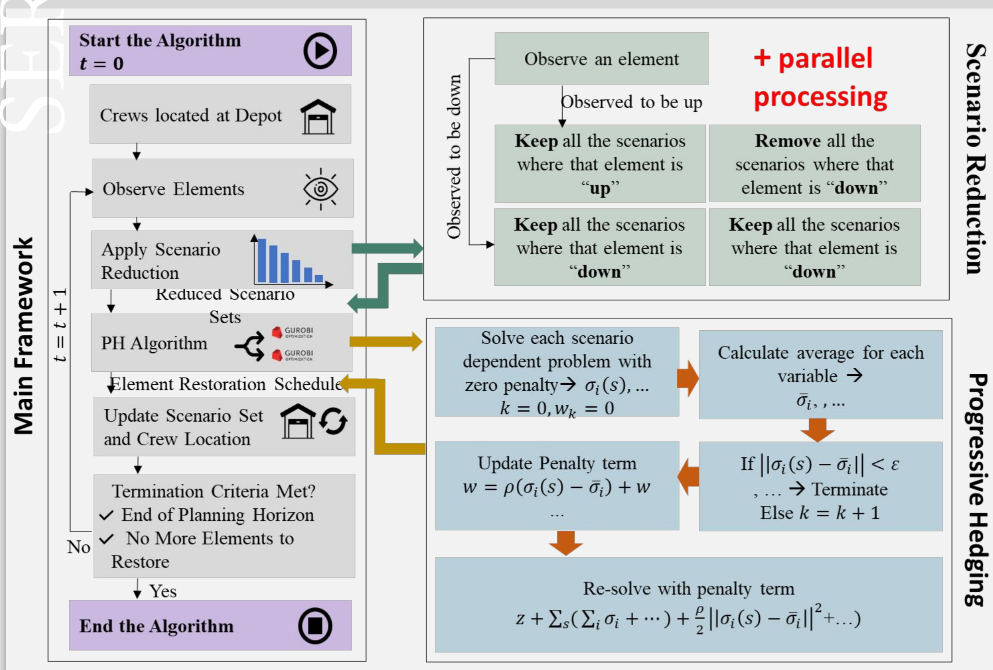
Binary and Integrality



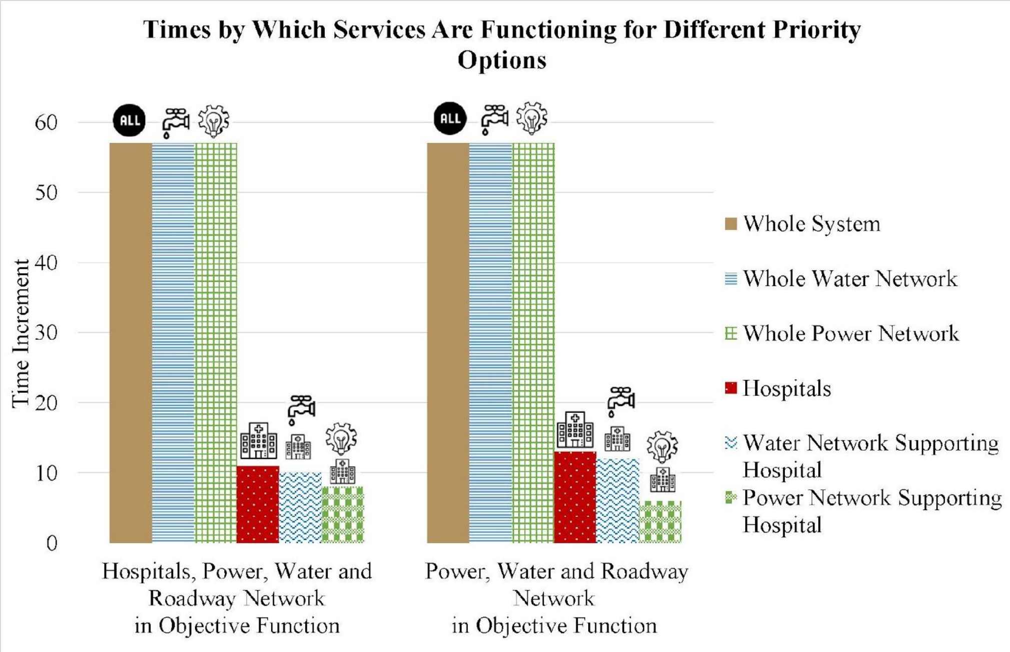
2-stage approximation



Rolling horizon



FINDINGS & RESILIENCE



Hospital services restored earlier if prioritized

Hospital resilience

With hospitals: 26

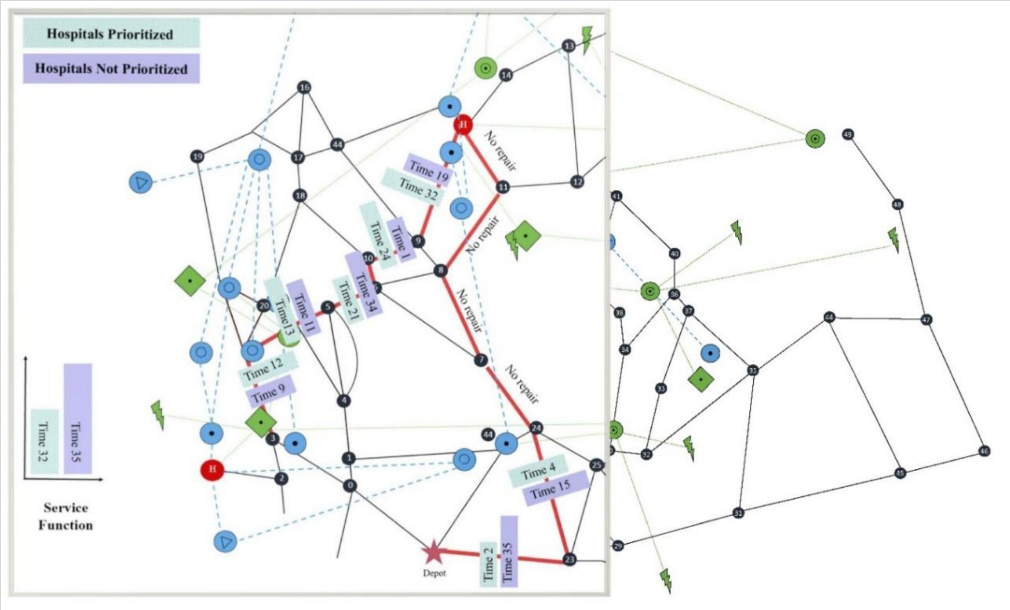
Without hospitals: 28

Full-system resilience

With hospitals: 89

Without hospitals: 86

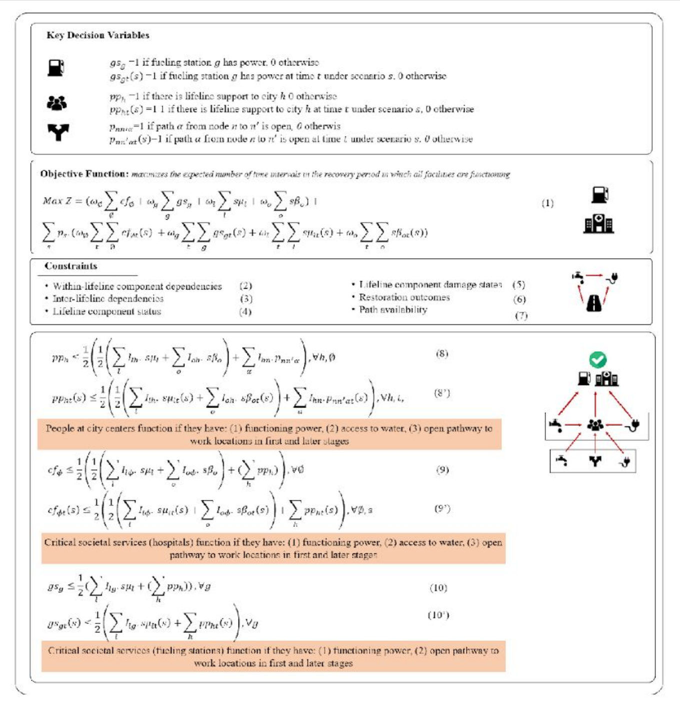
Resilience: expected time to hospital recovery over all scenarios

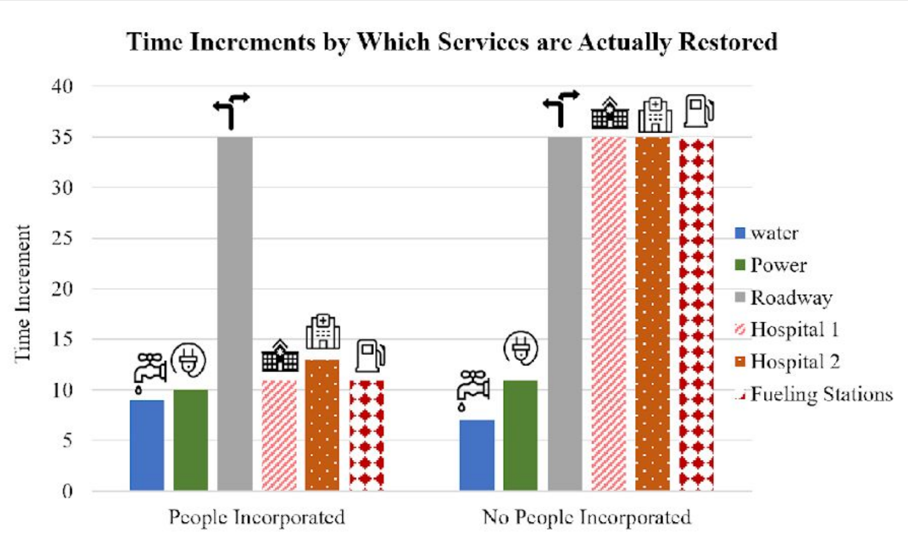


Prioritizing hospitals □ quicker restoration of road links that support access to hospitals & lifeline elements

HUMAN INFRASTR. LIFELINE

❖ Human infrastructure as a lifeline





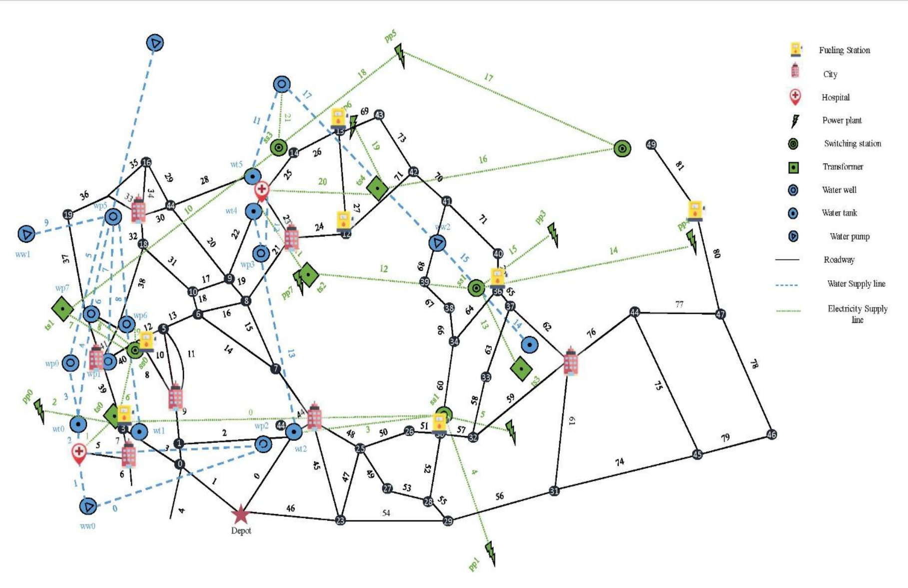
Resilience

Hospital

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

Fueling station

- **People** incorporated: 11
- **No people** incorporated: 35



CLIMATE CHANGE

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

SEA LEVEL RISE & INVESTMENT

❖ 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

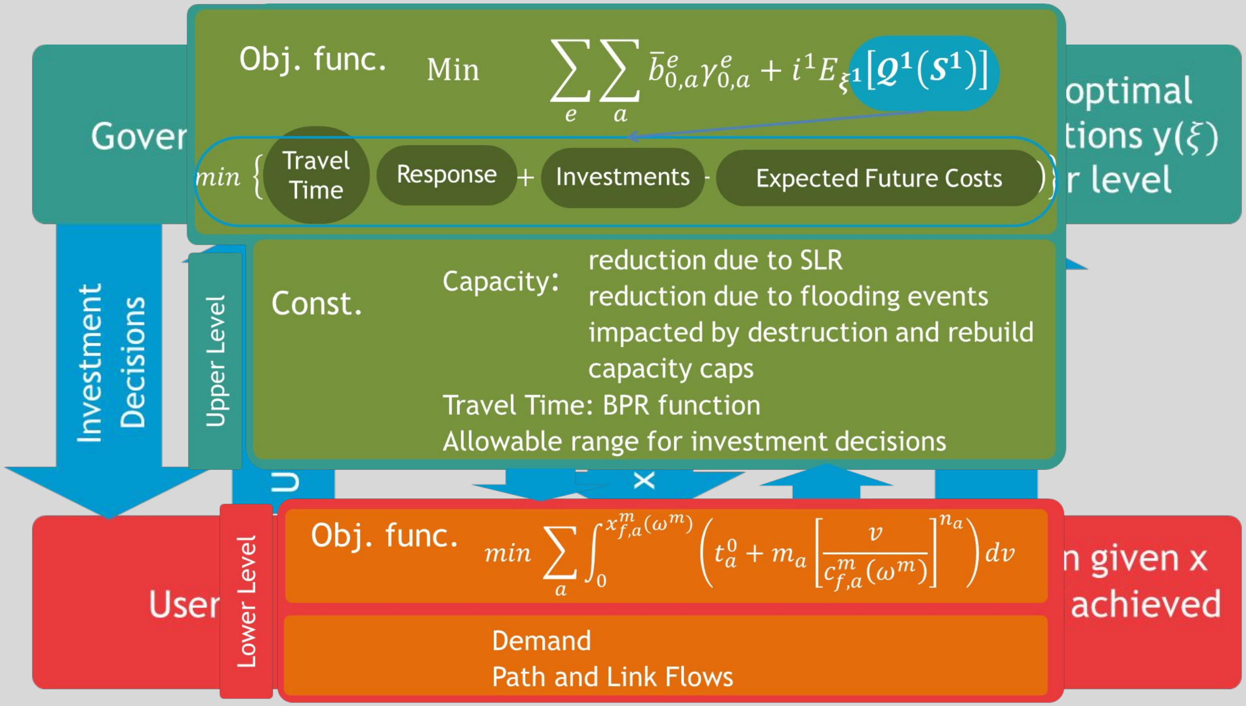
  to minimize direct (repairs) + indirect costs (disruption to users)

  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

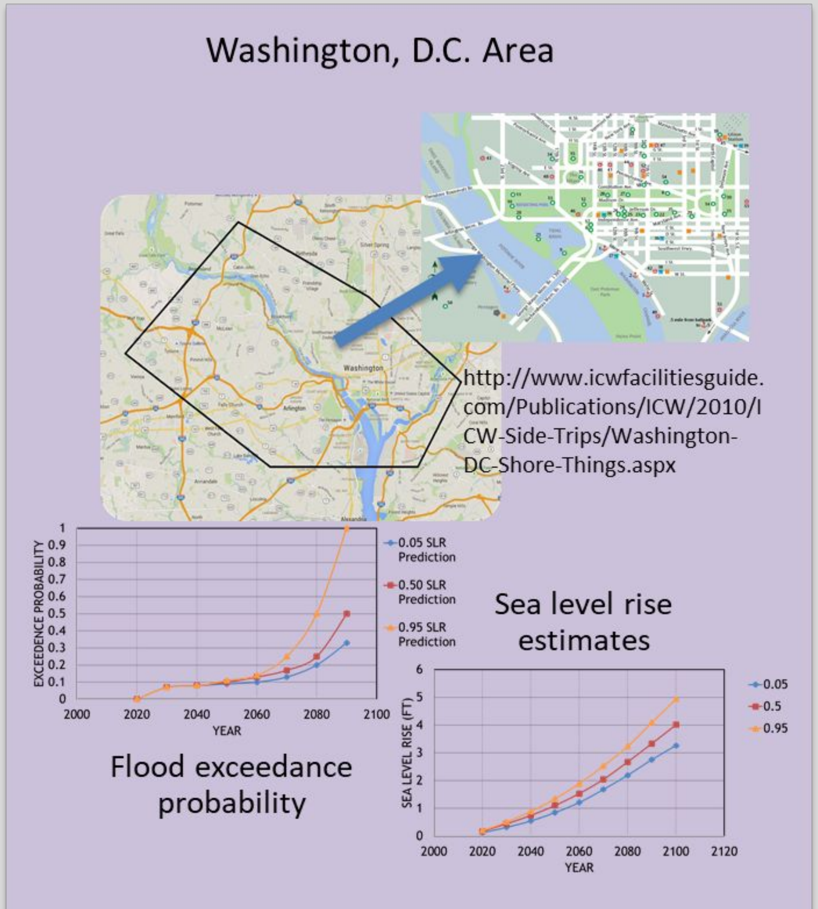


STOCHASTIC FUTURE

❖ 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



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?

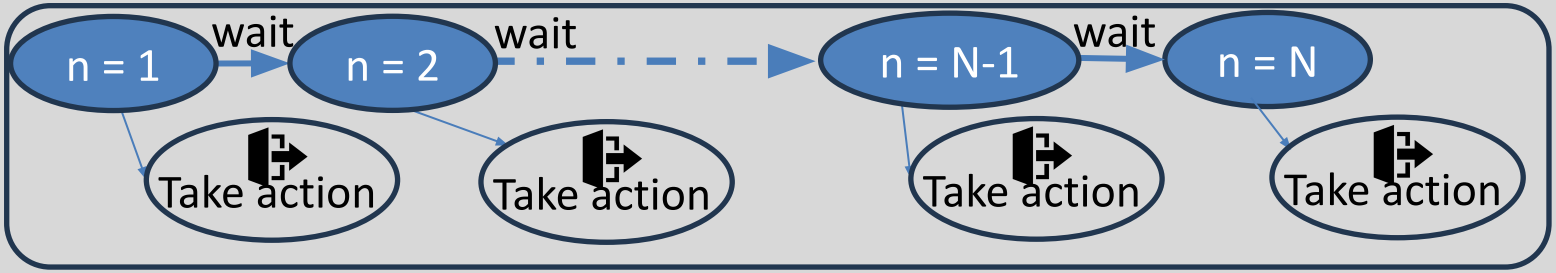
(iii) How system performs if investments are made for one future scenario but a different scenario is realized?

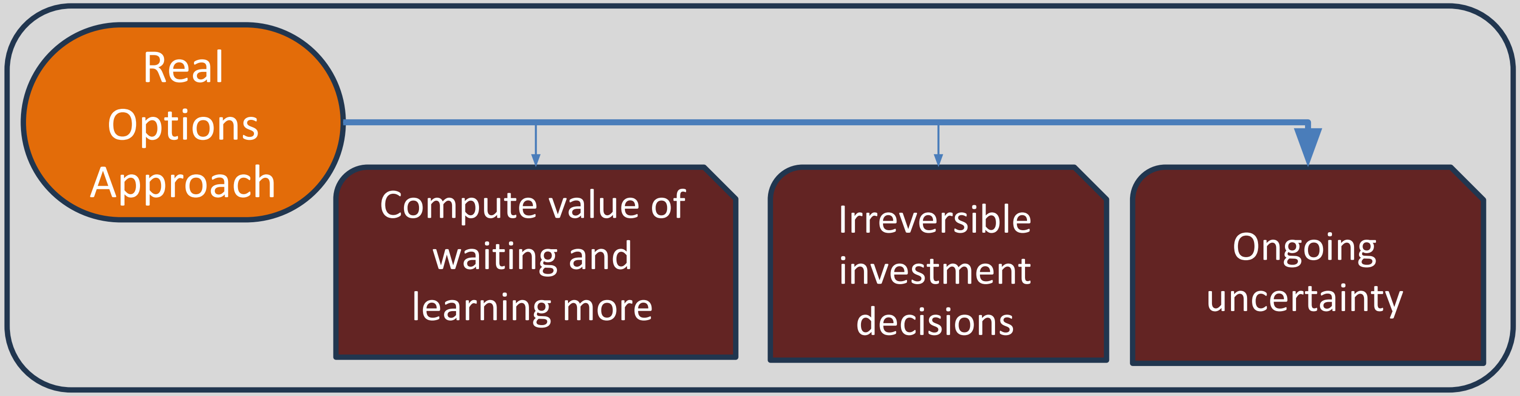
(iv) What is value of hedging against multiple possible futures?

(v) How much improvement in investment effectiveness is gained through accurate prediction?

OPTIMAL STOPPING

A real options approach to transportation infrastructure protection investment timing





3 Step Approach

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

Monte Carlo Simulation

$$h^{\omega}_{t_n,0} = h^{\omega}_{t_{n-1},0} * (a_1)^n * e^{b_1 * \varepsilon}$$
$$h^{\omega}_{t_i,0} = h^{\omega}_{t_n,0} * (a_2)^i$$
$$r^{\omega}_{t_n,j} = (a_3)^n * r^{\omega}_{t_{n-1},j} * e^{b_3 * \varepsilon}$$
$$r^{\omega}_{t_i,j} = (a_4)^i * r^{\omega}_{t_n,j}$$

GUROBI OPTIMIZATION

$$\min_{\Gamma_{t_n}} \phi_{t_n} = \sum_{i=n}^{n+W-1} \left(E\left[\frac{z_{t_i}}{(1+\rho)^{i-n}}\right] \right) + E\left[\frac{z_{t_W}}{\rho(1+\rho)^{W-1}}\right]$$

z_{t_i} = *impact of SLR and Storm Surge Flooding*

Subject to 36 sets of constraints

$$\Phi_{t_n,\omega} = max\left\{\pi_{t_n,\omega}, \frac{E[\Phi_{t_{n+1},\omega}]}{(1+\rho)^{\Delta t}}\right\} = max\left\{\pi_{t_n,\omega}, \frac{f_{t_n}(\pi_{t_i,\omega} | i \in \{0,1,\ldots,n\})}{(1+\rho)^{\Delta t}}\right\}$$

CONCLUSIONS

- 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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