This presentation does not necessarily reflect the views of the United States Government, and is only the view of the author

Science and Practice of Resilience Quantification

Igor Linkov, PhD

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US Army Engineer Research and Development Center;

Founding President, International Society for Resilience Analysis;

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31 July 2026

US Army Corps of Engineers

U.S.ARMY

Science: Risk and Resilience

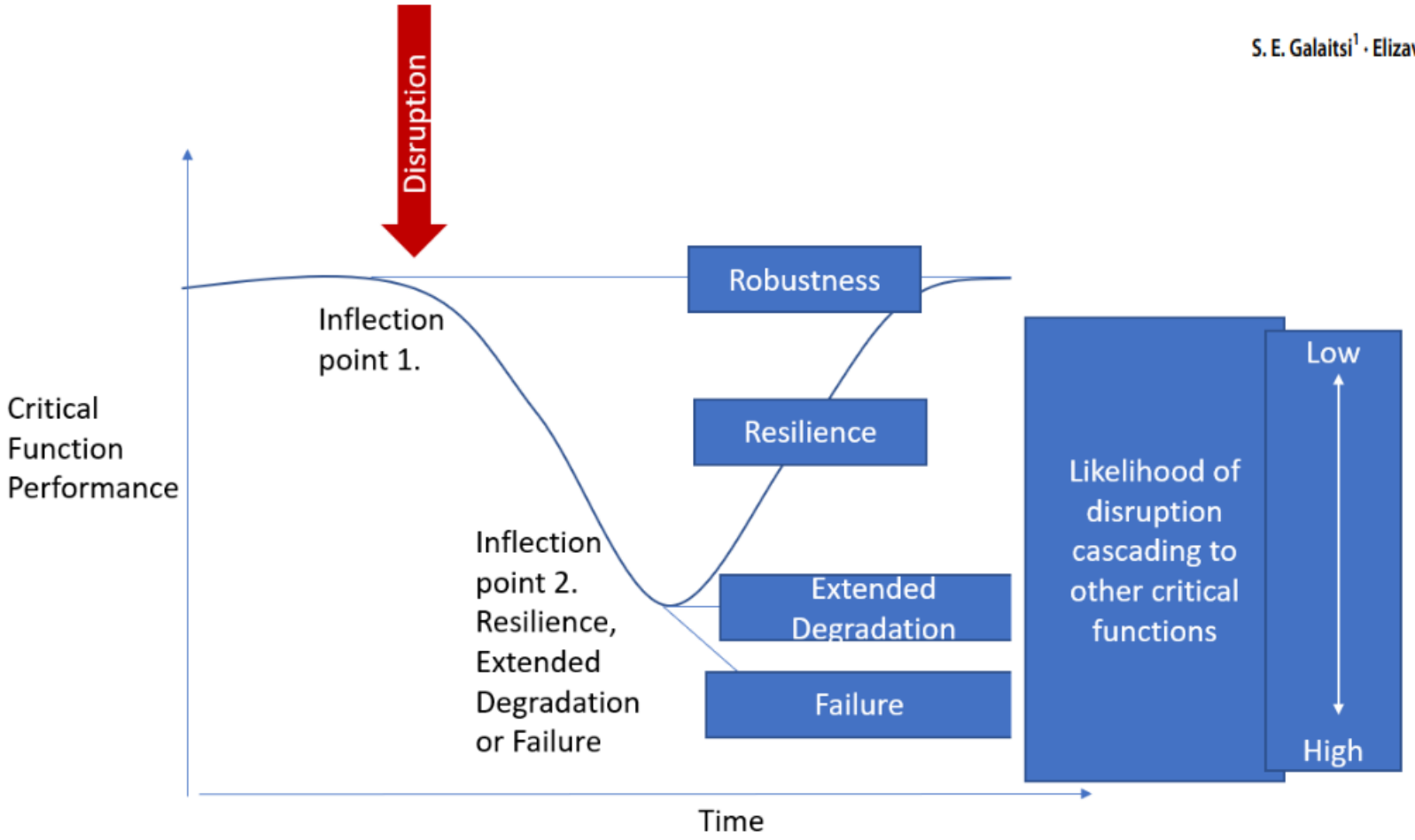
- **Problem with Risk the Way we Know It**
  - **Threats** – are compounding and more likely to occur as system interconnectedness continue to manifest.
  - **Science** – PRA and Scenario analysis are not capturing cascading failures and unknow unknowns
  - **Practice/Policy** –Frequent failures and backlash

- **Solution – Balancing Risk and Resilience Management**
  - **Threats -** From Threat Scenario to Systemic Threat Agnosticity through Compounding Threats/Cascading Failures
  - **Science --** From Language of Probabilities to Networks and Stress Testing
  - **Policy –** Joint Risk/Resilience Governance, Tools

Practice/

Crisis Management, Risk and Resilience

Risk~ Threat*Vulnerability*Consequence

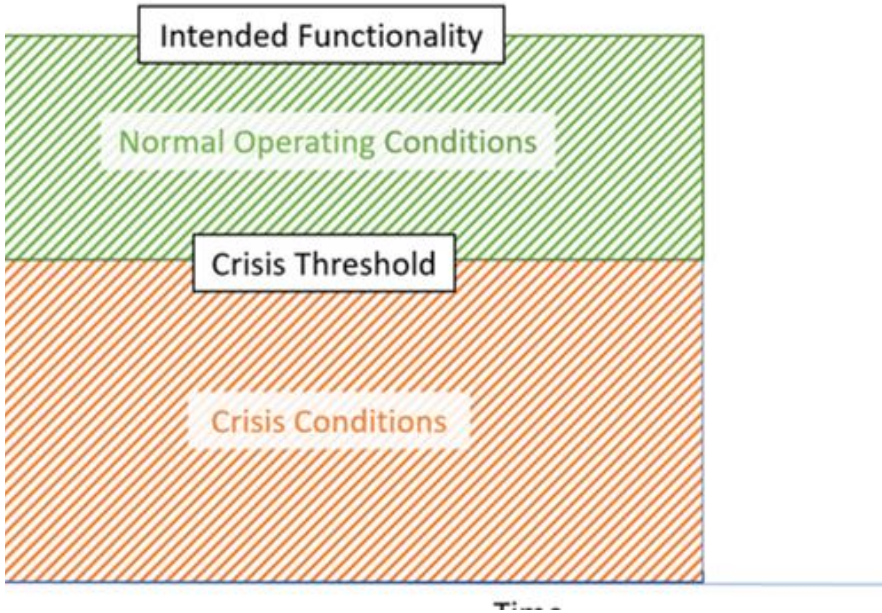


International Journal of Disaster Risk Science
https://doi.org/10.1007/s13753-023-00494-x
www.ijdrs.com
www.springer.com/13753

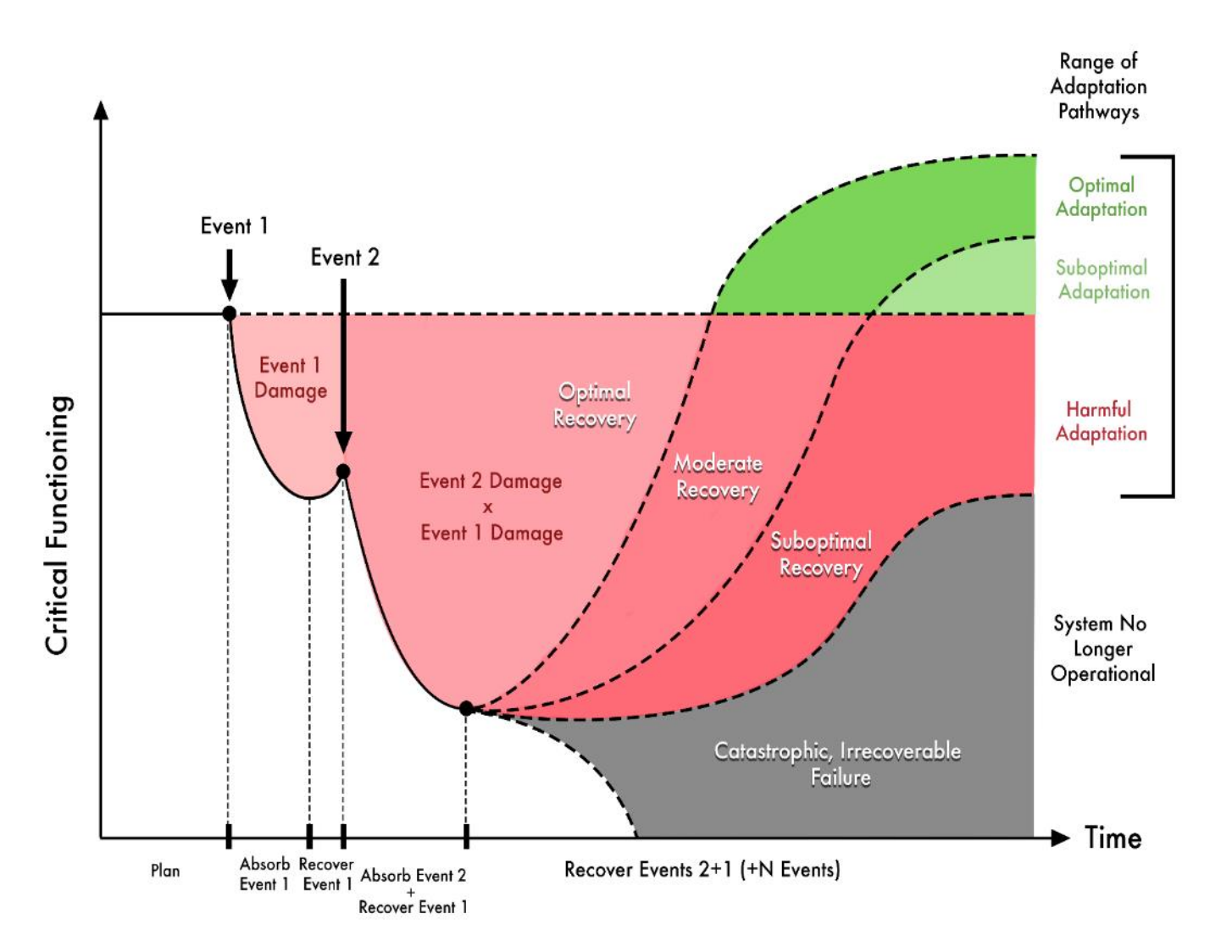
ARTICLE

Business Continuity Management, Operational Resilience, and Organizational Resilience: Commonalities, Distinctions, and Synthesis

S. E. Galaitsi[1] · Elizaveta Pinigina[1] · Jeffrey M. Keisler[2] · Gianluca Pescaroli[3] · Jesse M. Keenan[1,4] · Igor Linkov[1]



Disruptions - Compounding Events/ Cascading Failures



ELSEVIER

Progress in Disaster Science
Volume 15, October 2022, 100244

Modeling critical infrastructure resilience under compounding threats: A systematic literature review

Emily M. Wells [a b], Mariel Boden [a], Ilana Tseytlin [a c], Igor Linkov [a]

- Critical functions of a system drop after Event 1
- Event 2 happens before recovery from Event 1 is complete
- Nuanced interactions between Event 1 and Event 2 can increase impact to critical functions
  - Is this additive? Multiplicative? Exponential?
- Resilience looks at all aspects of the event(s): plan, absorb, recover, and adapt

EU RESILIENCE REGULATIONS

The Digital Operational Resilience Act (DORA) (2022)

- to strengthen the cybersecurity and overall digital resilience of the financial sector.
- aims to create a single, consistent framework for ICT risk management across EU member states, replacing a fragmented landscape of rules.

EU Cyber Resilience Act (CRA, 2022)

- To improve the cybersecurity of all products with digital elements sold in the EU.
- Covers most hardware and software products with digital components, including smart devices, operating systems, and apps. Exceptions exist for sectors with their own specific regulations, such as medical devices and aviation.

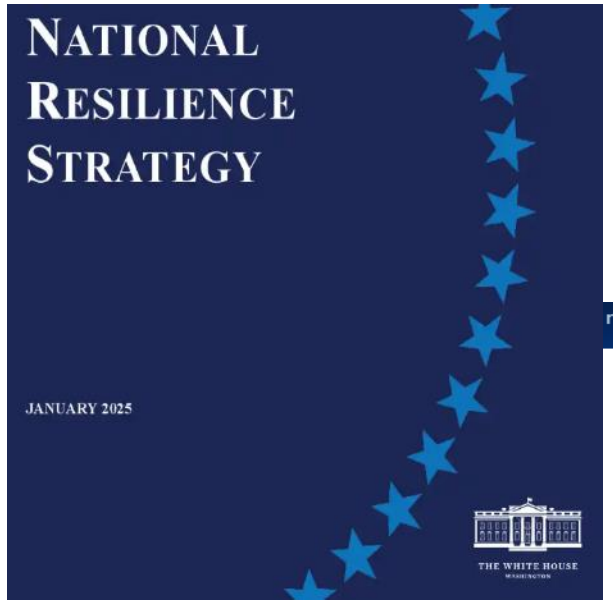
Critical Entities Resilience (CER) Directive (2024)

- To ensure the resilience of essential services and critical infrastructure in the EU against natural and man-made disruptions.
- Covers a wide range of sectors deemed critical, such as energy, transport, banking, public health, and digital infrastructure.

US Army Corps of Engineers

U.S.ARMY

POLICY



material "frozen in time". The website is no longer updated and links to external websites and some internal pages may not work.

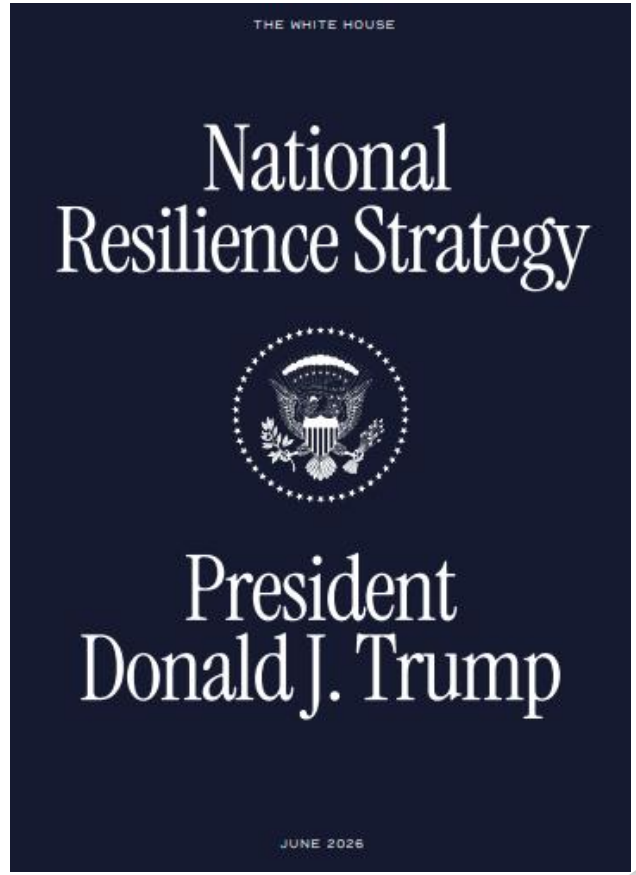
Administration | The Record | The Issues | Briefing Room

APRIL 30, 2024

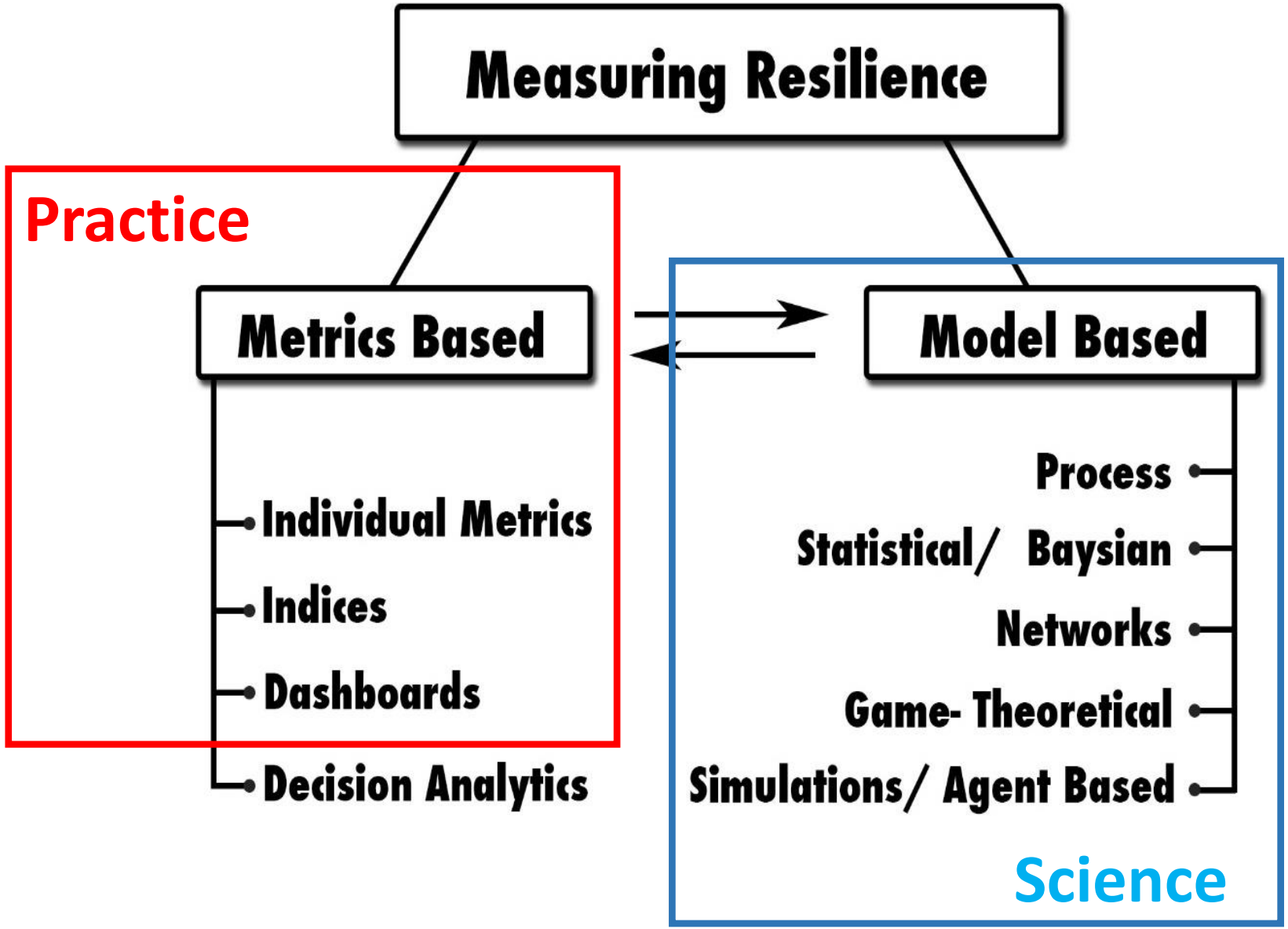
National Security Memorandum on Critical Infrastructure Security and Resilience

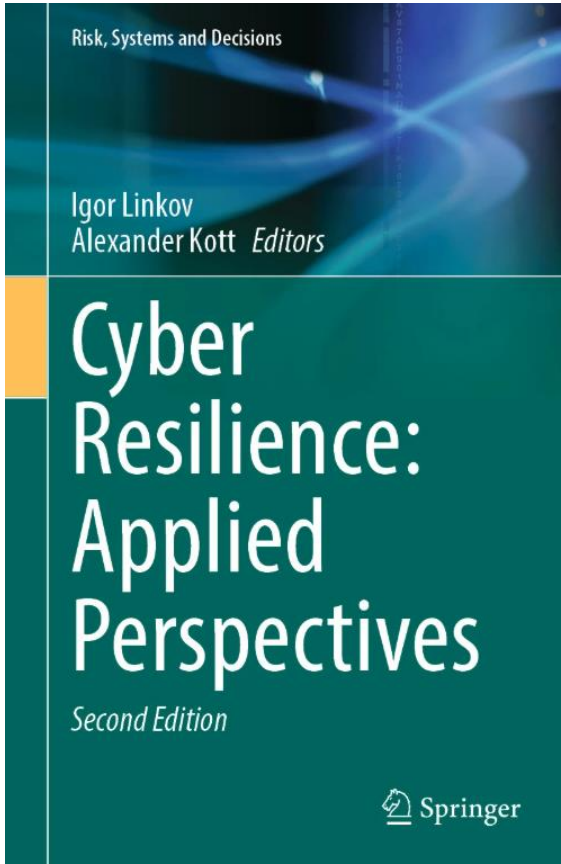
BRIEFING ROOM › PRESIDENTIAL ACTIONS

NATIONAL SECURITY MEMORANDUM/NSM-22



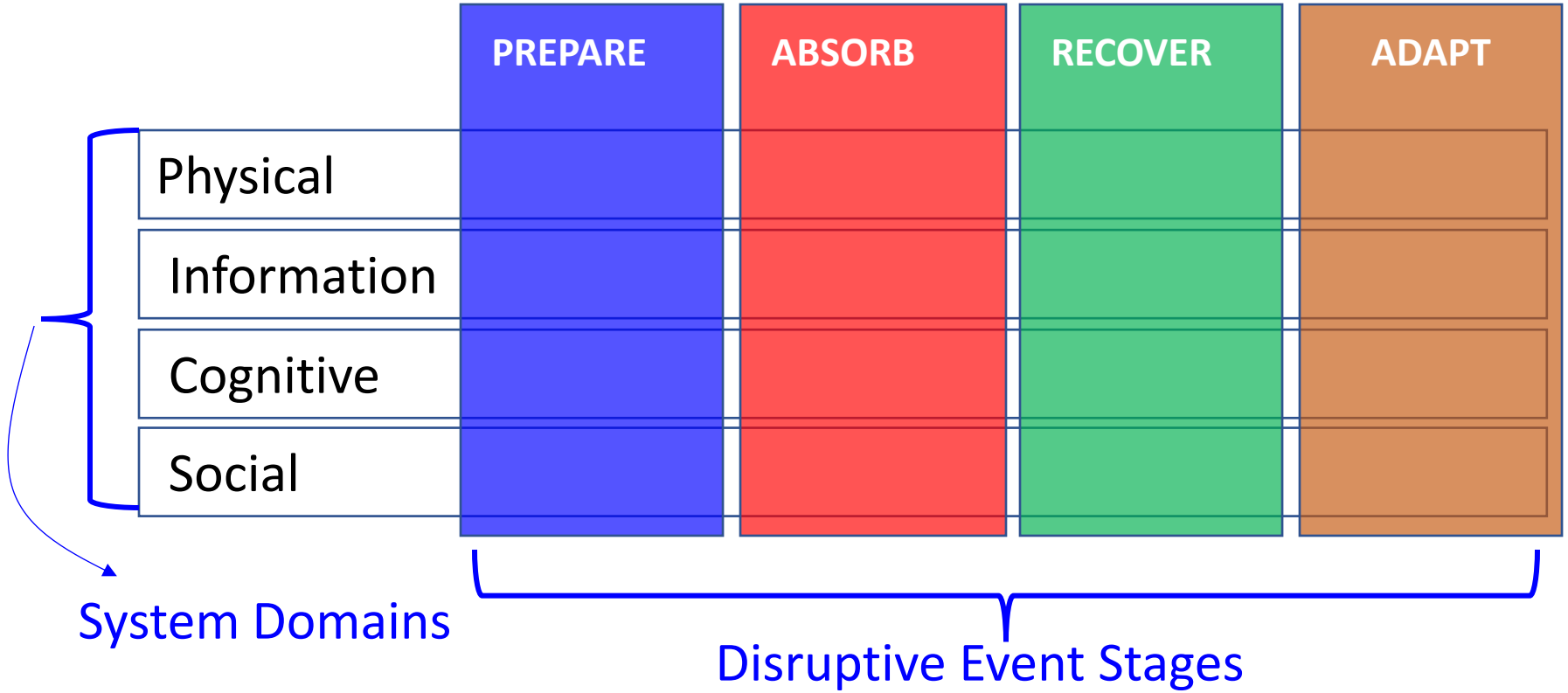
How Do We Quantify Risk and Resilience?

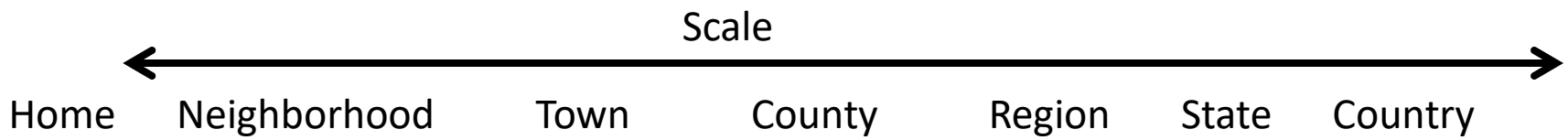




After 2025

Resilience Matrix





Assessment using Stakeholder Values

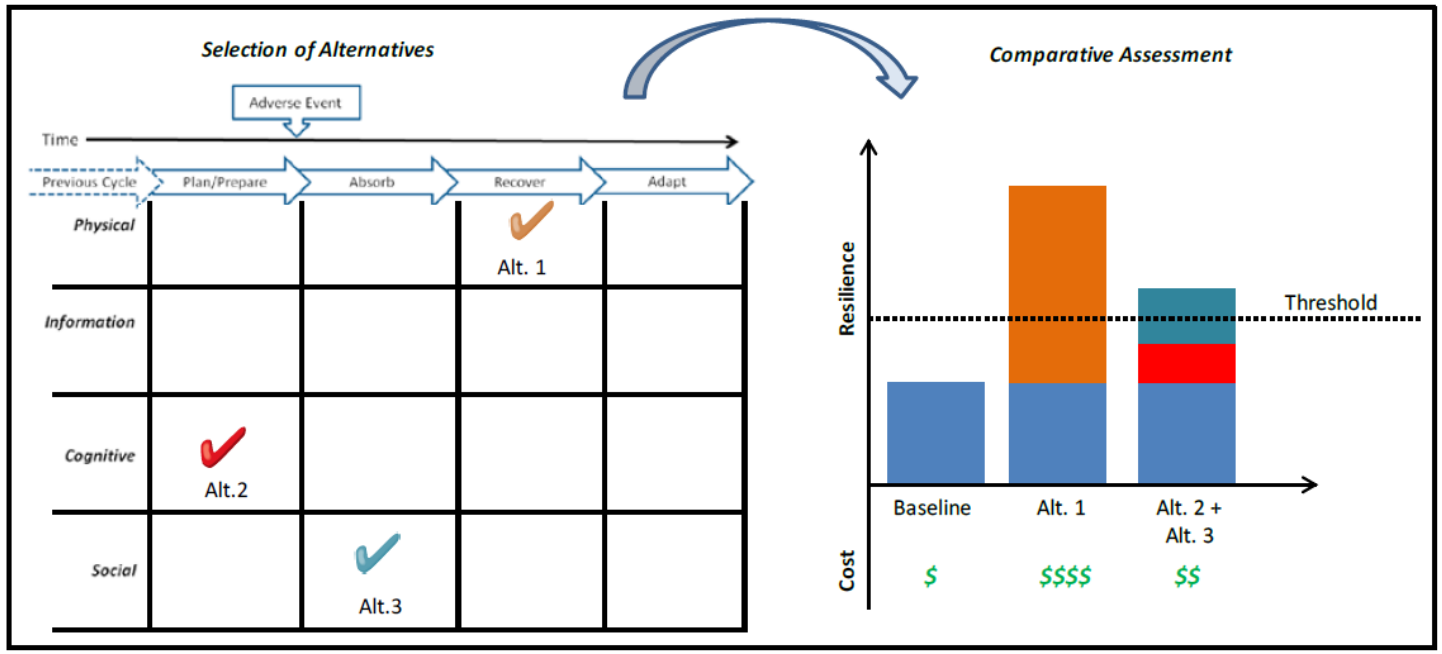


Figure 5: Comparative Assessment of Resilience-Enhancing Alternatives

Use developed resilience metrics to comparatively assess the costs and benefits of different courses of action

After Fox-Lent et al., 2015

ENHANCING RISK REGISTERS USING RESILIENCE MATRIX

	Resilience				
	Risk				
	Absorb			Recover	Adapt
Dam Sector	**Threat** (incident with potential to harm system)	**Vulnerability** (known weakness in the infrastructure)	**Consequence** (impact if threat were to happen)		
Physical	Earthquake	Aging infrastructure, insufficient spillway capacity	Structural failure, loss of power generation, downstream flooding	Mobilize emergency crews, restore services via temporary repairs	Update building codes, retrofit infrastructure
	Extreme flooding				
Information	Cyber attack on control systems	Lack of network segmentation	Loss of remote control	Isolate affected systems, restore backups	Implement stronger cybersecurity measures, employee training
		Outdated software	Uncontrolled water release		
Social	Misinformation about dam failure online	Limited community trust	Public panic, mass evacuation	Activate public information channels, coordinate local authorities	Build trust through community engagement, simulation exercises
		Lack of public communication protocol			

USACE APPLICATION TO WATERSHED RESILIENCE

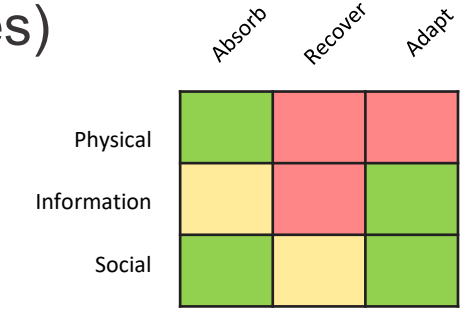
Matrix-Based Screening Tool for quantifying USACE Watershed Resilience

5 Step process to develop a Resilience Profile

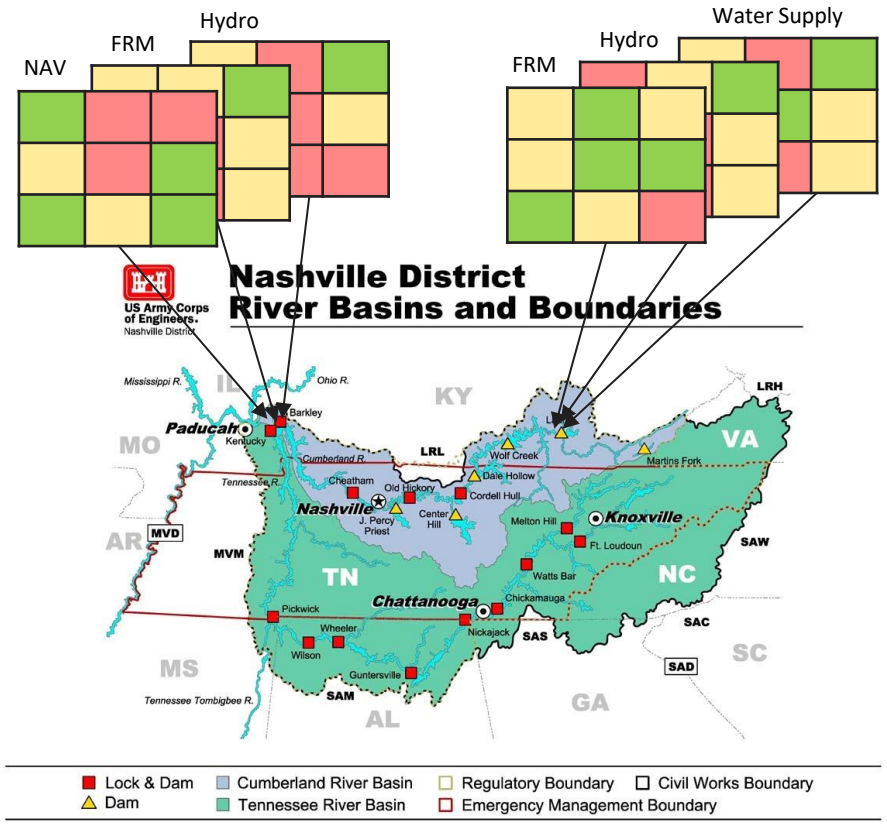
1. Define the Purpose
2. Define the System
3. Develop a Resilience Profile
4. ID Areas of Consideration
5. Develop Courses of Action

Resilience Profile

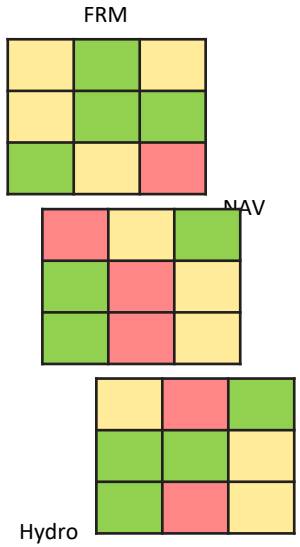
- Standardized (consistent dimensions of Resilience Matrix, normalized to 1-5 score)
- Flexible (Metric Library for USACE or partner agencies)



Project Scale



Basin Scale



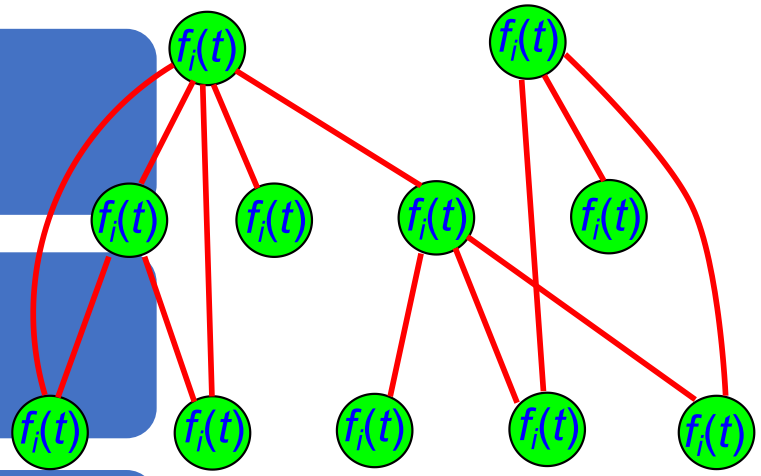
Network-based Resilience Theory?

System's *critical functionality* (*K*)

Network topology: *nodes* ($\mathcal{N}$) and *links* ($\mathcal{L}$)

Network *adaptive algorithms* ($\mathcal{C}$) defining how nodes' (links') properties and parameters change with time

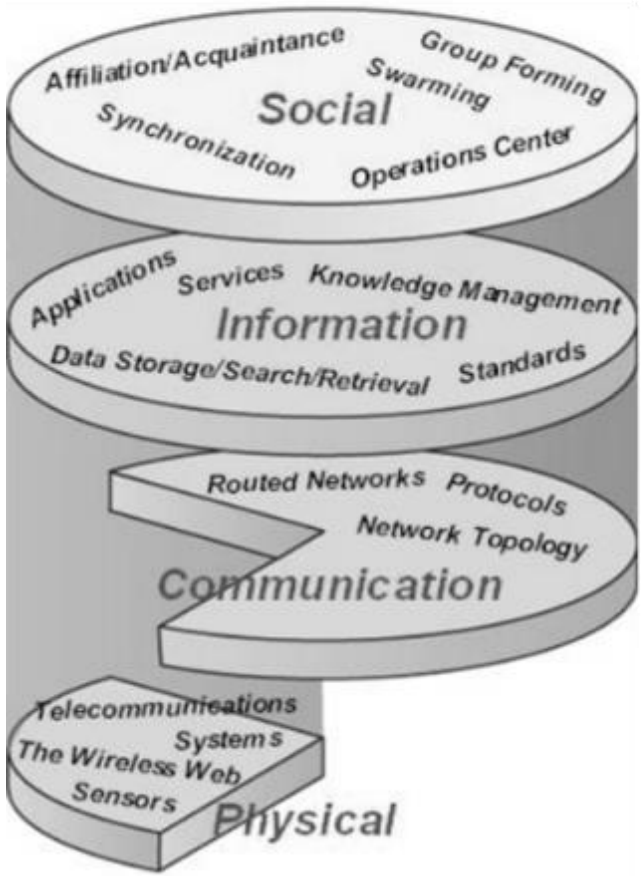
A *set of possible damages* stakeholders want the network to be resilient against ($\boldsymbol{E}$)



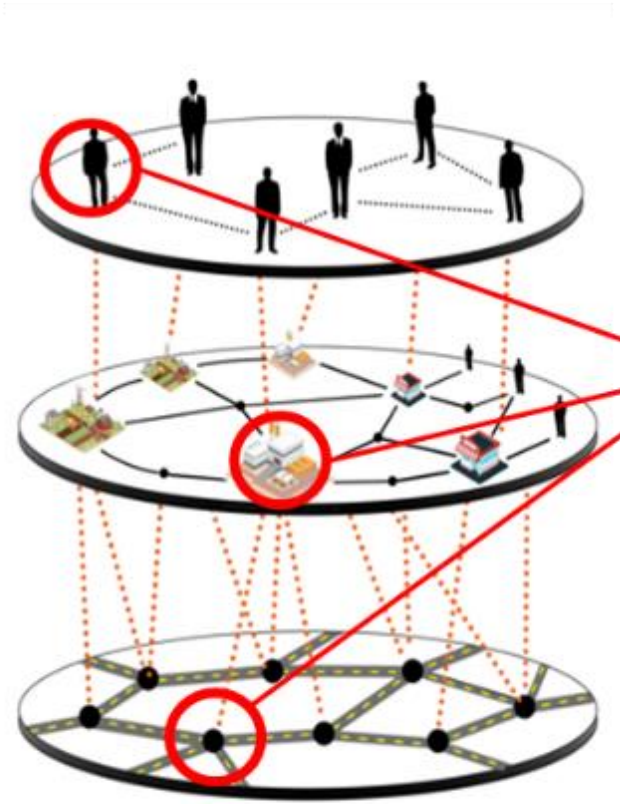
$$R = f(\mathcal{N}, \mathcal{L}, \mathcal{C}, \boldsymbol{E})$$

Vision for System Resilience

Real World



Model



Operations

Management Alternatives

The case for value chain resilience

Igor Linkov, Savina Carluccio, Oliver Pritchard, Áine Ní Bhreasail, Stephanie Galaitsi, Joseph Sarkis and Jeffrey M. Keisler

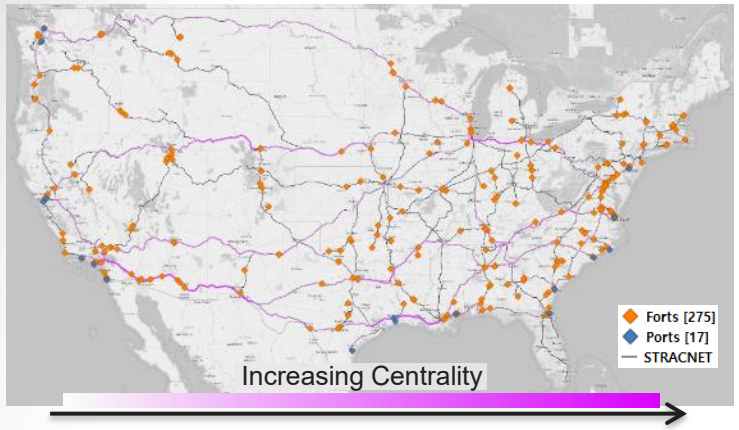
Management Research Review

2040-8269
DOI 10.1108/MRR-08-2019-0353

HOW TRANSPORTATION RESILIENCE IS QUANTIFIED

ERDC

Network Structure Metrics
Connectivity, giant component size, cliques, betweenness centrality, diameter, etc.

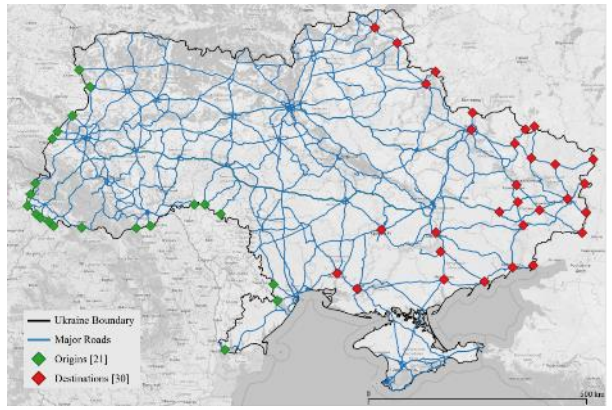


e.g. betweenness centrality of US strategic railway

Mobility Performance Metrics
Travel time, traffic delay, congestion, queue length, speed, etc.

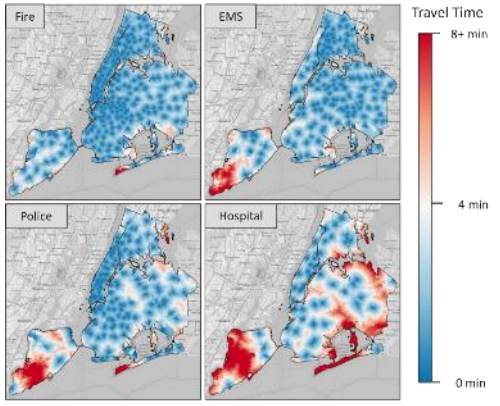
e.g. traffic of New York City

Logistics Metrics
Freight volume, delivery time, supply fulfillment, deployment time, etc.



e.g. logistics network of Ukraine

Societal/Equity Metrics
Access to hospitals, jobs, shelters, food, schools etc.

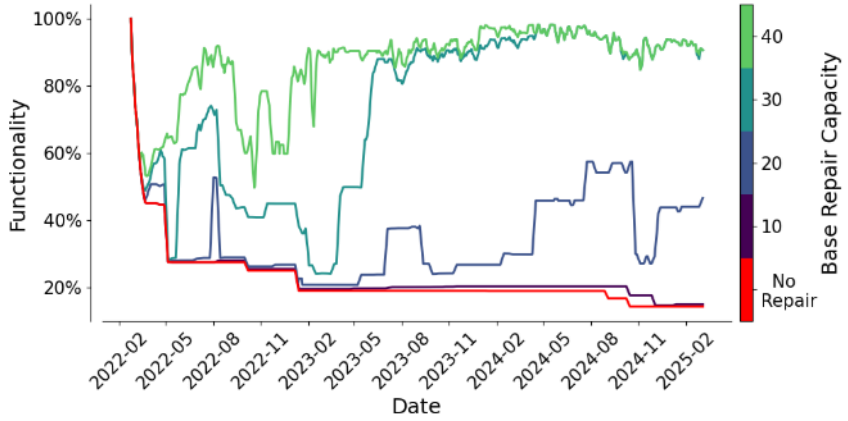


Blue Regions: Accessible Regions
Red Regions : Inaccessible Regions

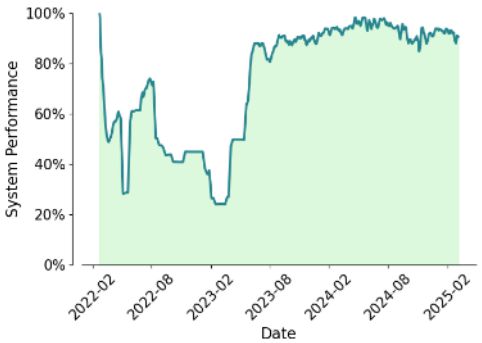
e.g. access to emergency services

Various performance metrics are measured at each time step to quantify the degradation and recovery of system functionality.

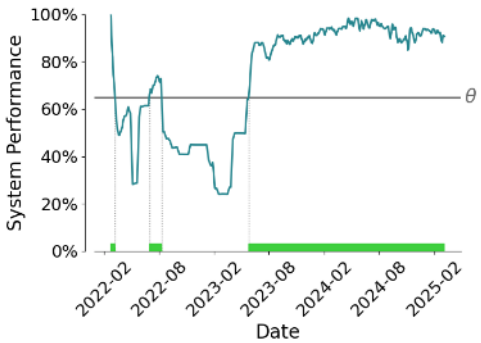
Resilience Curve



Resilience Quantification



Resilience Score (R)
(Area under the curve)



Operational Availability (A_θ)
(Days above threshold)

New York City Under Crisis: Which regions *lose* emergency services?

Transportation Research Interdisciplinary Perspectives
Volume 25, May 2024, 101111

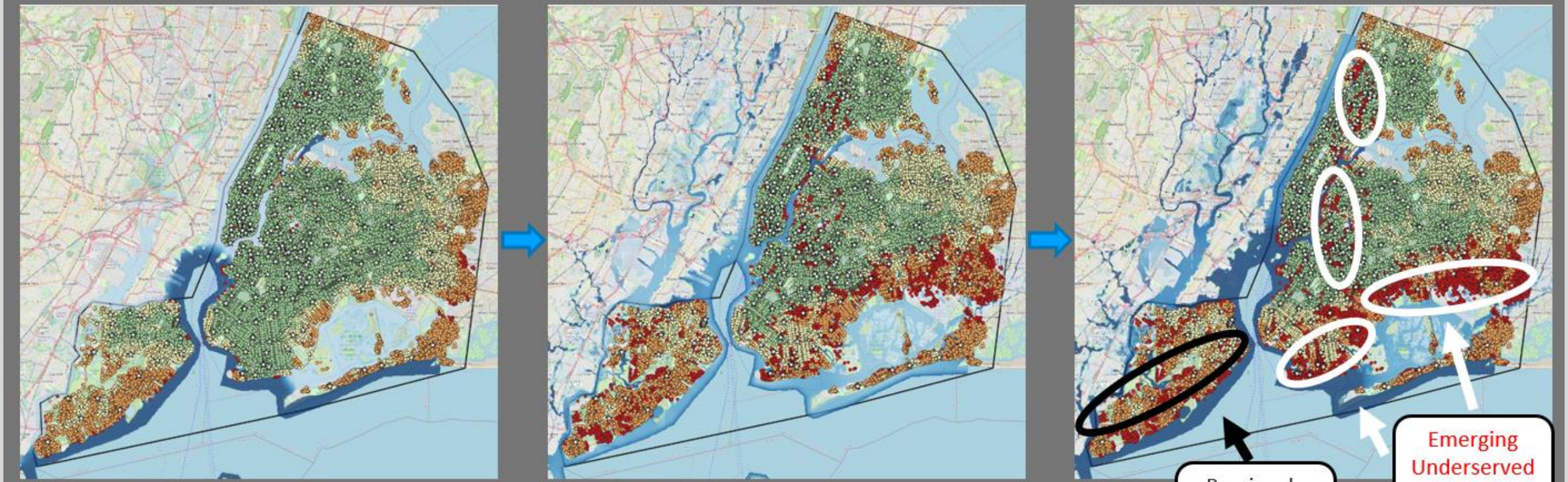
Access to Emergency Services: A New York City Case Study

Sukhwan Chung [a], Madison Smith [a], Andrew Jin [a], Luke Hogewood [a], Maksim Kitsak [b], Jeffrey Cegan [a], Igor Linkov [b]

Beginning of the Flood

Intermediary Flood

Peak of the Flood



Green: Maximally Accessible
Yellow: Medium Accessible
Orange: Minimally Accessible
Red: No Access

ERDC ENVIRONMENTAL LABORATORY

Transportation Research Interdisciplinary Perspectives 32 (2025) 101507

Contents lists available at ScienceDirect

Transportation Research Interdisciplinary Perspectives

journal homepage: www.sciencedirect.com/journal/transportation-research-interdisciplinary-perspectives

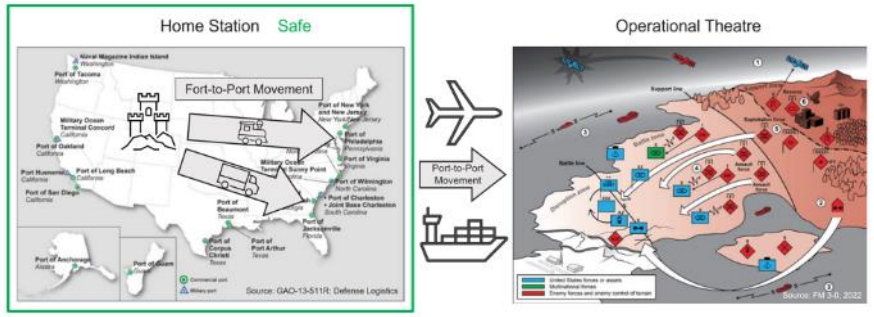
US Strategic highways and railways

Contested logistics: Resilience of strategic highways and railways

Sukhwan Chung [a], Daniel Sardak [a], Maksim Kitsak [b], Andrew Jin [a], Igor Linkov [a,*]

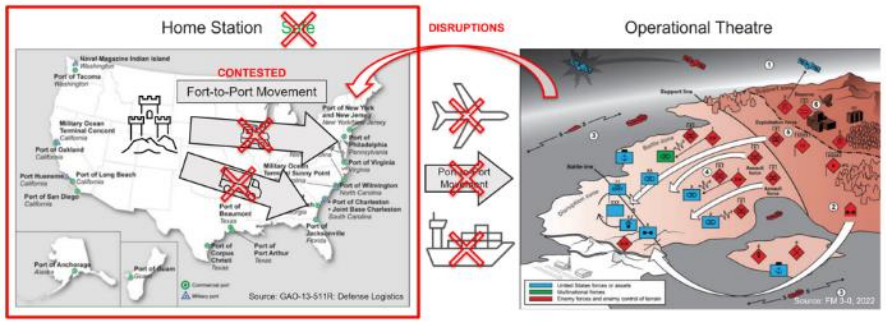
What vulnerabilities exist in the fort-to-port stage of U.S. power projection?

Predictable & Secure

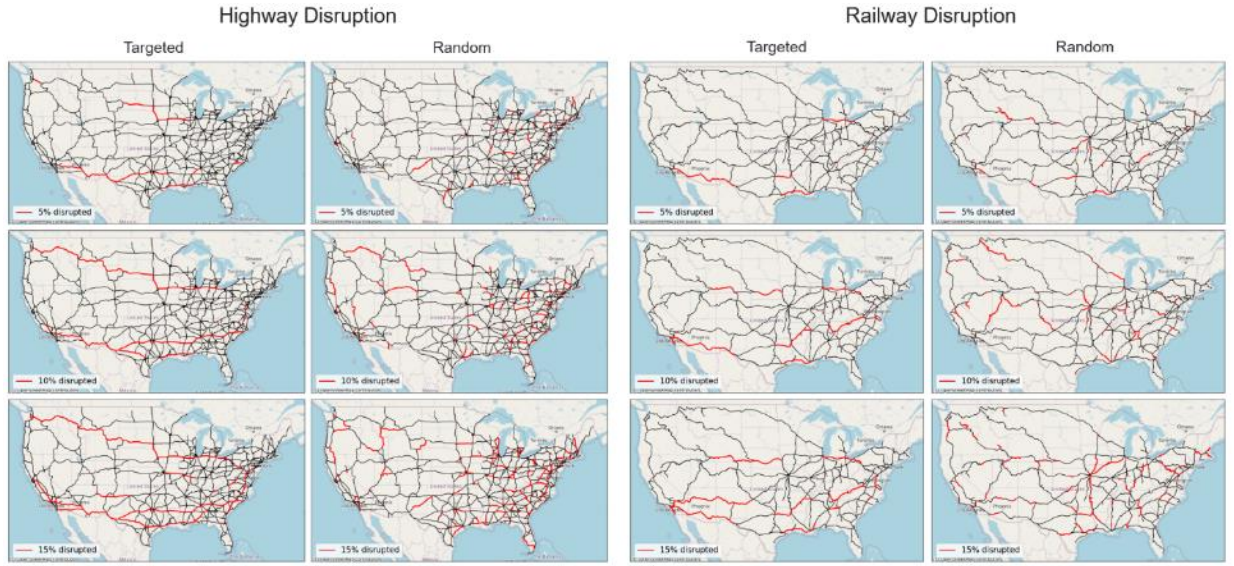


Previously, uncontested and predictable deployments from home stations to theaters.

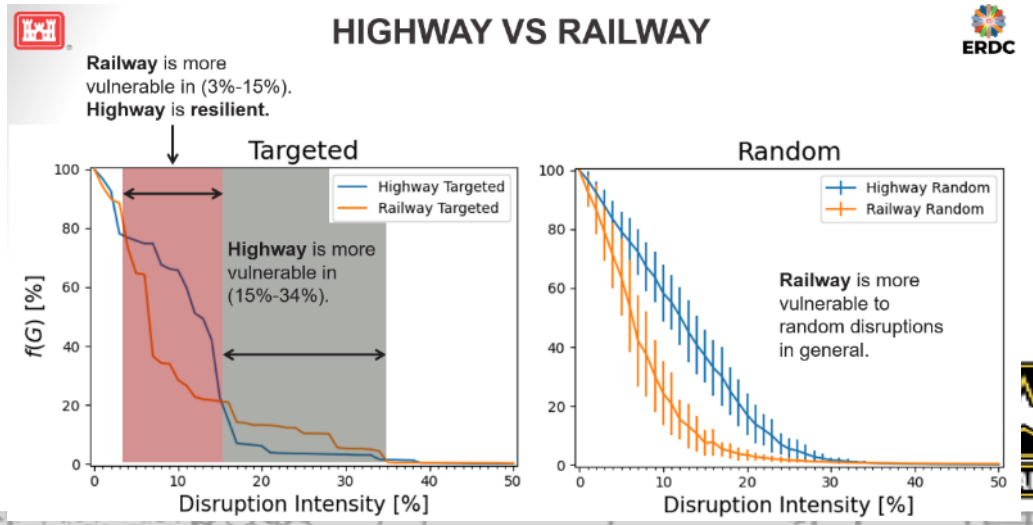
Unreliable & Contested



Adversaries can now target supply routes, ports, and infrastructures deep within friendly territory.



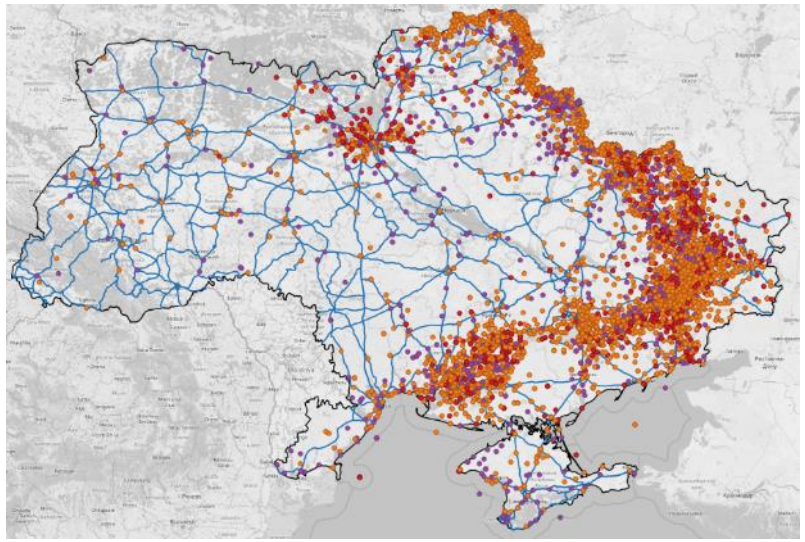
- **Targeted** Disruption: Remove the roads/rails with the *highest centrality*.
- **Random** Disruption: Remove the roads/rails at *uniformly random*.



Russia Is consistently Disrupting Ukraine's Road Network

Endless cycle of disruption and repair of roads are occurring across Ukraine.

Disruptions across Ukraine



DISRUPTION

REPAIR

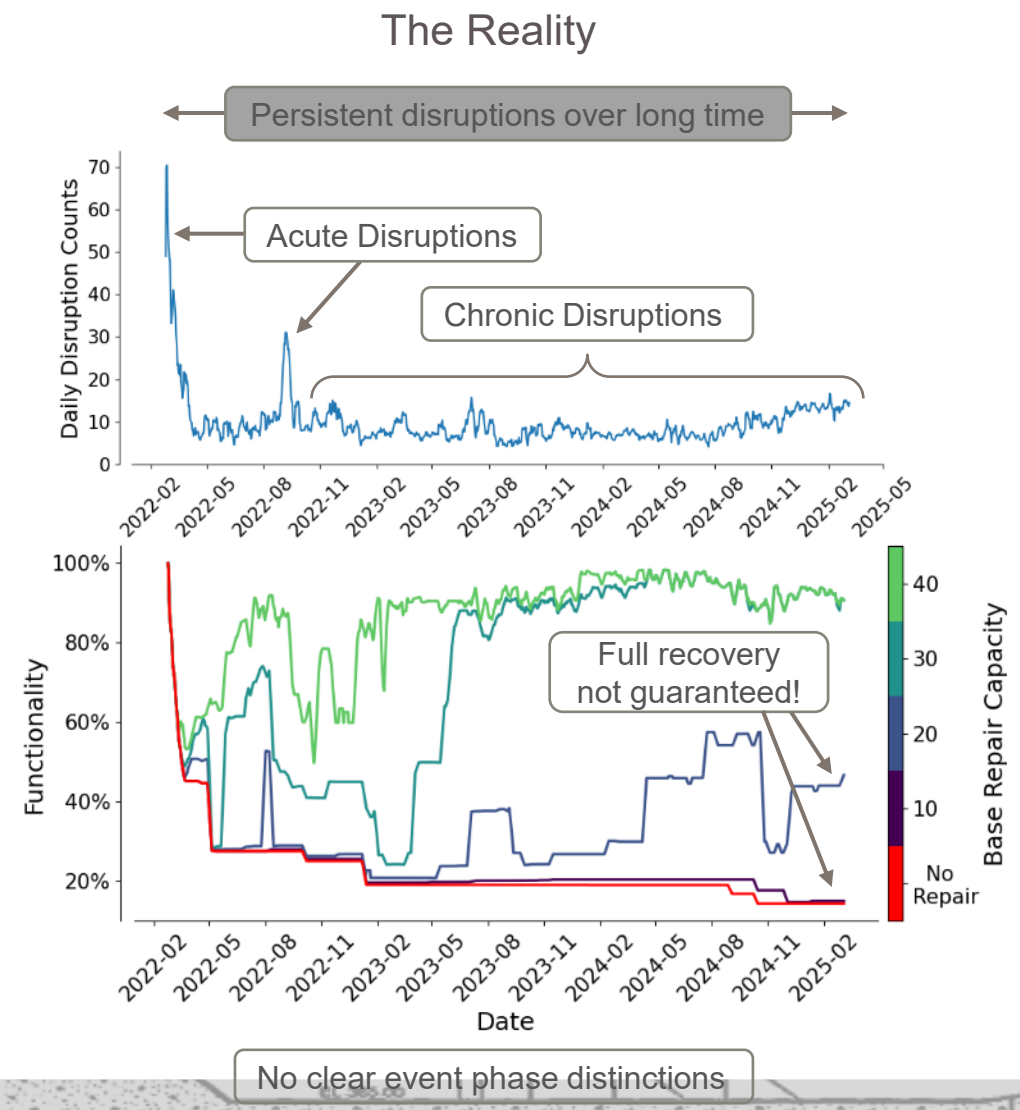
https://www.reuters.com/graphics/UKRAINE-CRISIS/zdpxokkxavm/
https://www.nytimes.com/2022/11/07/magazine/ukraine-rebuild-[illegible].html
https://www.theguardian.com/world/2023/apr/01/ukraine-rebuild-bucha-prompts-corruption-reconstruction

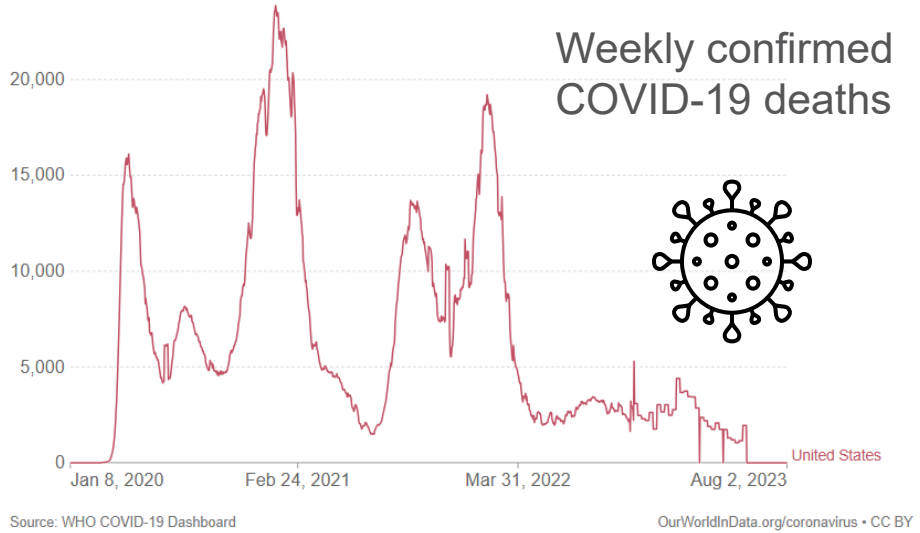
US Army Corps of Engineers

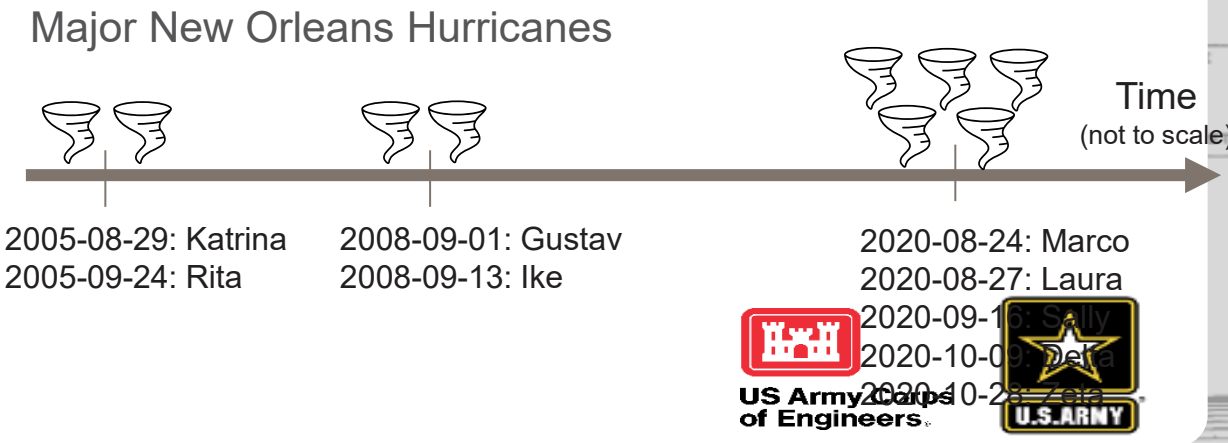
U.S.ARMY

Traditional resilience model fails against chronic disruption

In reality, disruptions imposes both acute surges and chronic degradation, preventing the system from fully recovering.



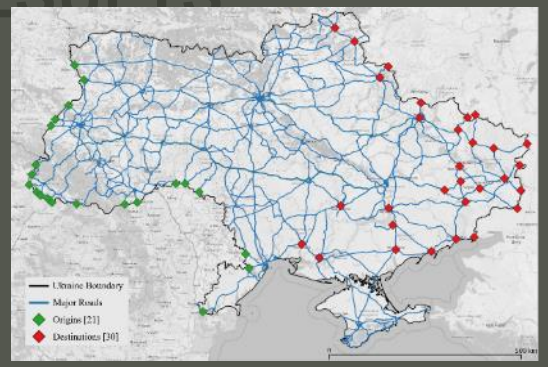




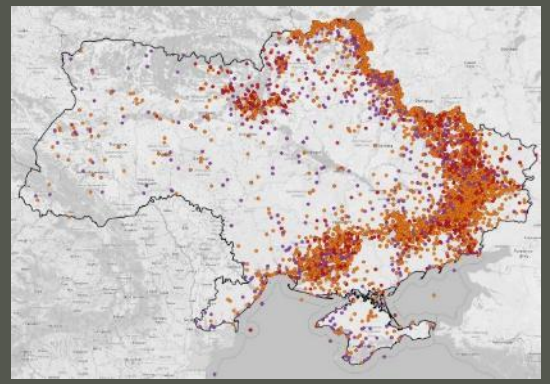
RESULTS

STEP 1: GIS Analysis

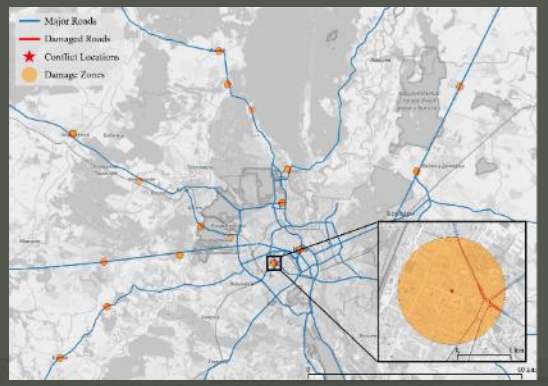
Logistics Network Modeling



Disruption Analysis

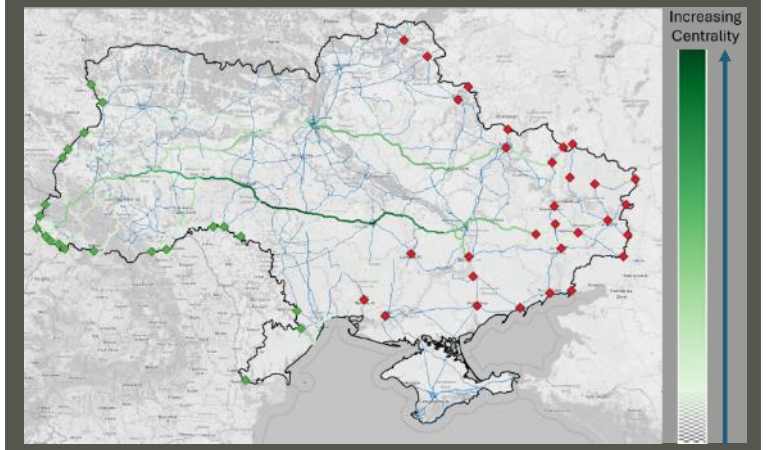


Impact Calculation

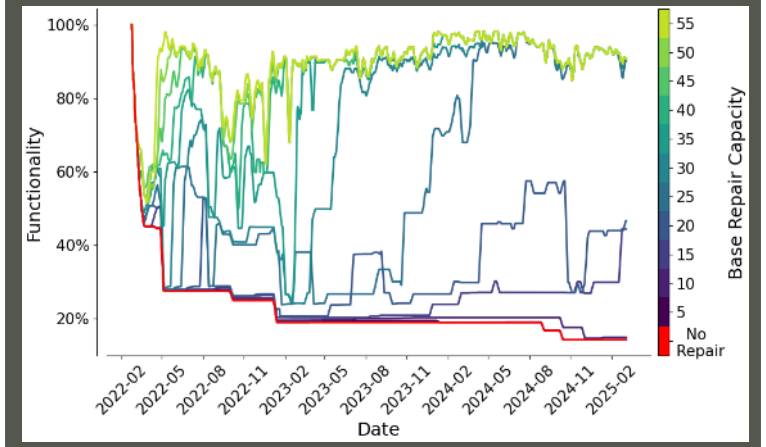


STEP 2: Simulation

Critical Route Identification

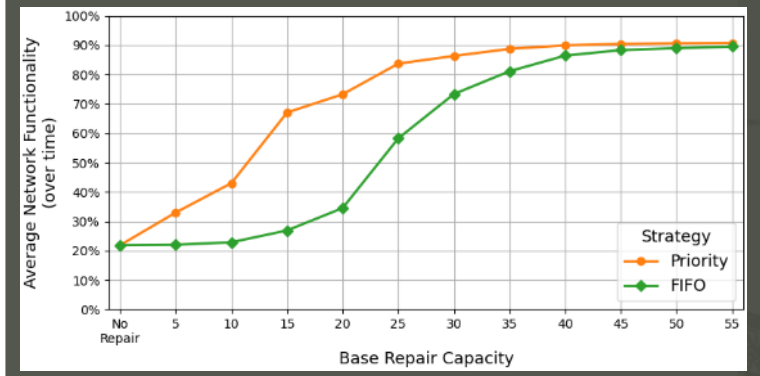


Recovery Measurement

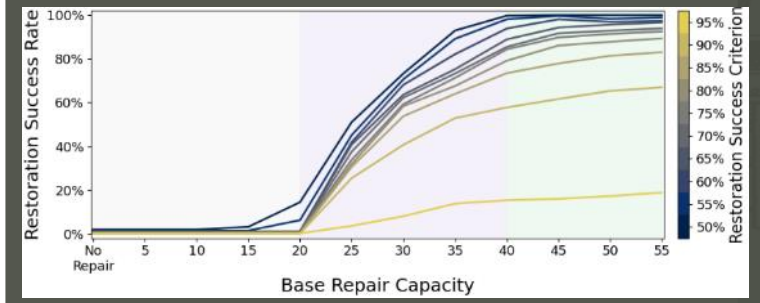


STEP 3: Resilience Analysis

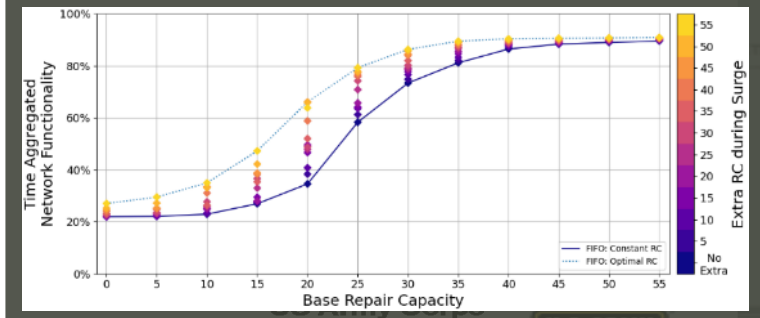
Restoration Strategy Comparison



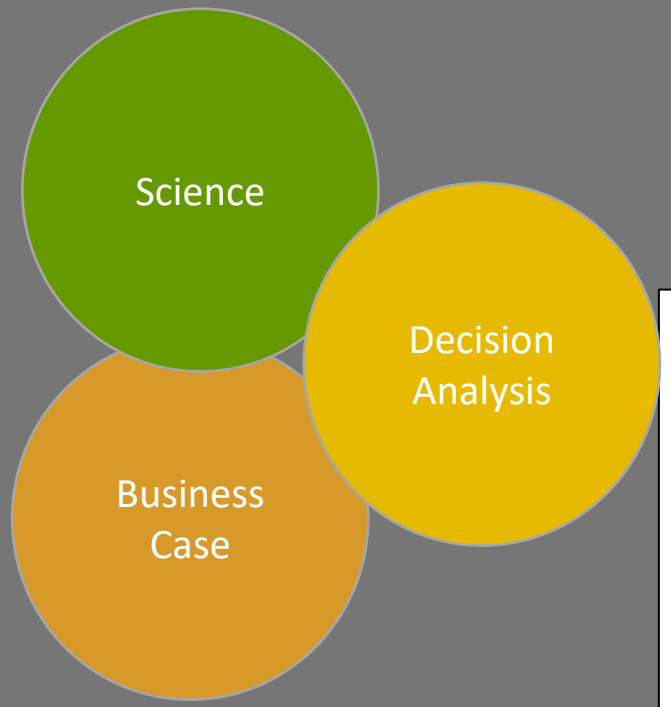
Minimum Capacity Identification



Surge Analysis



Business Case for Resilience



Transportation Network Model + Regional Economic Models, Inc.

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

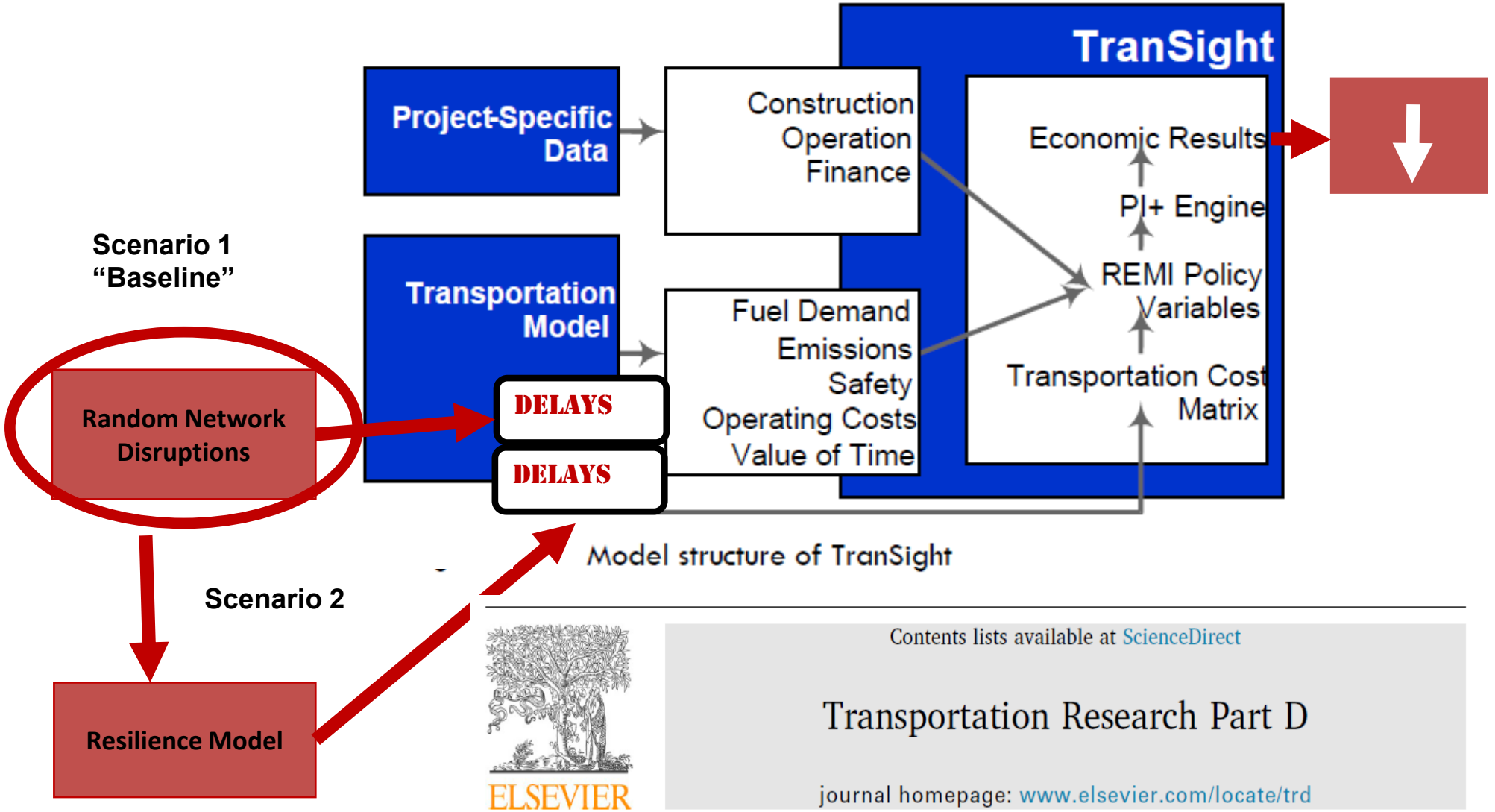
Lack of resilience in transportation networks: Economic implications

SCIENCE ADVANCES | RESEARCH ARTICLE

NETWORK SCIENCE

Resilience and efficiency in transportation networks

Alexander A. Ganin,[1,2] Maksim Kitsak,[3] Dayton Marchese,[2] Jeffrey M. Keisler,[4] Thomas Seager,[5] Igor Linkov[2]*



Model structure of TranSight

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

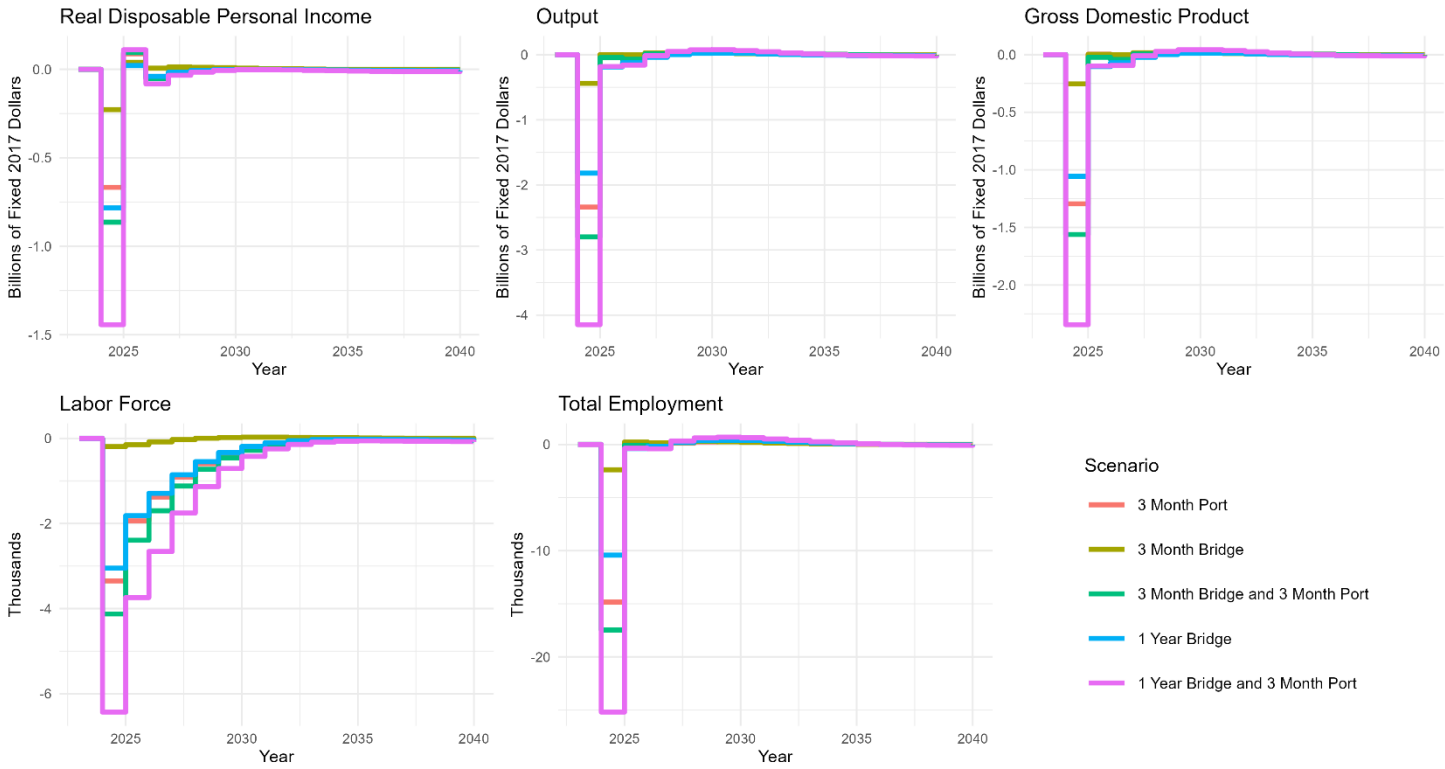
Lack of resilience in transportation networks: Economic implications

The Key bridge collapse

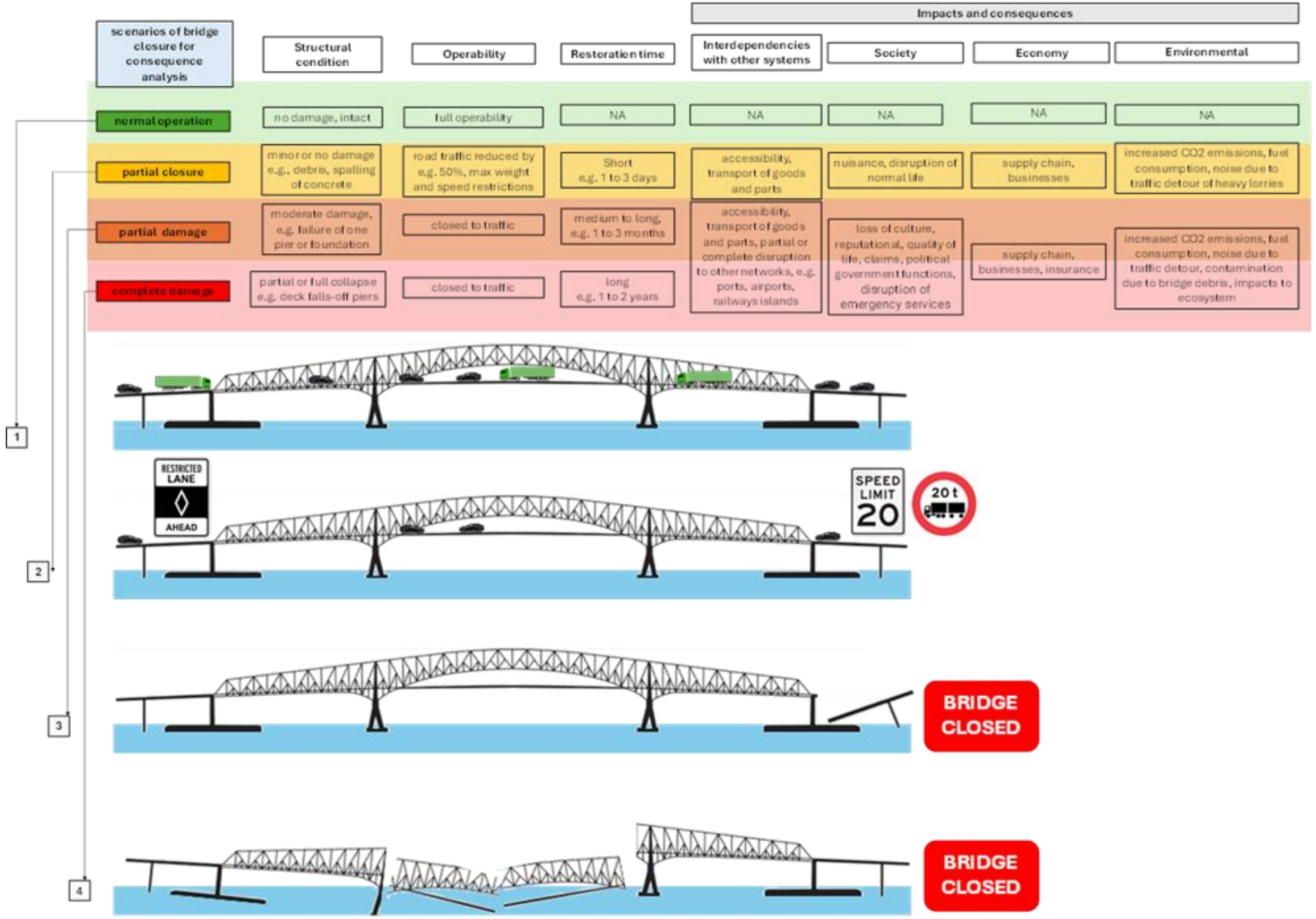
- A case study in a cascading failure with system-wide ripple effects
- Debris from bridge blocked off access to the Port of Baltimore
- Estimated $15 million USD lost **per day** for 3 months due to port closure
- As of September, port is still not fully operational
- Ongoing impacts to workers at the Port of Baltimore

Results: Economic impacts

- Net total of 2,381 jobs lost due to bridge collapse alone, vs. 17,225 for combined scenario
- Bridge closure alone resulted in $234 million USD loss to GDP, compared to $1.561 billion USD in combined bridge and port closure
- Disparities highlight how critical it is to consider potential cascading failures

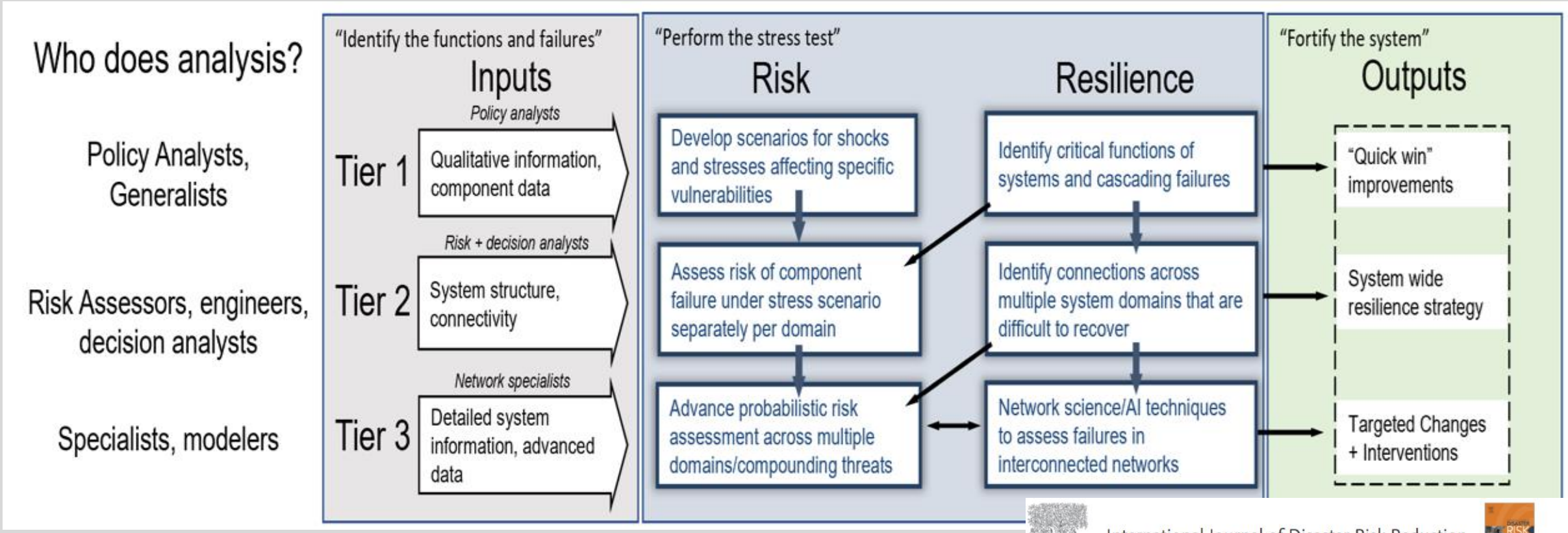


- Bridge design must evolve beyond probability of failure
- Resilience of region to compound failures must be considered
- Resilience-based design requires collaboration between engineers, local authorities, and policy makers



Integrated Risk/Resilience Stress Testing

How Do We Increase Resilience In Complex, Interconnected Infrastructure?



Three-Tiered Approach:

Tier 1: Define and identify more important critical functions & risks

Tier 2: Refine with interconnections, and define KPI

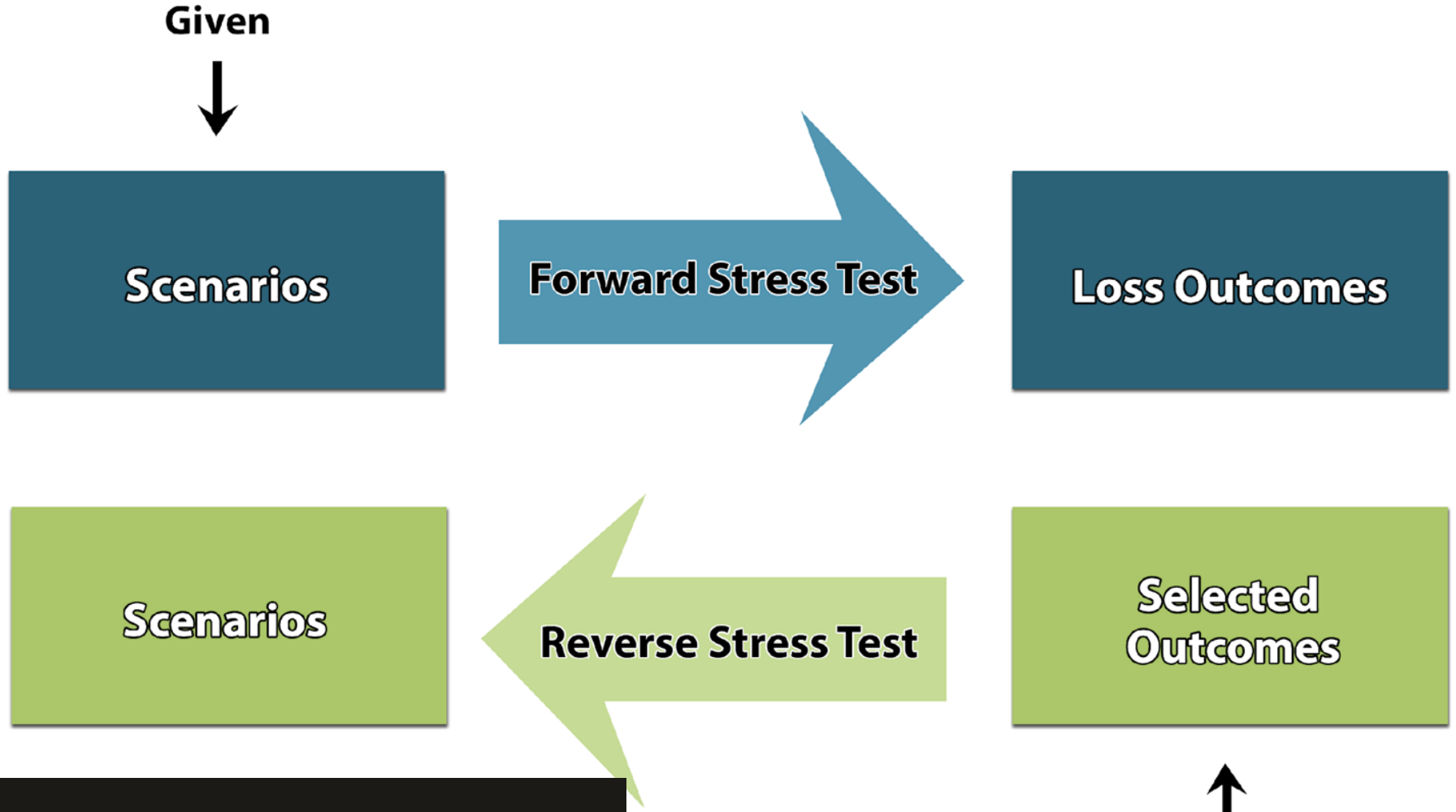
Tier 3: Asset-level data-driven analysis


ELSEVIER
International Journal of Disaster Risk Reduction
Volume 82, November 2022, 103323

Resilience stress testing for critical infrastructure

Igor Linkov [a b], Benjamin D. Trump [a c], Joshua Trump [d], Gianluca Pescaroli [e], William Hynes [f], Aleksandrina Mavrodieva [g h], Abhilash Panda [h i]

Reversed Stress Testing



arXiv

Physics > Data Analysis, Statistics and Probability

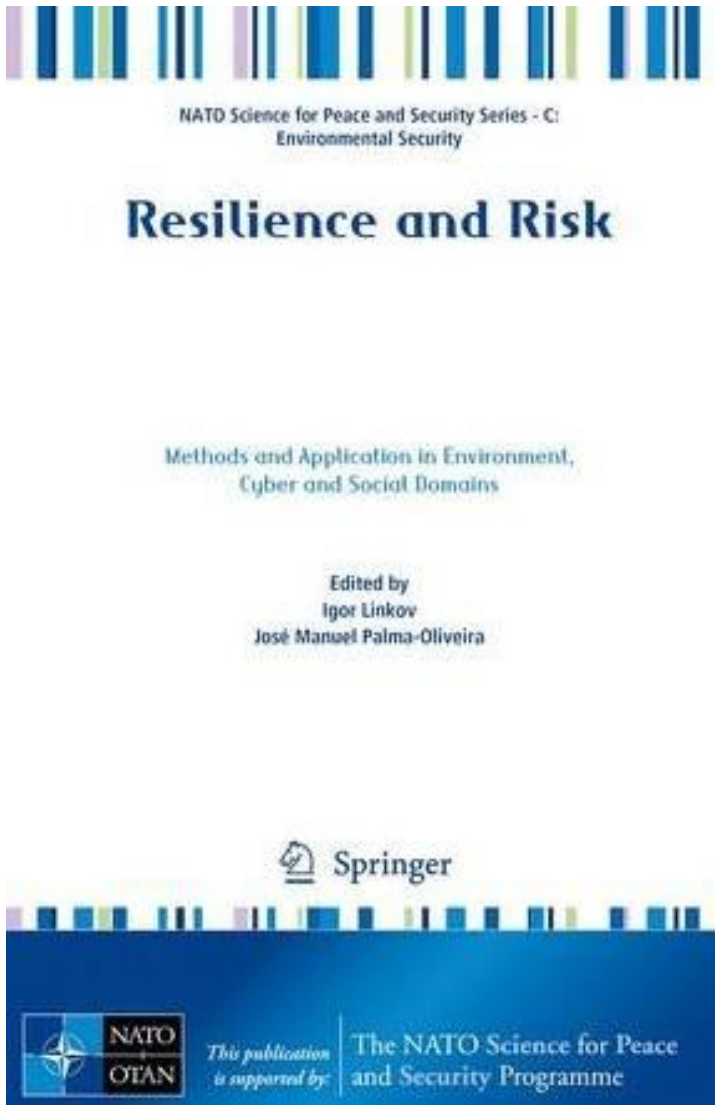
[Submitted on 10 Nov 2025 (v1), last revised 26 Nov 2025 (this version, v2)]

Reverse Stress Testing for Supply Chain Resilience

Madison Smith, Michael Gaiewski, Sam Dulin, Laurel Williams, Jeffrey Keisler, Andrew Jin, Igor Linkov

US Army Corps of Engineers

U.S.ARMY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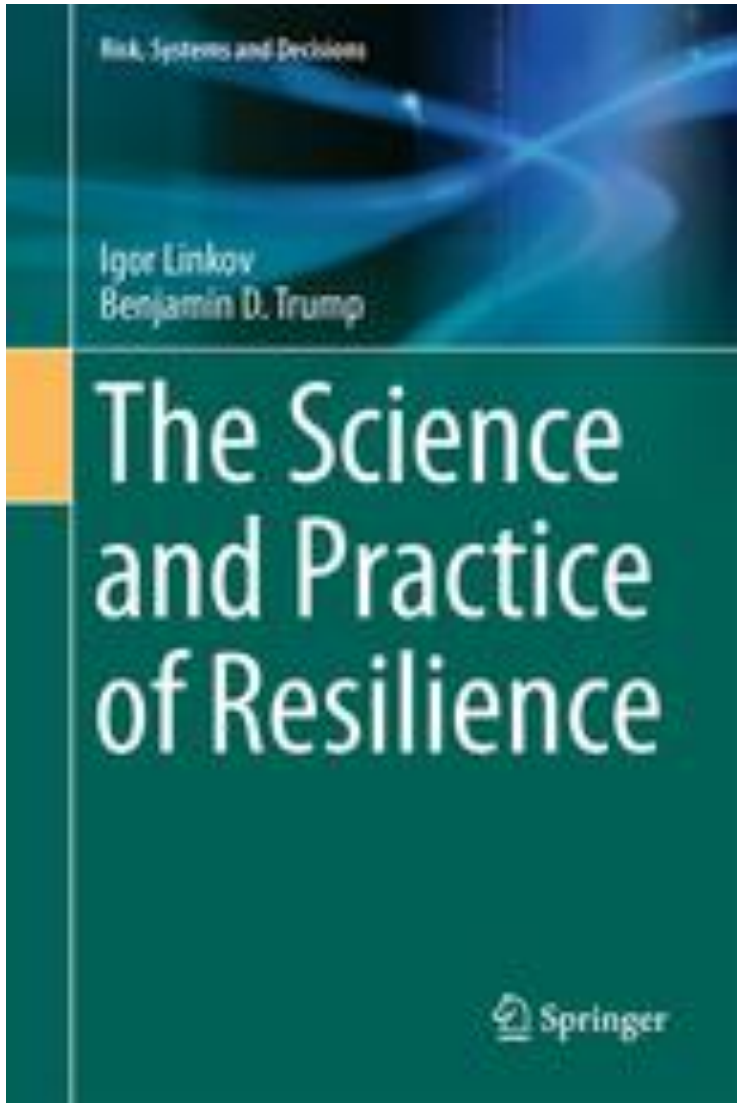
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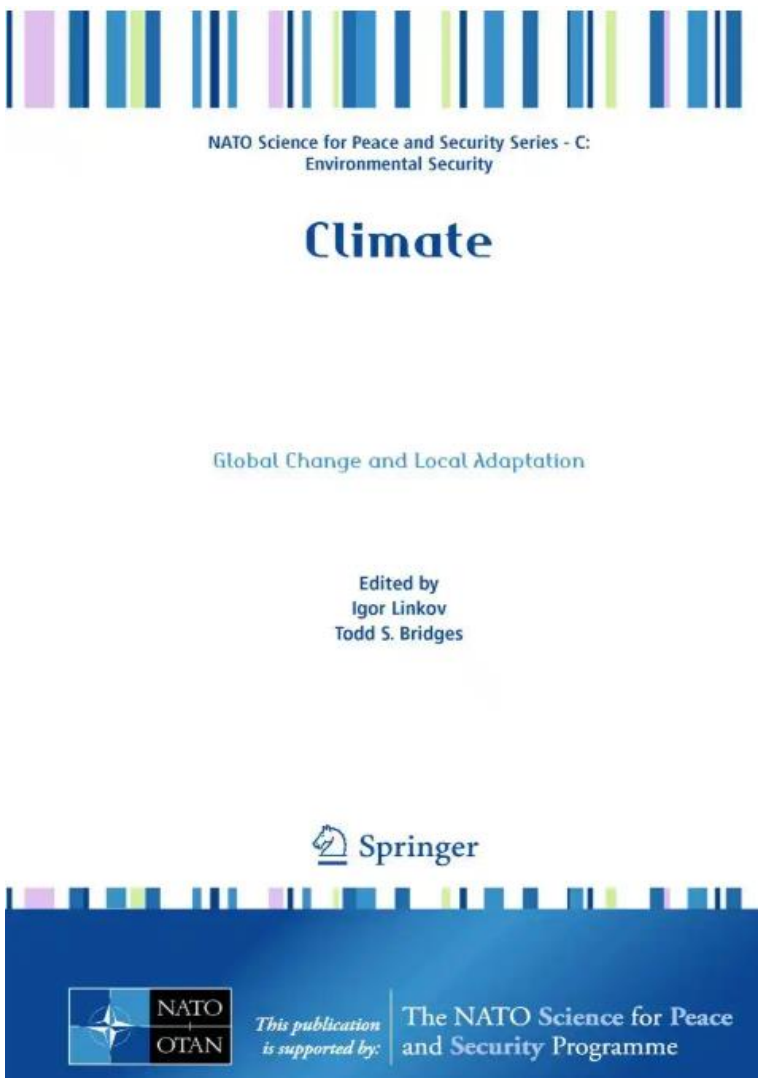
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INTERNATIONAL ASSOCIATION FOR RESILIENCE ANALYSIS(IARA)

Building international standards for resilience analysis, training, and practice

WHO ARE WE?

The International Association for Resilience Analysis (IARA) is a developing global professional body dedicated to advancing rigorous, evidence-based approaches to resilience across many different disciplines.

Resilience remains inconsistently defined and poorly operationalized. Without shared frameworks and internationally acceptable standards, resilience efforts continue becoming fragmented, difficult to evaluate, and challenging to translate into effective policy or practice.

MISSION STATEMENT

IARA's mission is to strengthen resilience in practice by:

- Developing shared conceptual and methodological foundations for resilience analysis
- Advancing interdisciplinary collaboration across sectors and systems
- Establishing professional training and certification pathways
- Supporting evidence-based resilience policy and decision-making worldwide

Please Contact: Dr. Igor Linkov
Igor.Linkov@usace.army.mil.

CORE FUNCTIONS

Conceptual Foundations

- Develop shared frameworks and methodological guidance for resilience assessment.

Research and Focus Groups

- Convene experts to address emerging resilience challenges including:
  - Cascading threats
  - AI integration
  - Infrastructure resilience
  - Workforce adaptation
- Provide a journal for publishing academic papers

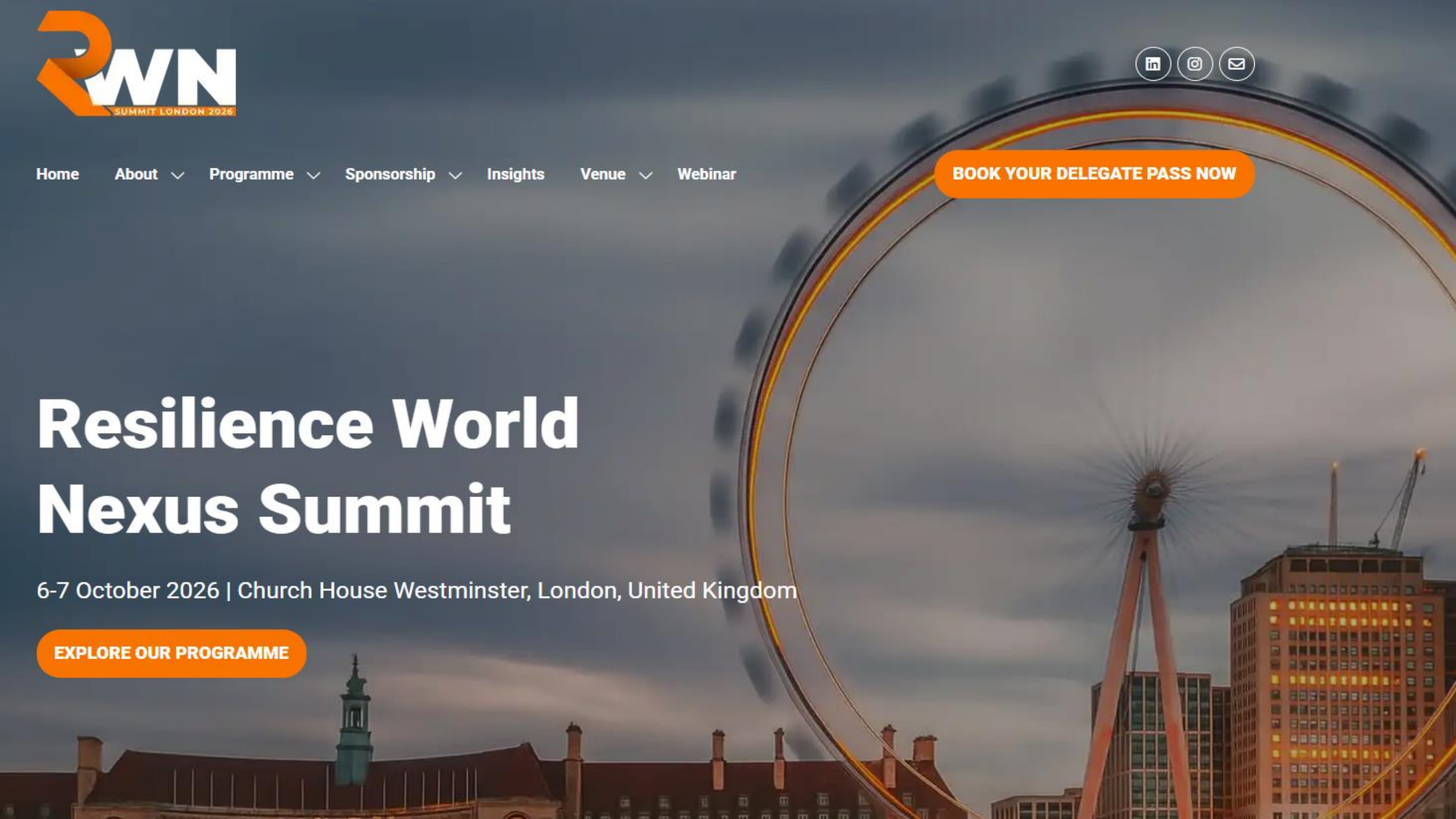
Training and Certifications

- Design competency-based education and future certification pathways for resilience professionals.

Global Throughput

- Host annual meetings to align research, policy, and practice across sectors.

INTERESTED?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