The Value of Transportation Resilience:
Economic Impacts of Disruptions in Major U.S. Cities

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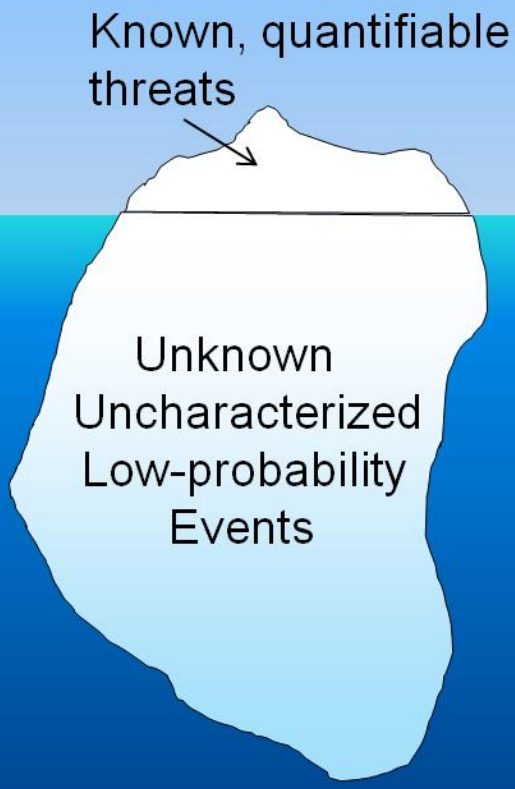
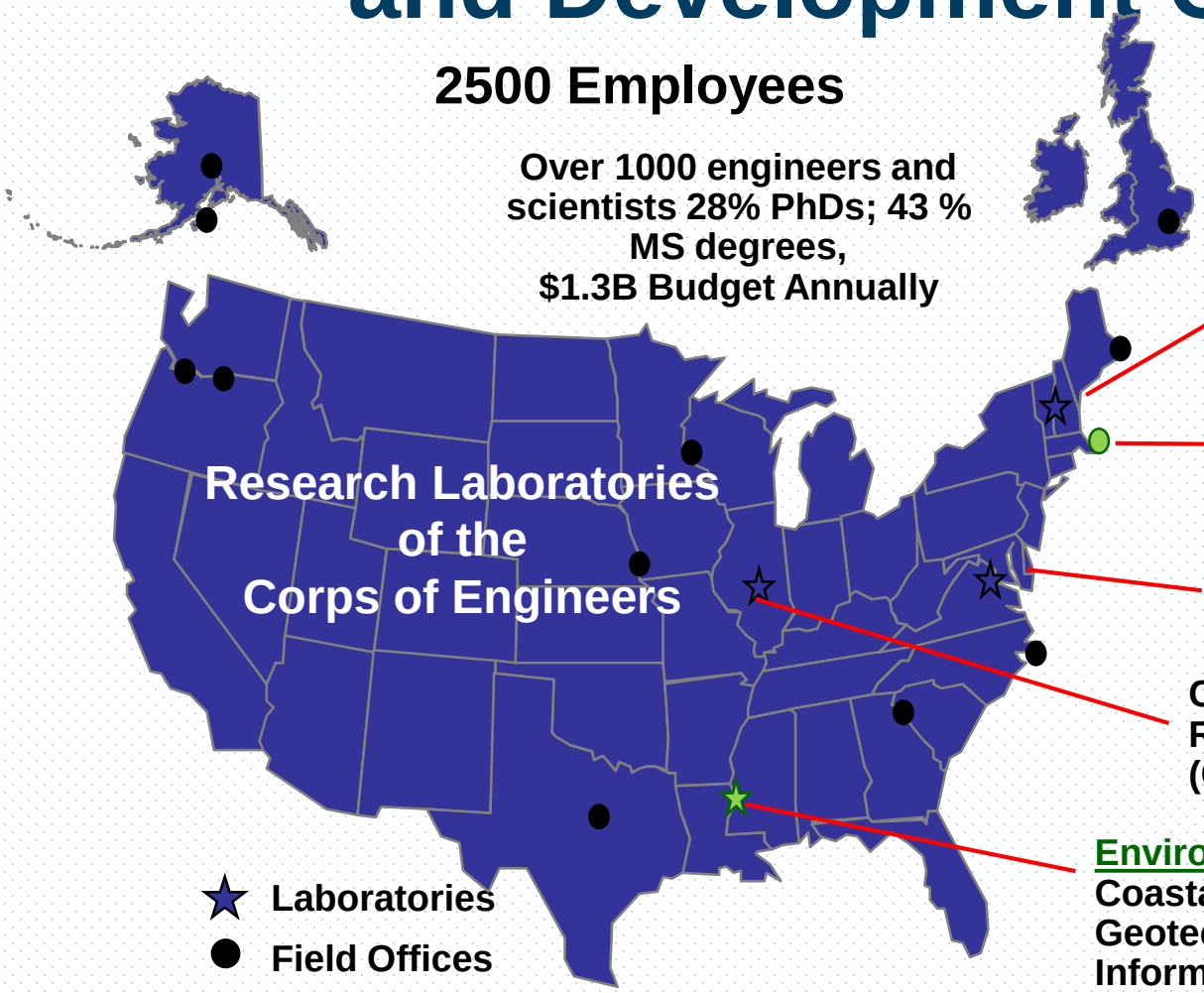


US Army Engineer Research and Development Center

2500 Employees

Over 1000 engineers and scientists 28% PhDs; 43 % MS degrees,
$1.3B Budget Annually



Cold Regions Research Engineering Laboratory (Hanover, NH)

Risk and Decision Science Team Boston, MA)

Topographic Engineering Center (Alexandria, VA)

Construction Engineering Research Laboratory (Champaign, IL)

Environmental Laboratory
Coastal & Hydraulics Laboratory
Geotechnical & Structures Laboratory
Information Technology Laboratory
Headquarters (Vicksburg, MS)

ERDC

Risk & Decision Science Team

- **Mission:** to improve decision-making and stakeholder engagement through application and development of risk and decision science techniques.

- **Execution:** through risk assessment, technology-supported stakeholder engagement, decision modeling, portfolio optimization, life cycle assessment, and software development.

- **Results:** help clients to describe relevant risks, identify and compare risk management alternatives, develop consensus among disparate stakeholder groups, and provide repeatable and transparent processes for future decisions.

Main Ideas

- Transportation is a complex and adaptive system and system analysis is necessary
- Resilience can be quantified using Metrics-based and Network Science tools
- Risk and Resilience has different economic impact and should be treated differently
- Economic Model should be connected with Resilience models to help in transportation planning

Calls for Resilience

The White House

Office of the Press Secretary

For Immediate Release October 31, 2013

Presidential Proclamation -- Critical Infrastructure Security and Resilience Month, 2013

CRITICAL INFRASTRUCTURE SECURITY AND RESILIENCE MONTH, 2013

BY THE PRESIDENT OF THE UNITED STATES OF AMERICA

A PROCLAMATION

Over the last few decades, our Nation has grown increasingly dependent on critical infrastructure, th
our national and economic security. America's critical infrastructure is complex and diverse, combini
both cyberspace and the physical world -- from power plants, bridges, and interstates to Federal bui
massive electrical grids that power our Nation. During Critical Infrastructure Security and Resilience
resolve to remain vigilant against foreign and domestic threats, and work together to further secure
systems, and networks.

"Resilience" means the ability to anticipate, prepare for, and ***adapt*** to changing conditions and ***withstand***, ***respond to***, and ***recover*** rapidly from disruptions.

The White House

Office of the Press Secretary

For Immediate Release May 11, 2017

Presidential Executive Order on Strengthening the Cybersecurity of Federal Networks and Critical Infrastructure

(vi) Effective immediately, it is the policy of the executive branch to build and maintain a modern, secure, and more **resilient executive branch IT architecture**.

EXECUTIVE ORDER

Risk -- “a situation involving exposure to danger [threat].”

Security -- “the state of being free from danger or threat.”

Resilience -- “the capacity to recover quickly from difficulties.”

Definitions by Oxford Dictionary

Don’t conflate risk and resilience

‘Risk’ and ‘resilience’ are fundamentally different concepts that are often conflated. Yet maintaining the distinction is a policy necessity. Applying a risk-based approach to a problem that requires a resilience-based solution, or vice versa, can lead to investment in systems that do not produce the changes that

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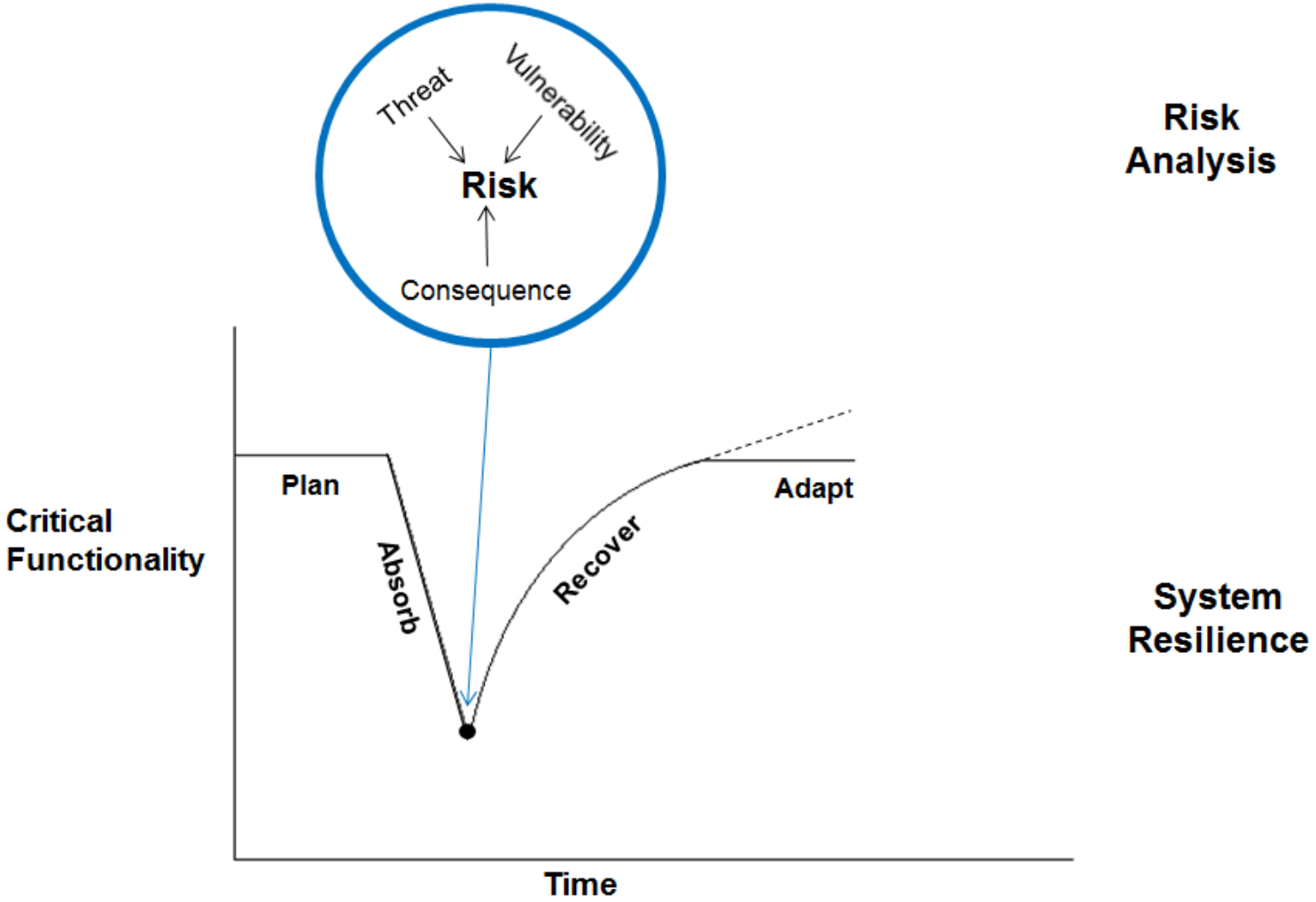
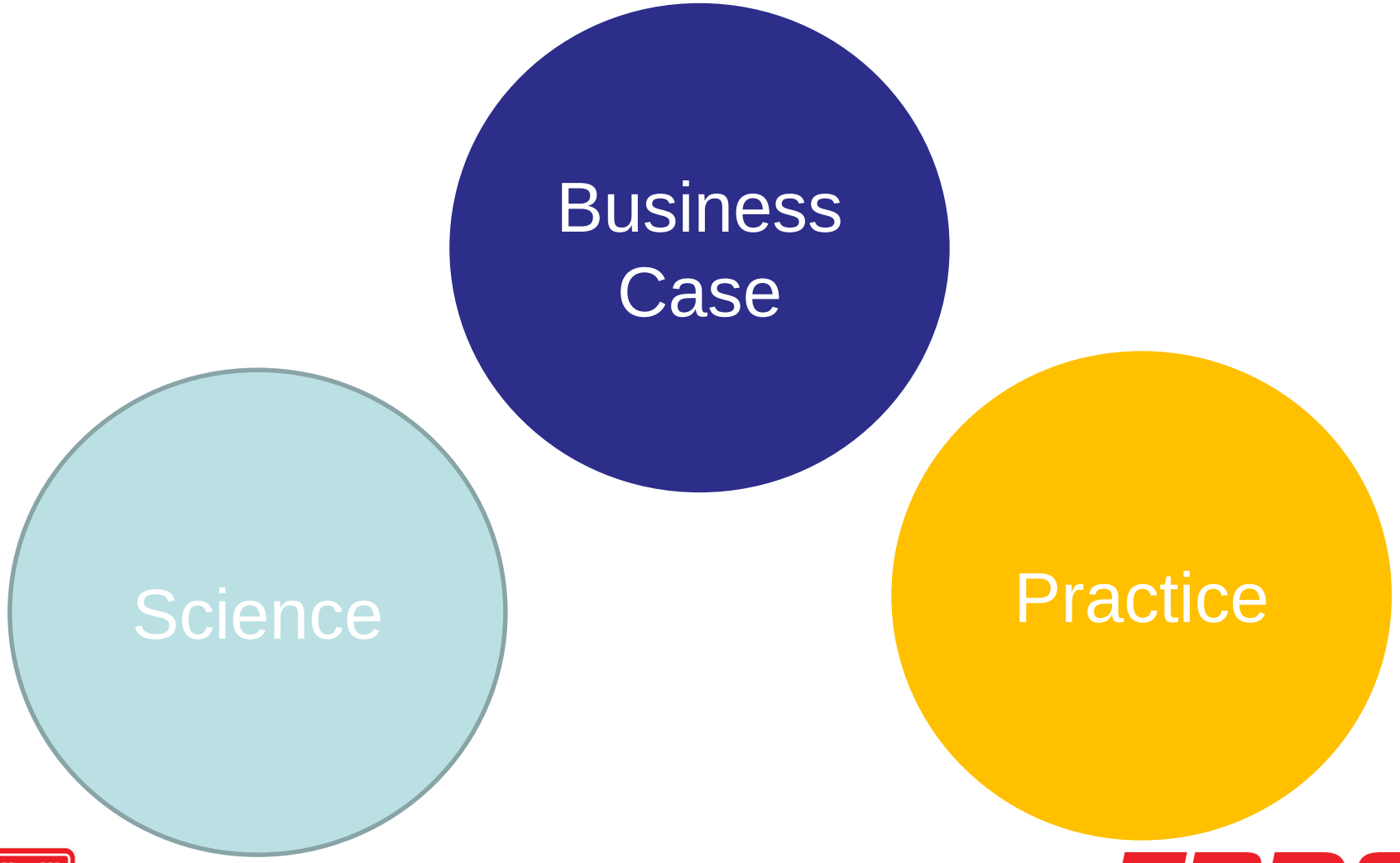
System Risk/Security and Resilience



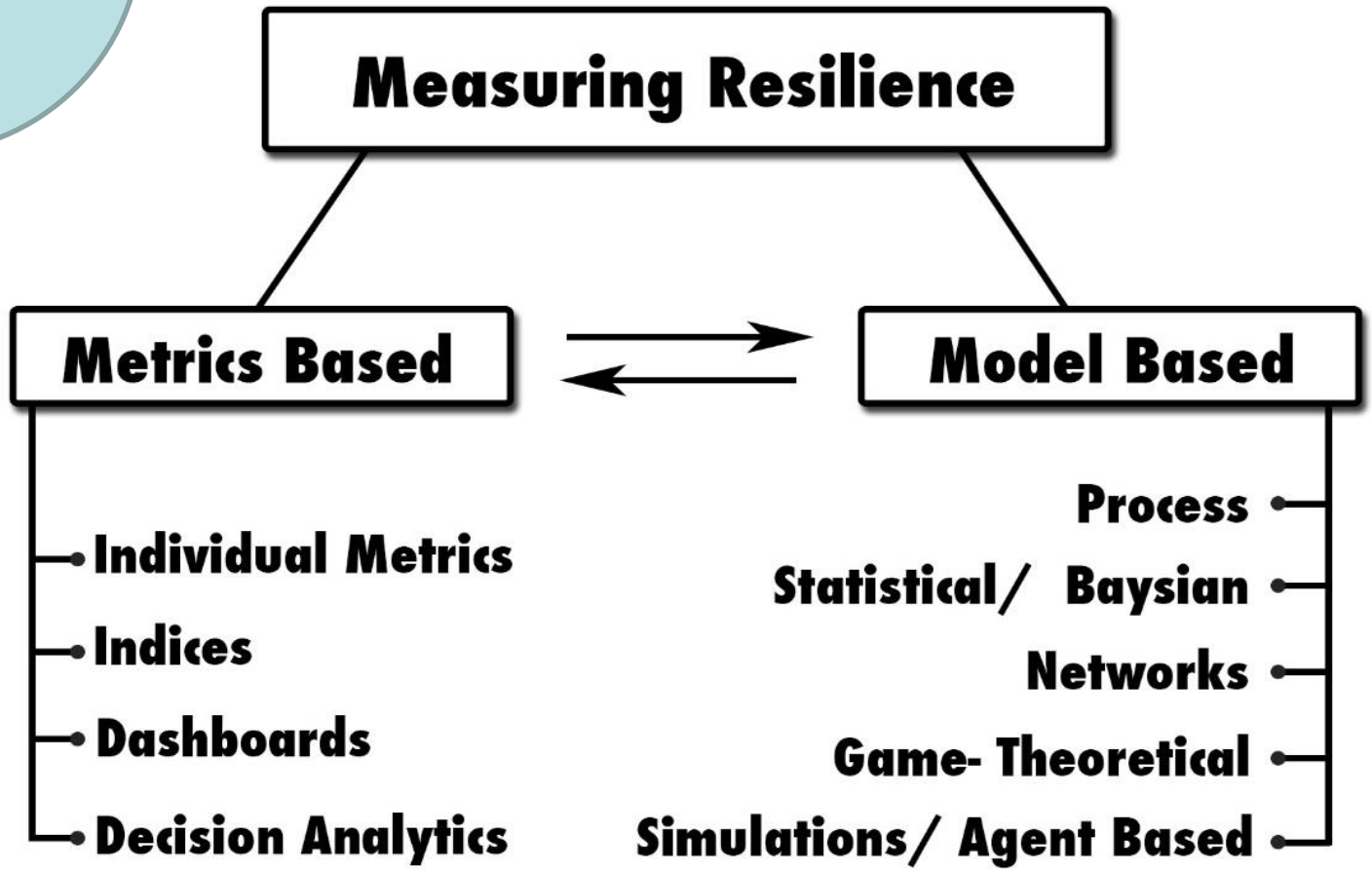
After Linkov et al, Nature Climate Change 2014

State of Practice



Science

Focus is on quantification



After Kott & Linkov book on Cyber Resilience of Systems and Networks (2019)

Science

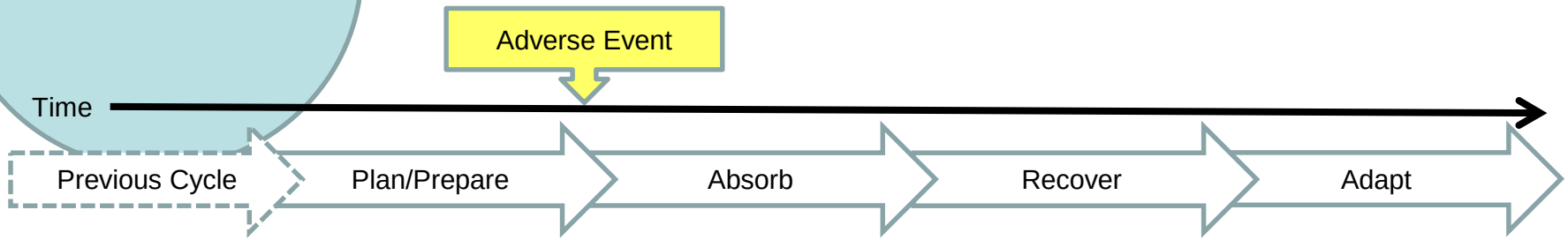
Issues with Using Metrics-Based Approaches to Measure Resilience

Lack of Causal Model
Changing environments and circumstances may change correlating factors
Changing business and management plans may change how previously causal factors interact
May not work in circumstances different than under those they were designed for

Not everything that counts can be counted, and not everything that can be counted counts.
Albert Einstein

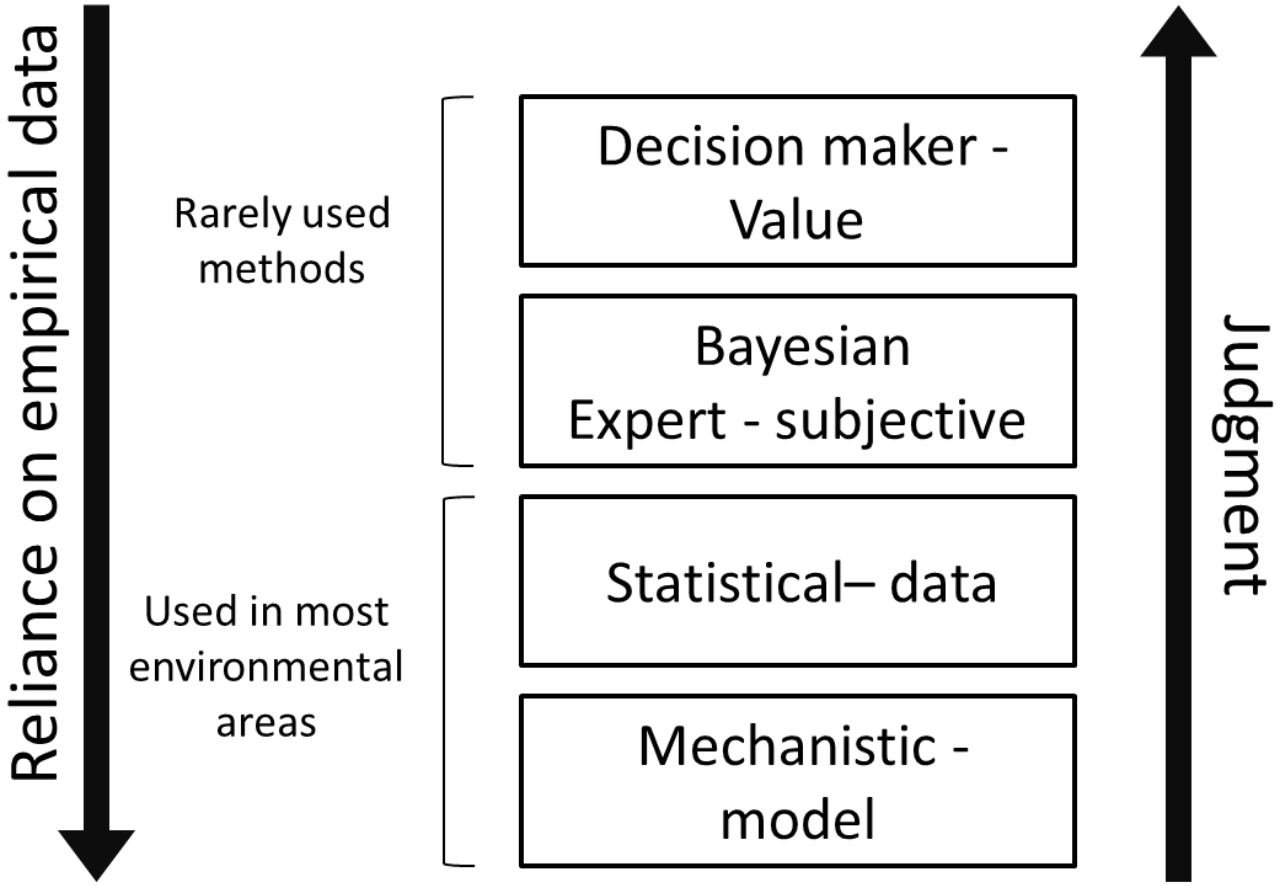
Issues From Whence Does Resilience Come?

Science



	Plan/Prepare	Absorb	Recover	Adapt
Physical	• State and capability of equipment and personnel, network structure	• Event recognition and system performance to maintain function	• System changes to recover previous functionality	• Changes to improve system resilience
Information	• Data preparation, presentation, analysis, and storage	• Real-time assessment of functionality, anticipation of cascading losses and event closure	• Data use to track recovery progress and anticipate recovery scenarios	• Creation and improvement of data storage and use protocols
Cognitive	• System design and operation decisions, with anticipation of adverse events	• Contingency protocols and proactive event management	• Recovery decision-making and communication	• Design of new system configurations, objectives, and decision criteria
Social	• Social network, social capital, institutional and cultural norms, and training	• Resourceful and accessible personnel and social institutions for event response	• Teamwork and knowledge sharing to enhance system recovery	• Addition of or changes to institutions, policies, training programs, and culture

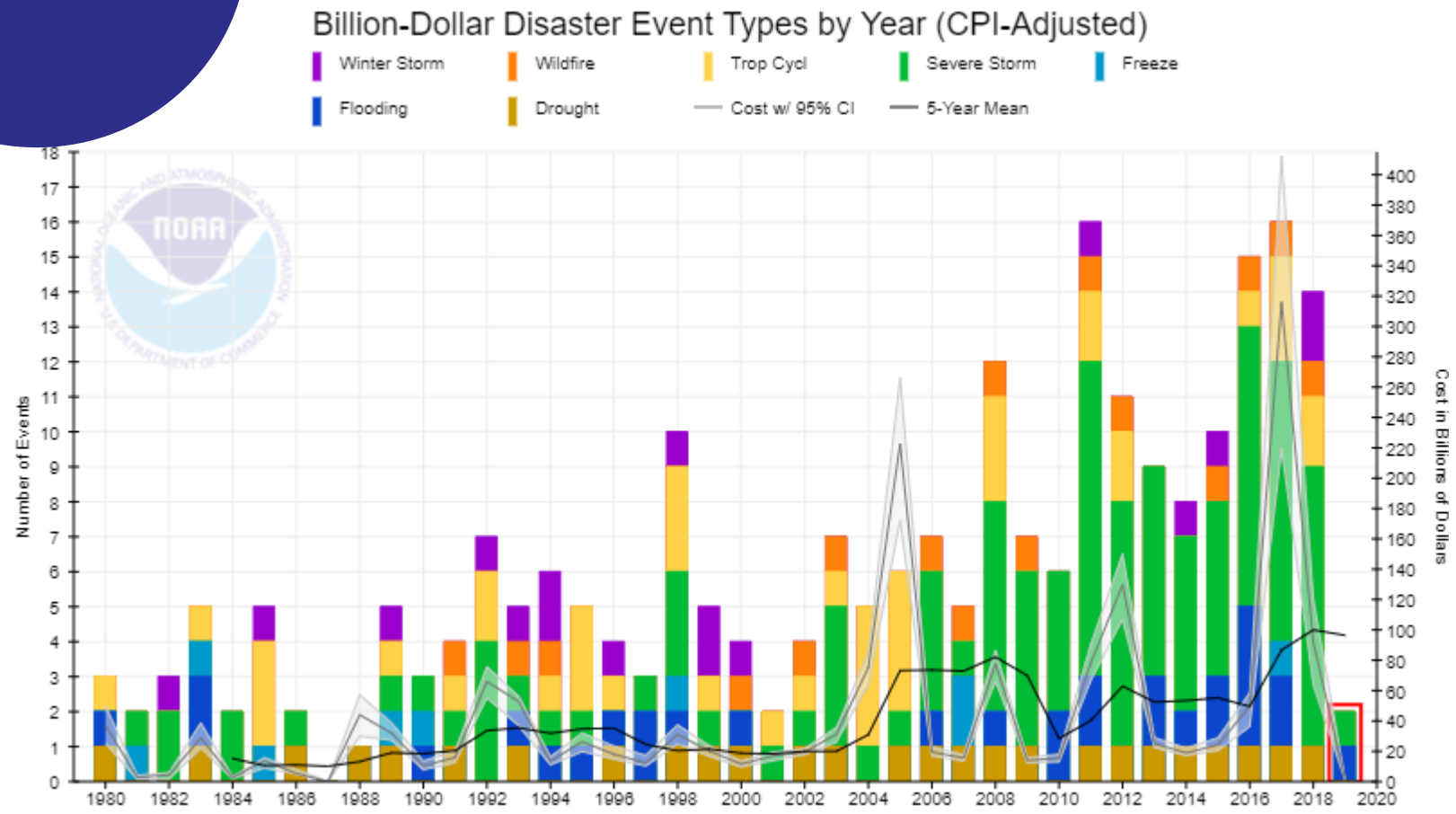
Ways to Model



From Keisler and Linkov, 2014

Business Case

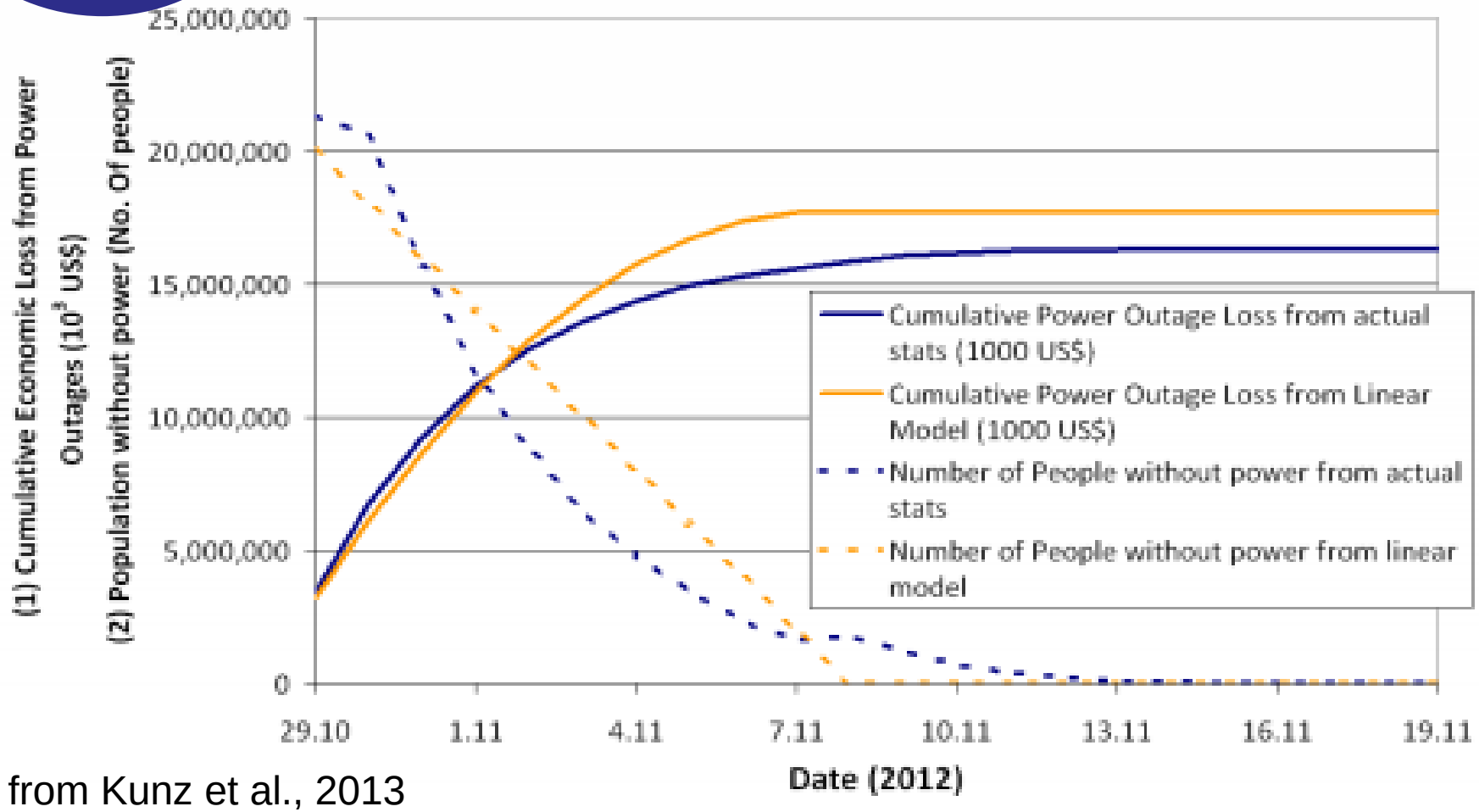
Reacting is More Expensive than Preventing



NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2019). https://www.ncdc.noaa.gov/billions/

Business Case

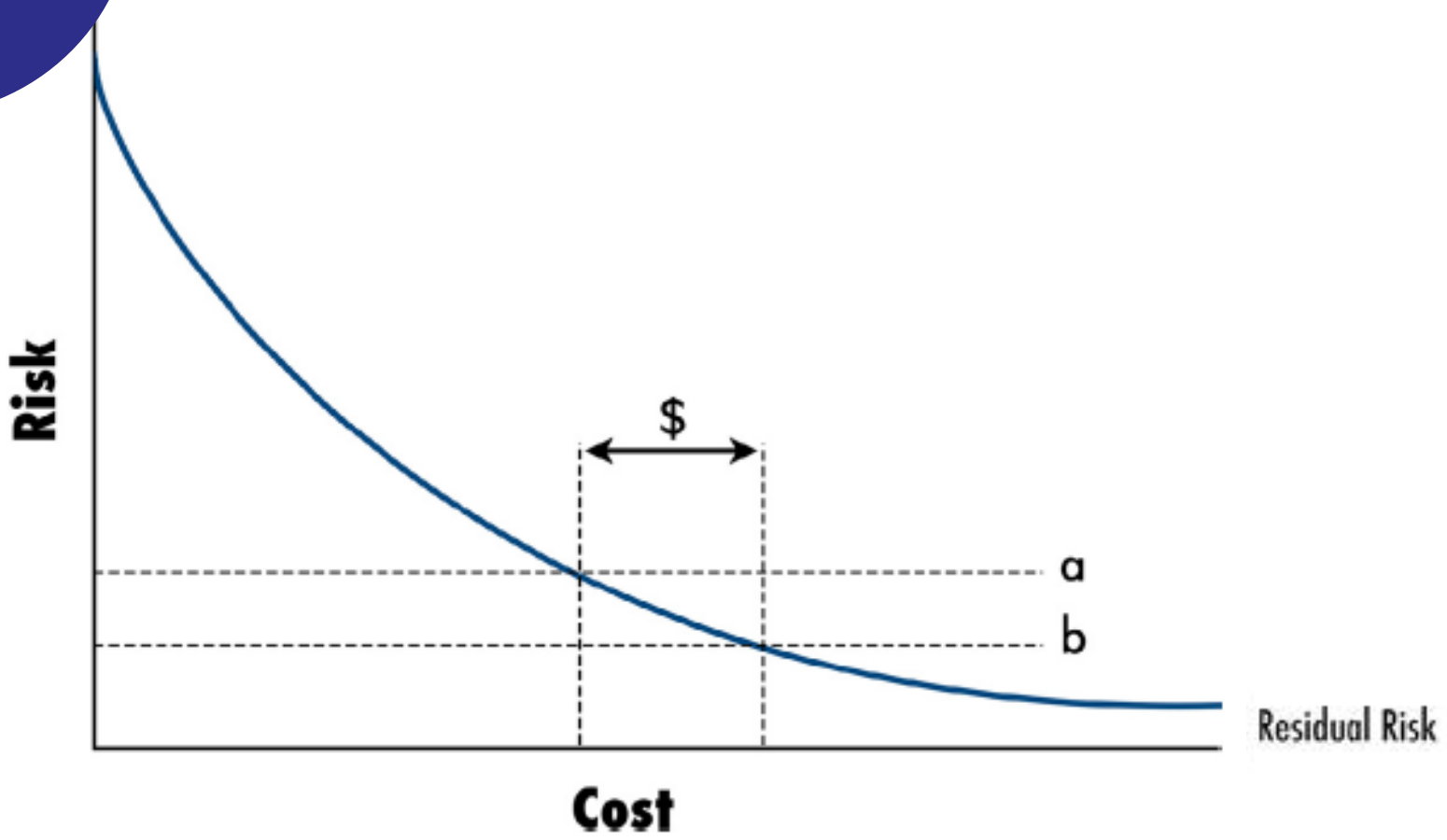
High Indirect Losses



from Kunz et al., 2013

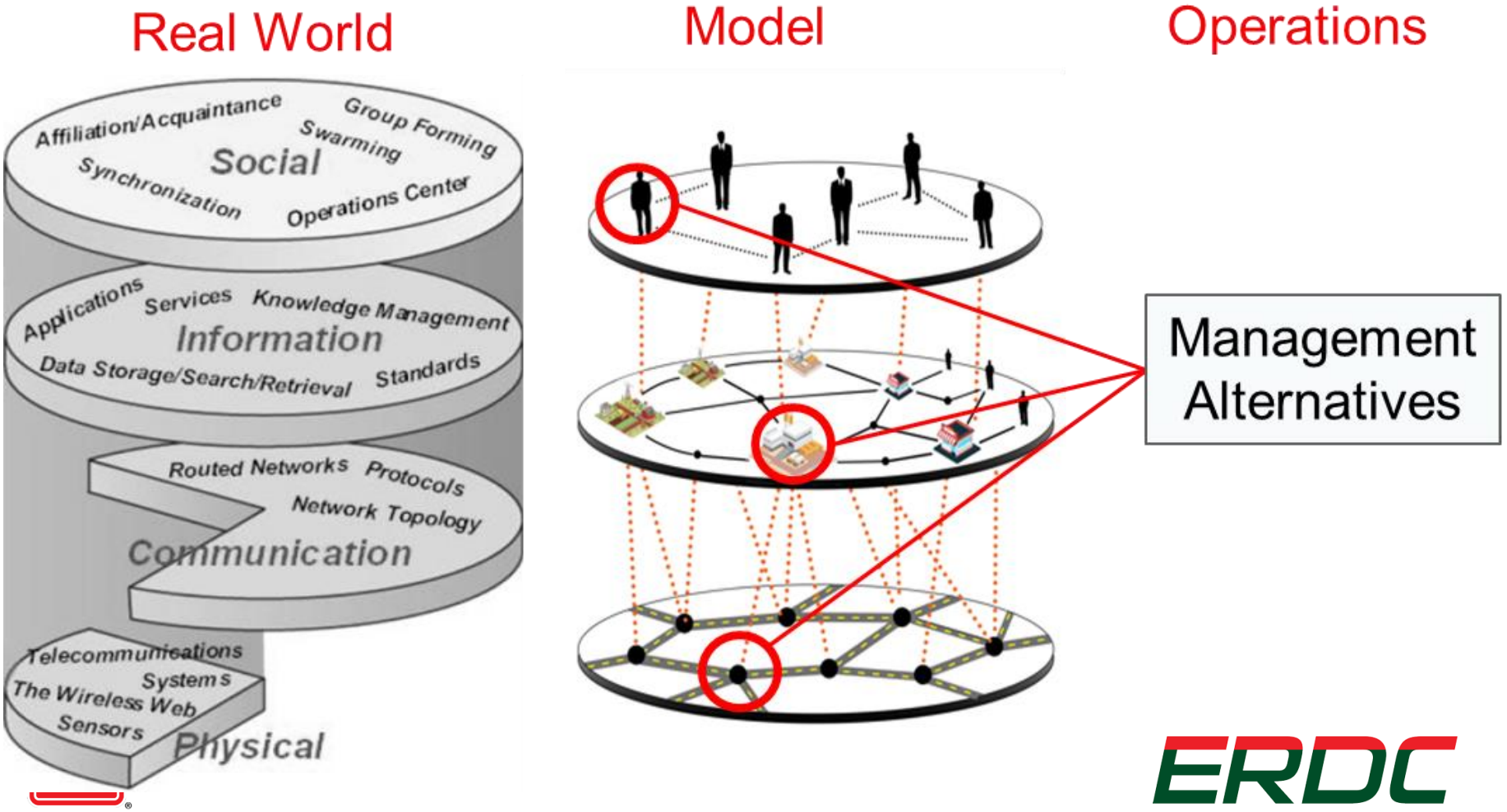
Business Case

Resilience Can Pick Up Where Risk Mitigation Ends



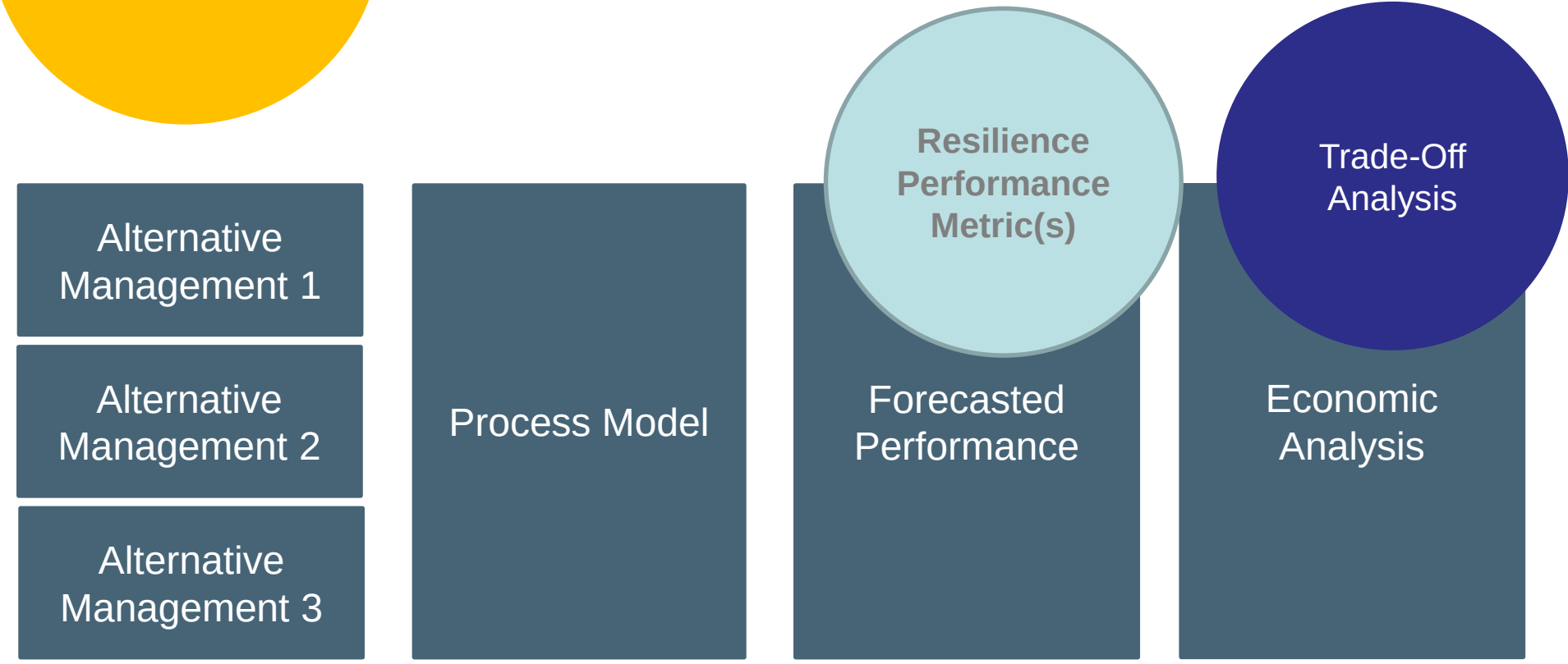
After Bostick et al. (2018) in Reliability Engineering and System Safety

Vision for Systems Resilience

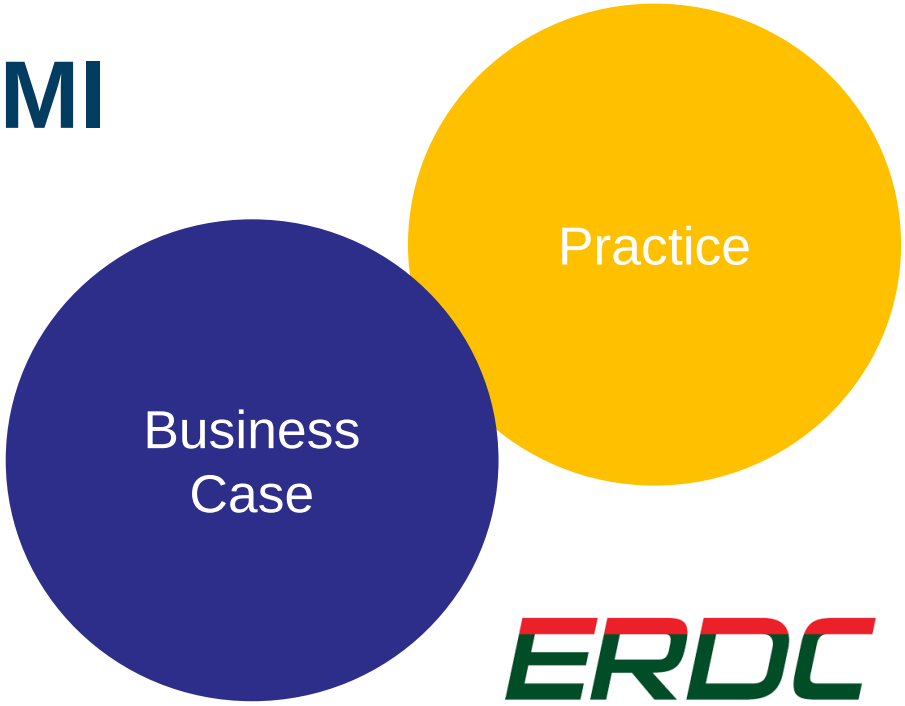


Formalize Resilience in Decision-Making

Practice



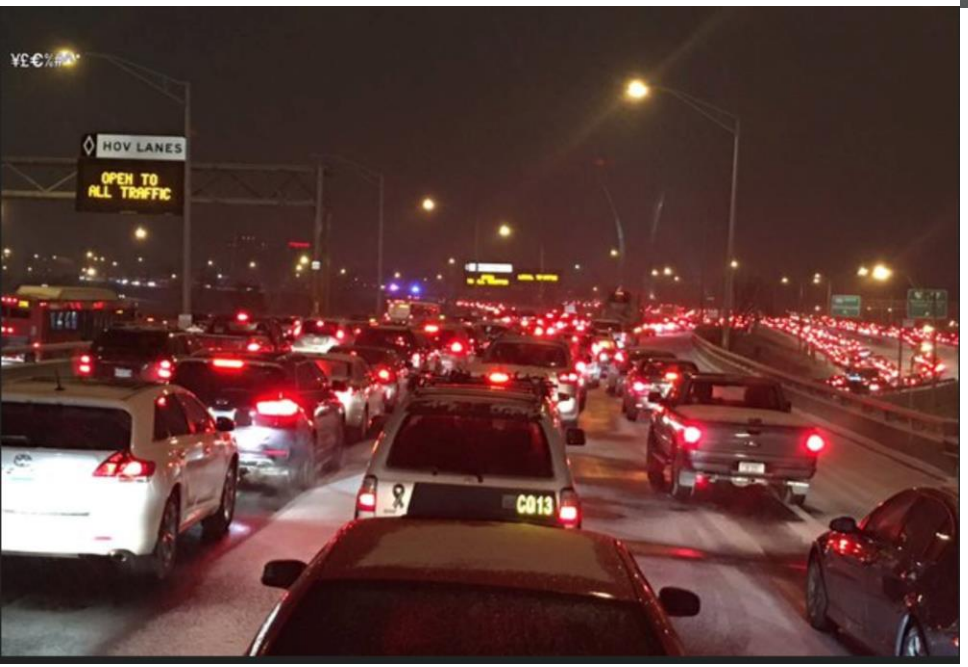
Case Study:
Transportation Network Model
+
REMI



Poor Efficiency:

System cannot not accommodate a large volume of commuters driving at the same time.

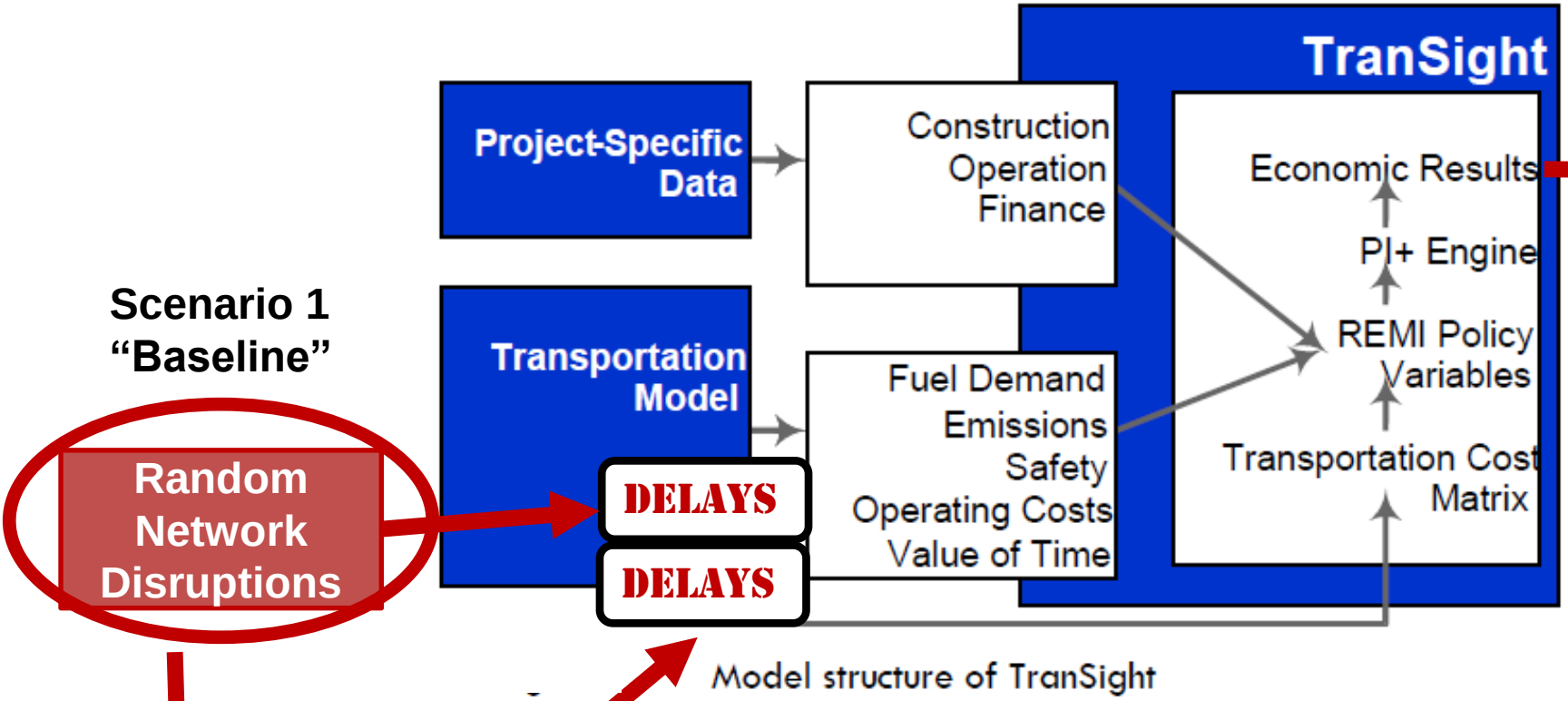
Traffic congestions are predictable and are typically of moderate level.



Lack of Resilience:

System cannot recover from adverse events (car accidents, natural disasters)

Traffic disruptions are not predictable and of variable scale.

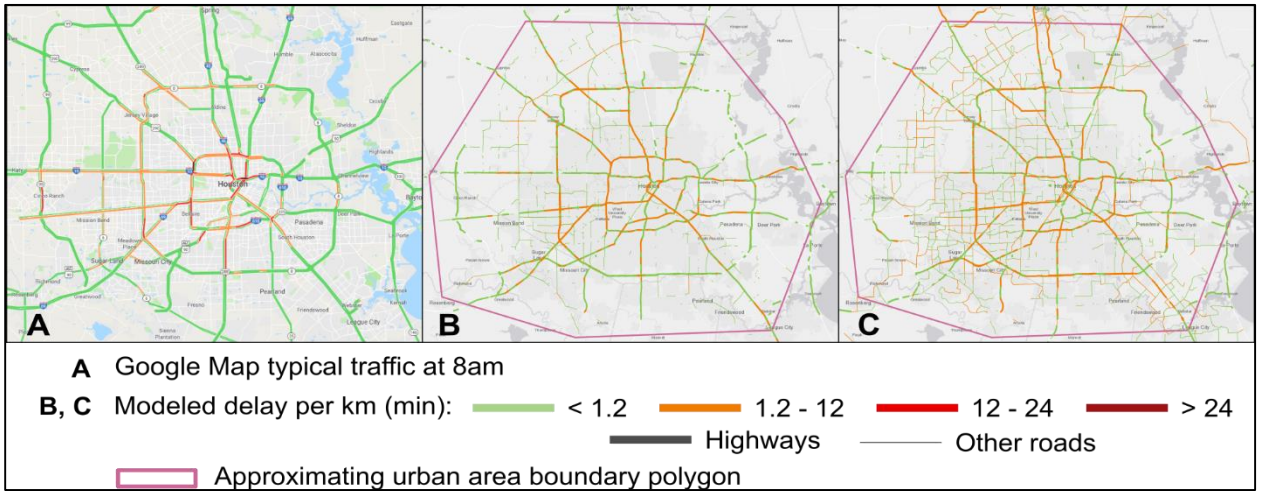


Model structure of TranSight

Interested in:

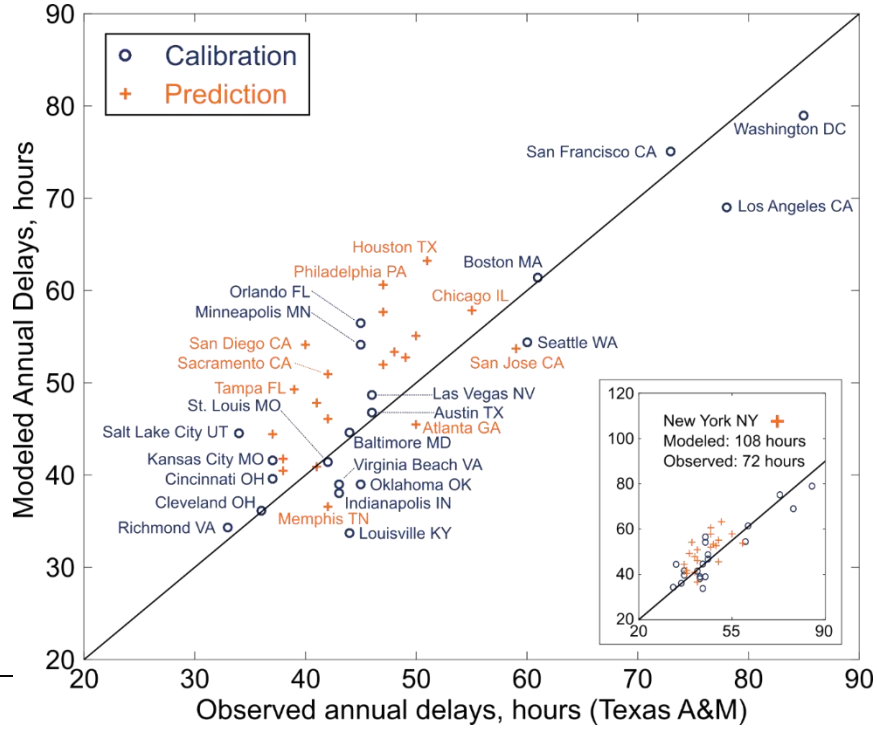
1. Temporal Patterns of Disruptions
2. Compare Multiple Cities

Transportation Network Model:

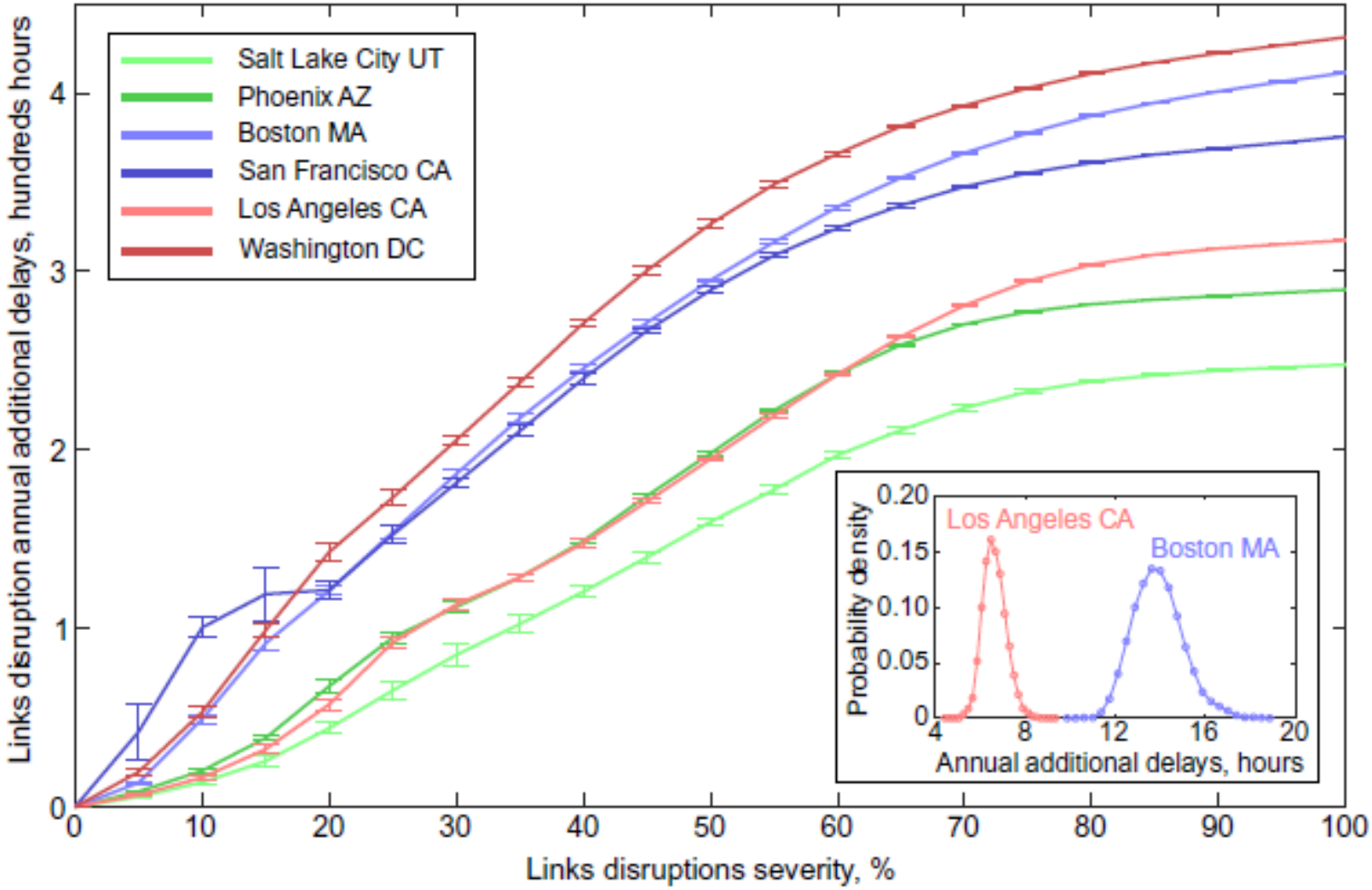


1) Build networks comprise of road links and intersection nodes
2) Assign travelers and routes
3) Calculate free flow travel times and actual travel times
4) Calculate normal delay
5) Calibrate model to data

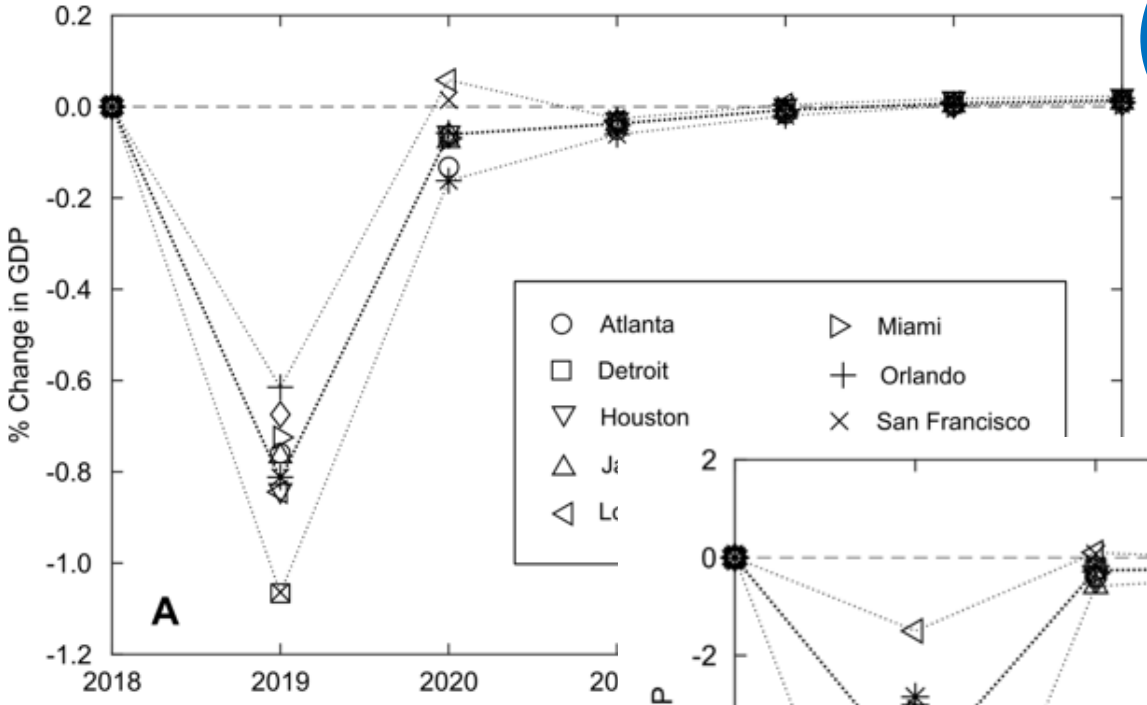
$$\langle \Delta T \rangle = \frac{1}{N_c} \sum_{\{ij\} \in \text{all roads}} L_{ij} \ell_{ij} \left(\frac{1}{v_{ij}} - \frac{1}{v_{ij}^0} \right)$$

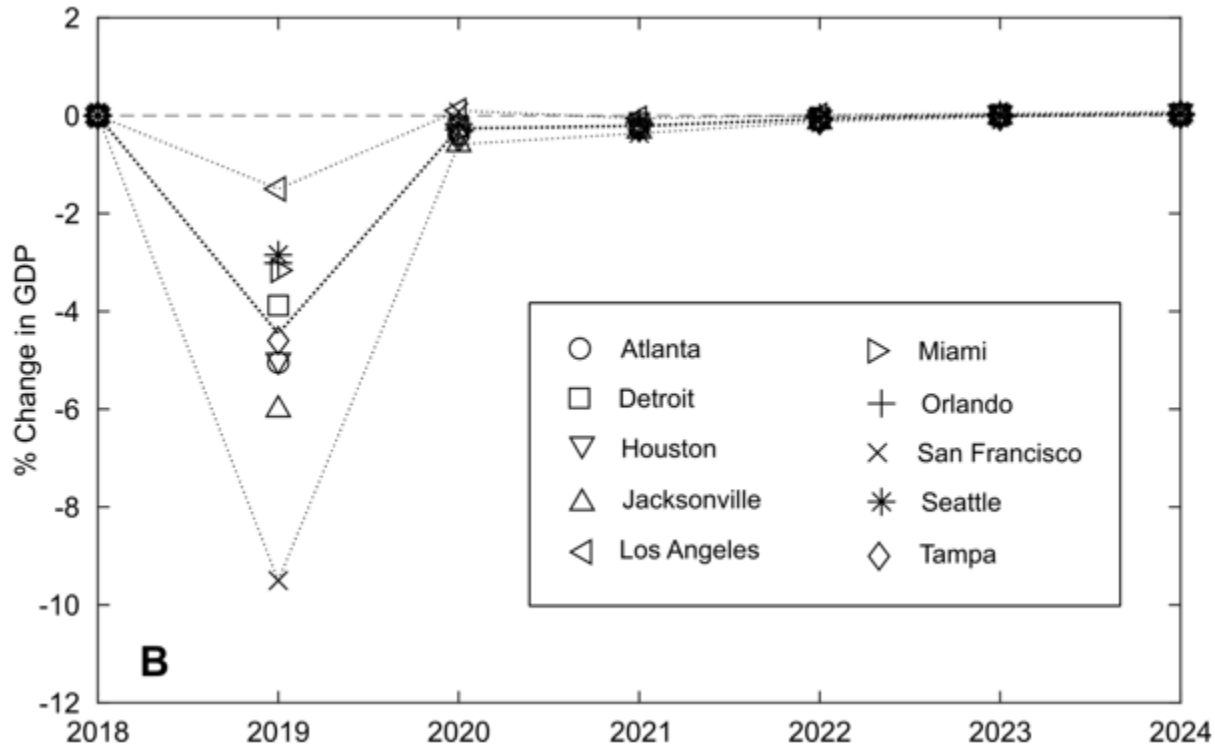


Transportation Networks in 40 Cities

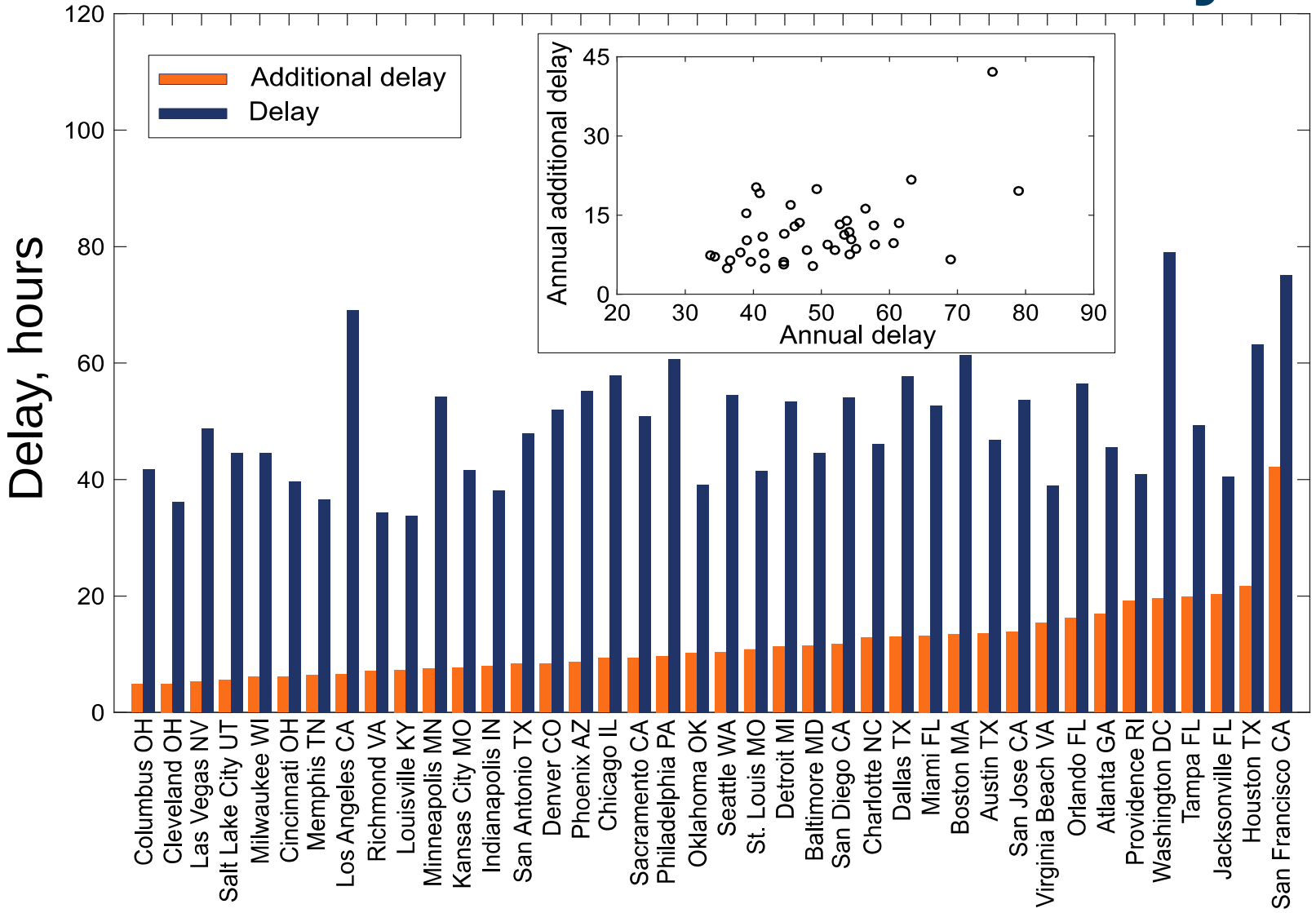


Temporal Pattern of Recovery) (5% disruption)



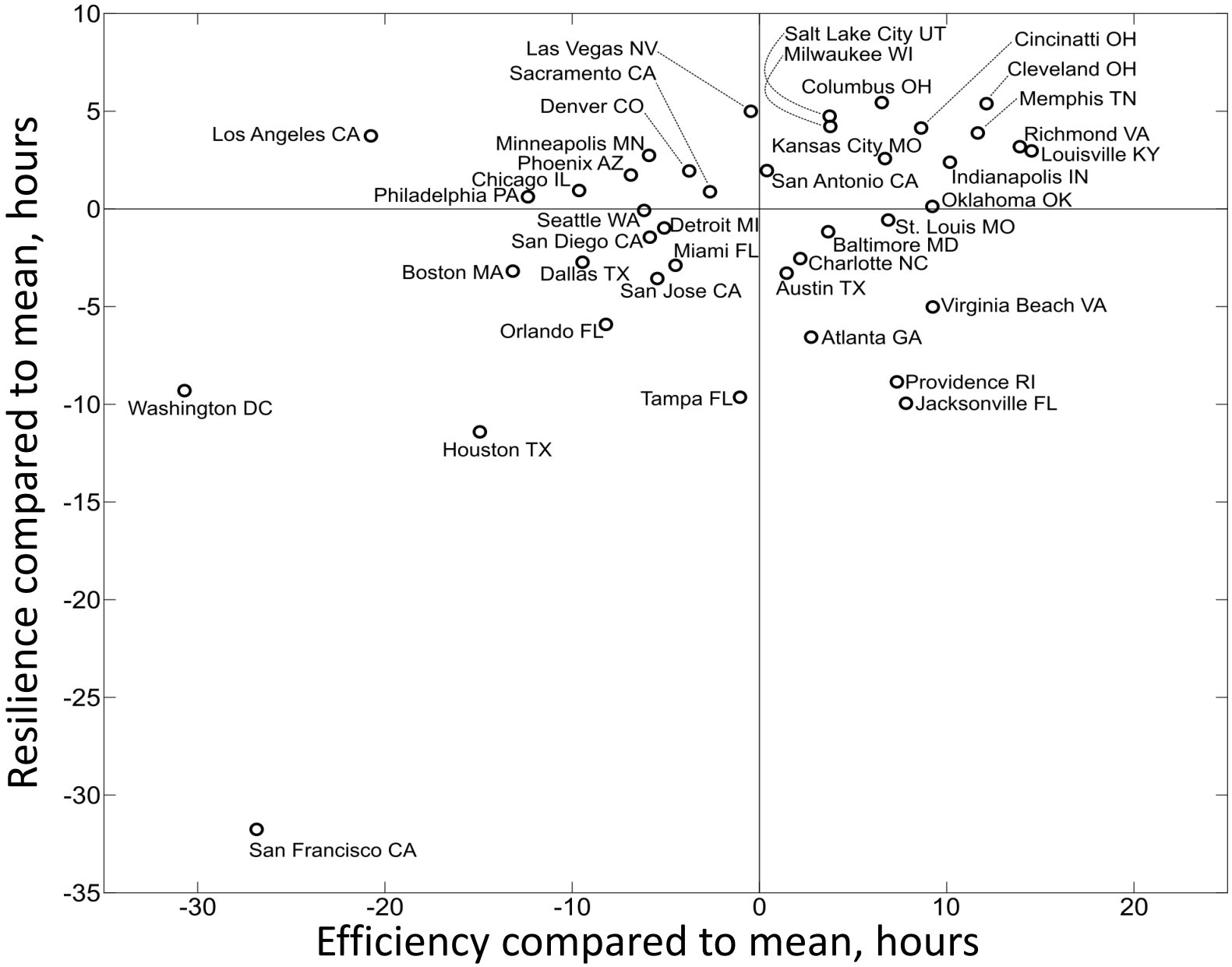


Lack of Resilience to 5% Disruption Adds Variable Additional Delay



Resilience *and* ***efficiency*** *vary greatly from city to city*

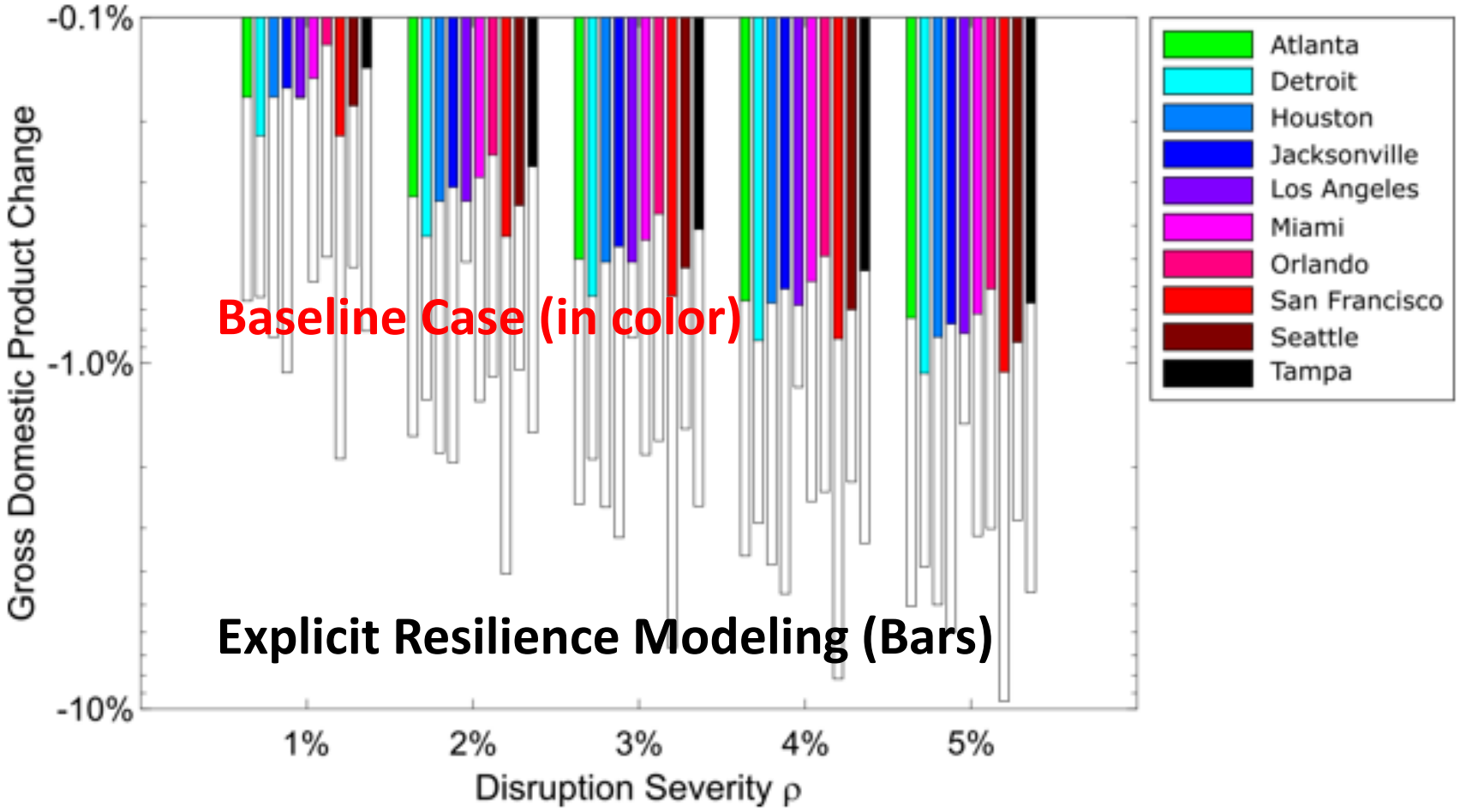
Resilience vs Efficiency at 5% disruption



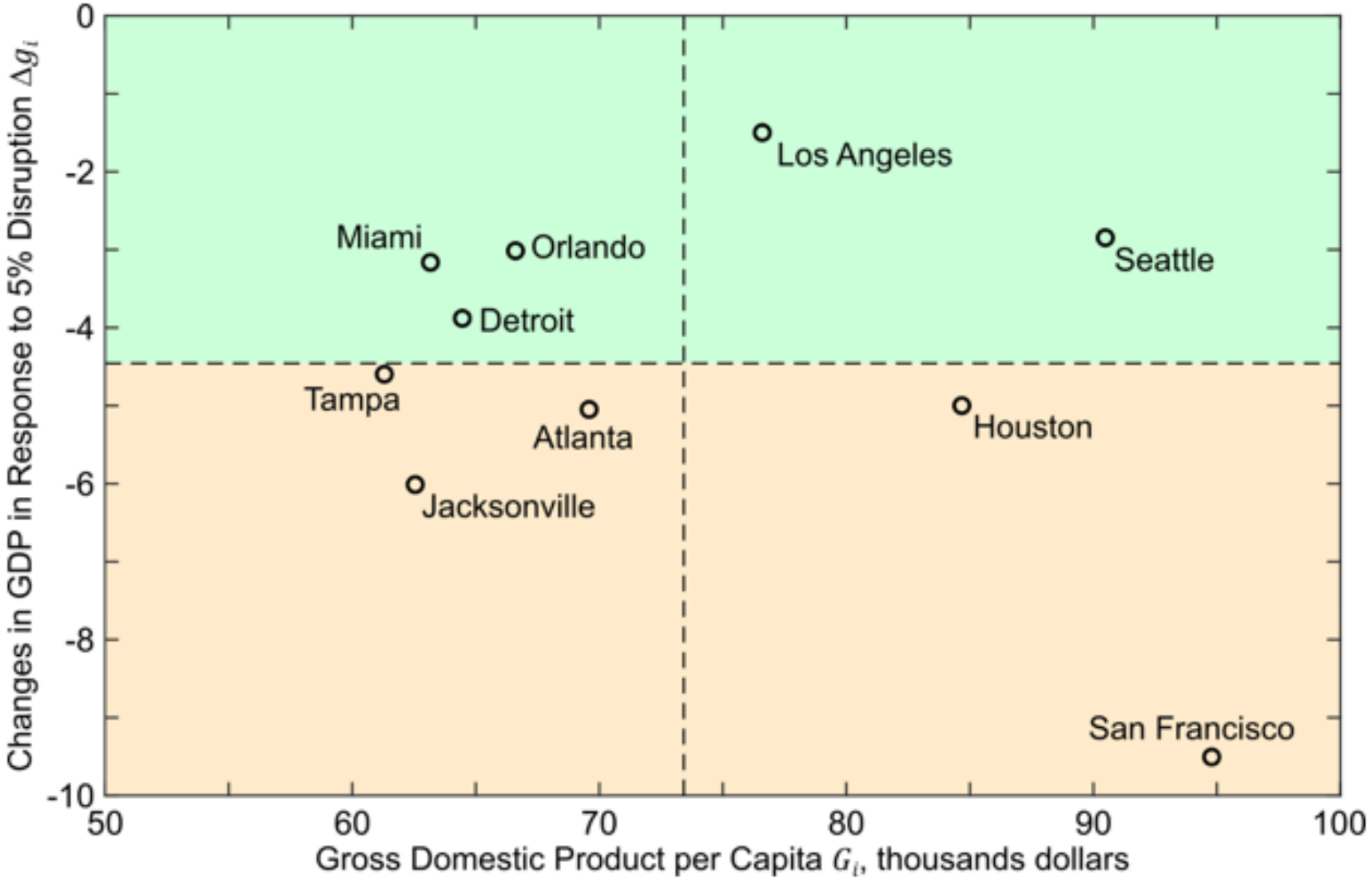
Increase in Transportation Costs

Transportation Cost Increase, $c(\rho)$	Fraction of Affected Roadways (Network Links), ρ				
	1%	**2%**	**3%**	**4%**	**5%**
Atlanta	4%	10%	16%	23%	**33%**
Detroit	3%	6%	9%	14%	19%
Houston	5%	11%	16%	24%	**32%**
Jacksonville	7%	13%	22%	**33%**	**44%**
Los Angeles	1%	3%	5%	7%	9%
Miami	4%	9%	13%	18%	23%
Orlando	4%	9%	14%	20%	**26%**
San Francisco	9%	20%	**34%**	**43%**	**51%**
Seattle	3%	6%	9%	13%	17%
Tampa	6%	12%	20%	**26%**	**37%**

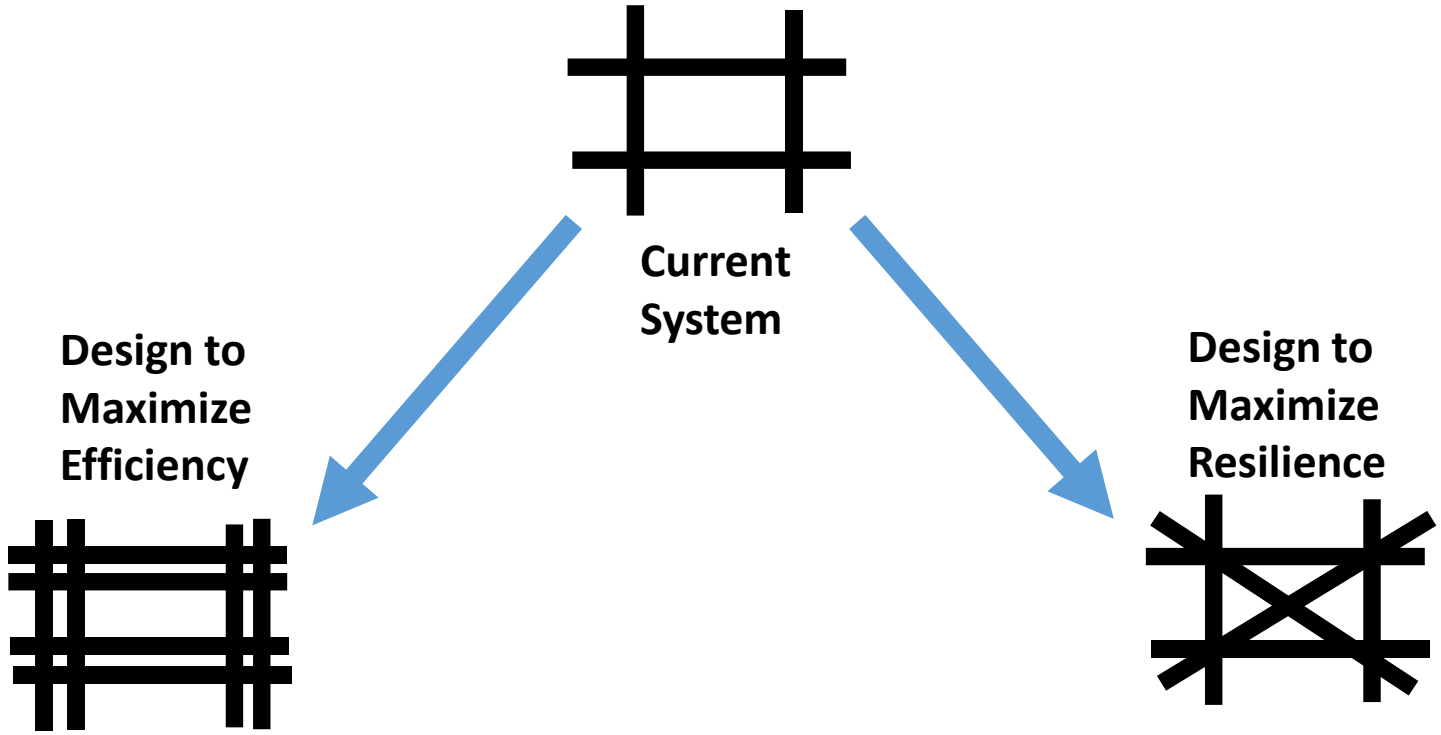
Impact on GDP



Impact on GDP and Size of Economy



Managing Resilience is Different than Efficiency



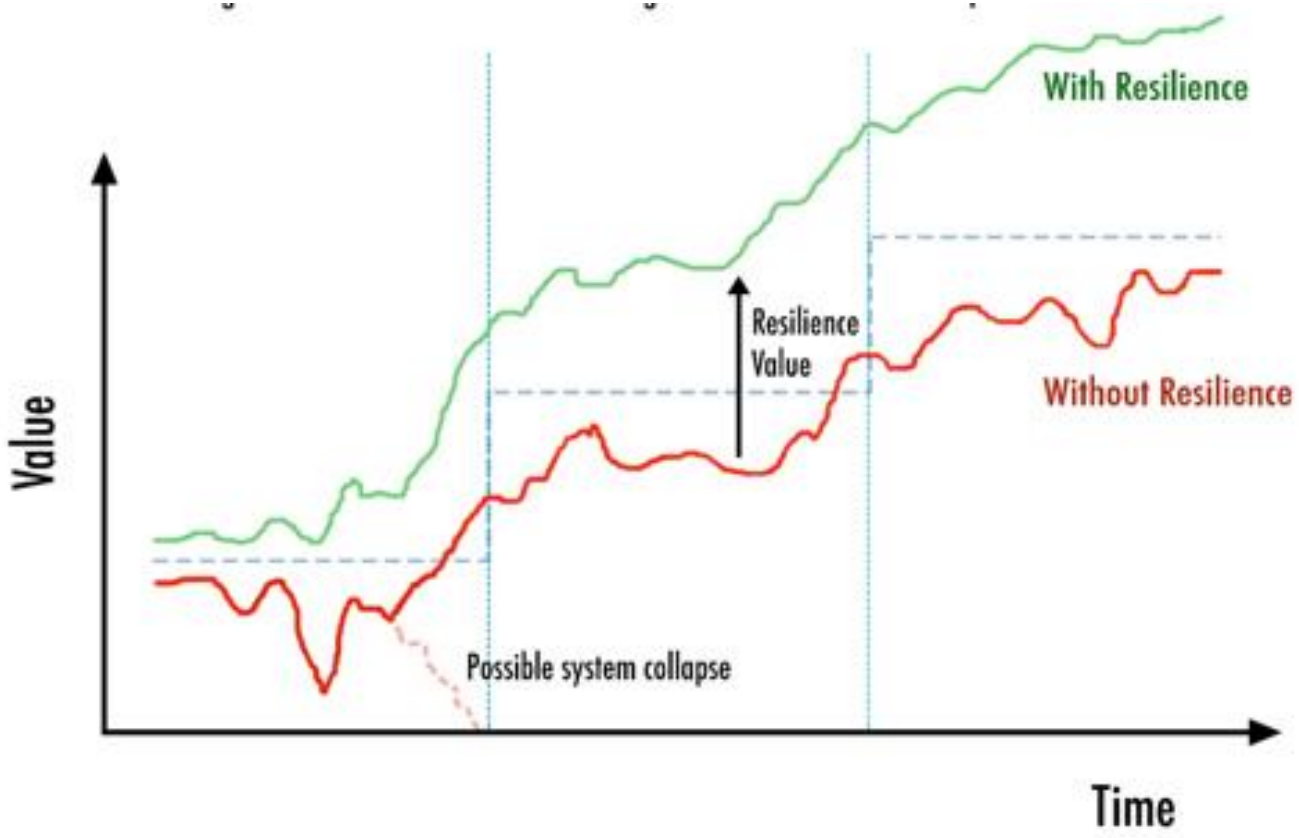
Efficiency

- the ability to move quickly when the network is functioning as designed
- cost effectively improved by increasing capacity on existing and highly utilized right of ways

Resilience

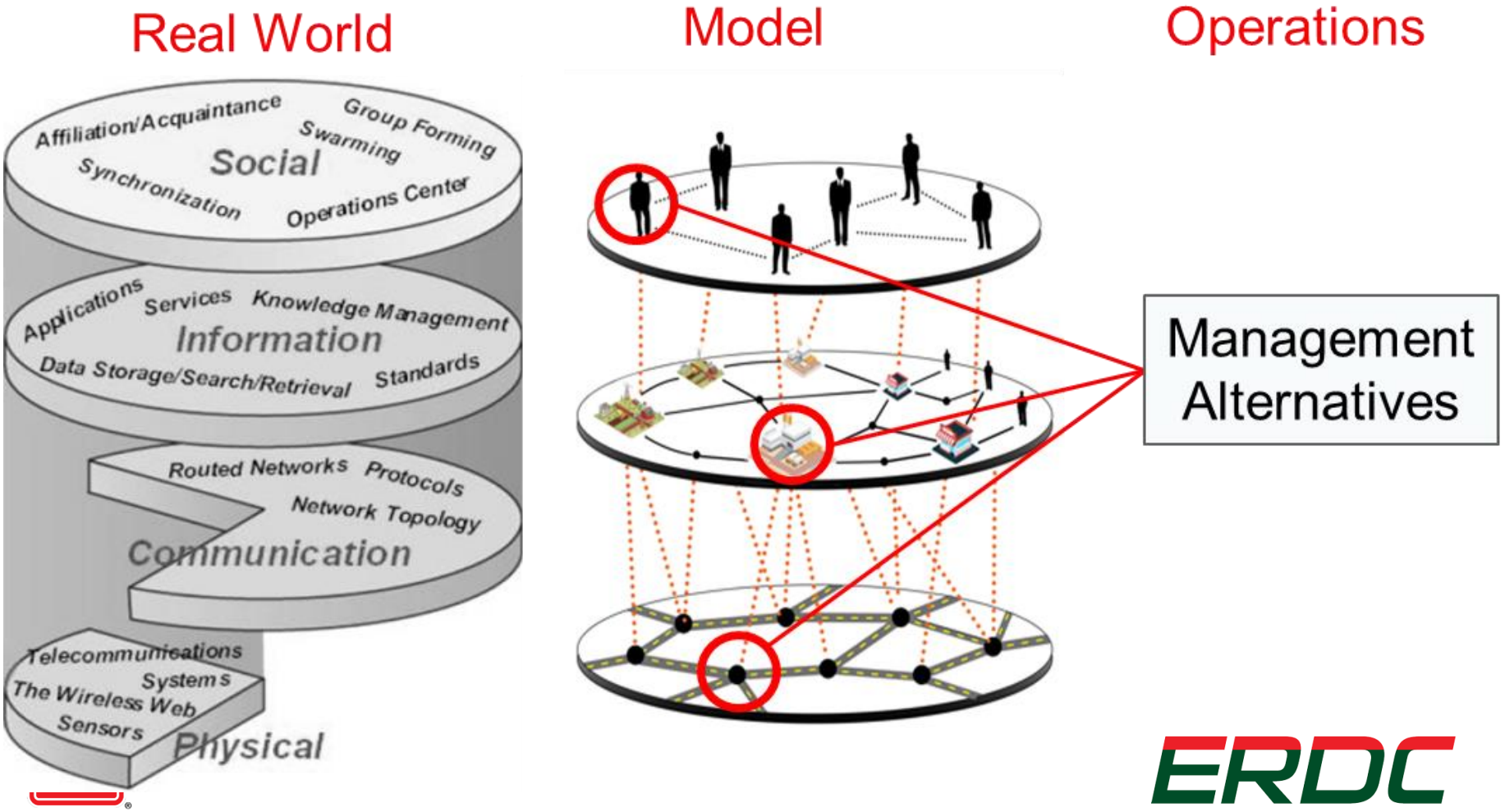
- the ability to limit delays from network component failures
- best improved by provide alternative route capacity when failure does occur

Resilience Value



After Linkov et al., 2019

Vision for Systems Resilience



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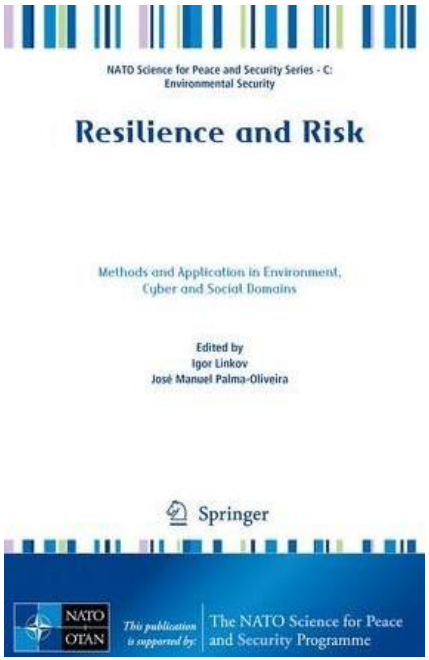
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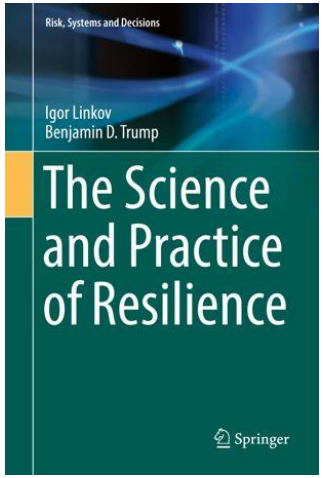
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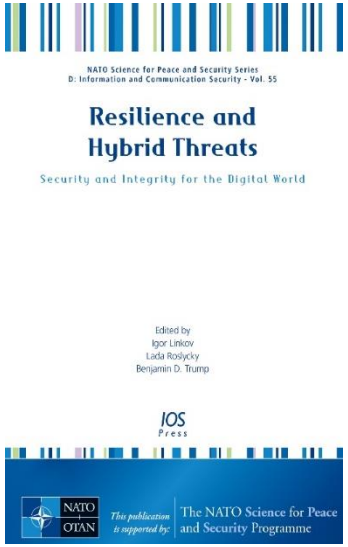
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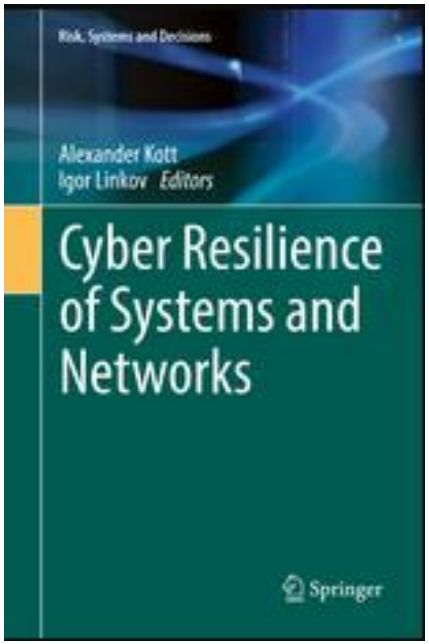
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