Resilience Assessment and Management in Transportation Networks

Igor Linkov

Risk and Decision Sciences Team,

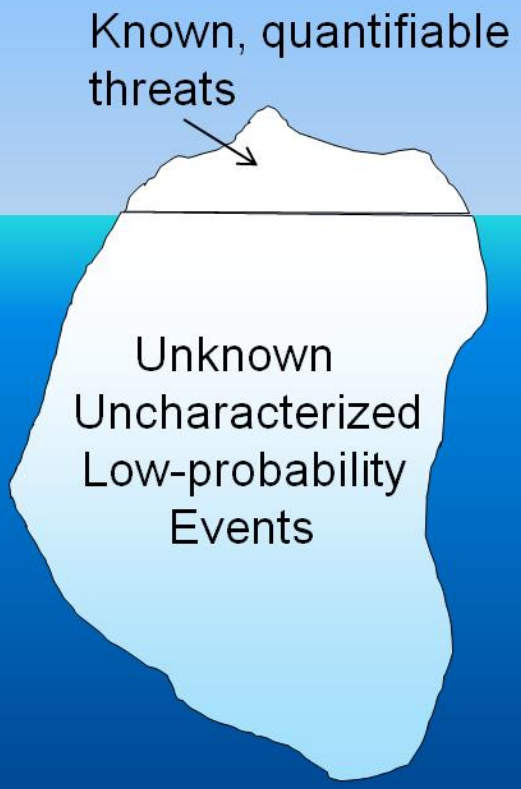
US Army Corps of Engineers

Adjunct Professor, Carnegie Mellon University and

University of Southern Denmark

1-6172339869

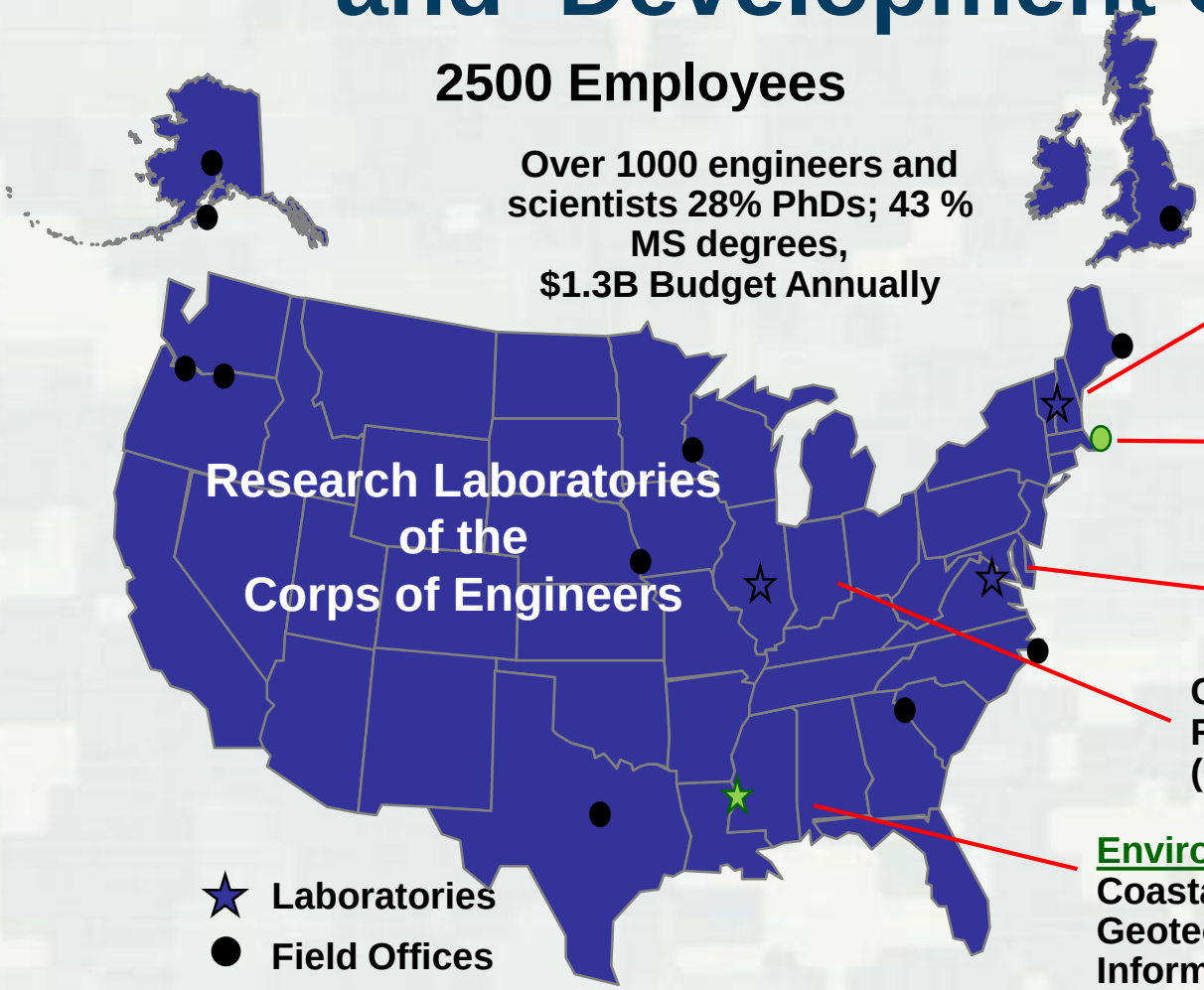
Igor.Linkov@usace.army.mil



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

Main Ideas

- Transportation is a complex and adaptive system and system analysis is necessary
- Risk and Resilience are different and should be treated differently
- Resilience can be quantified using Metrics-based and Network Science tools
- Efficiency, Resilience and Smartness are different, have different economic impacts and ways to manage

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

EXECUTIVE ORDER

(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**.

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

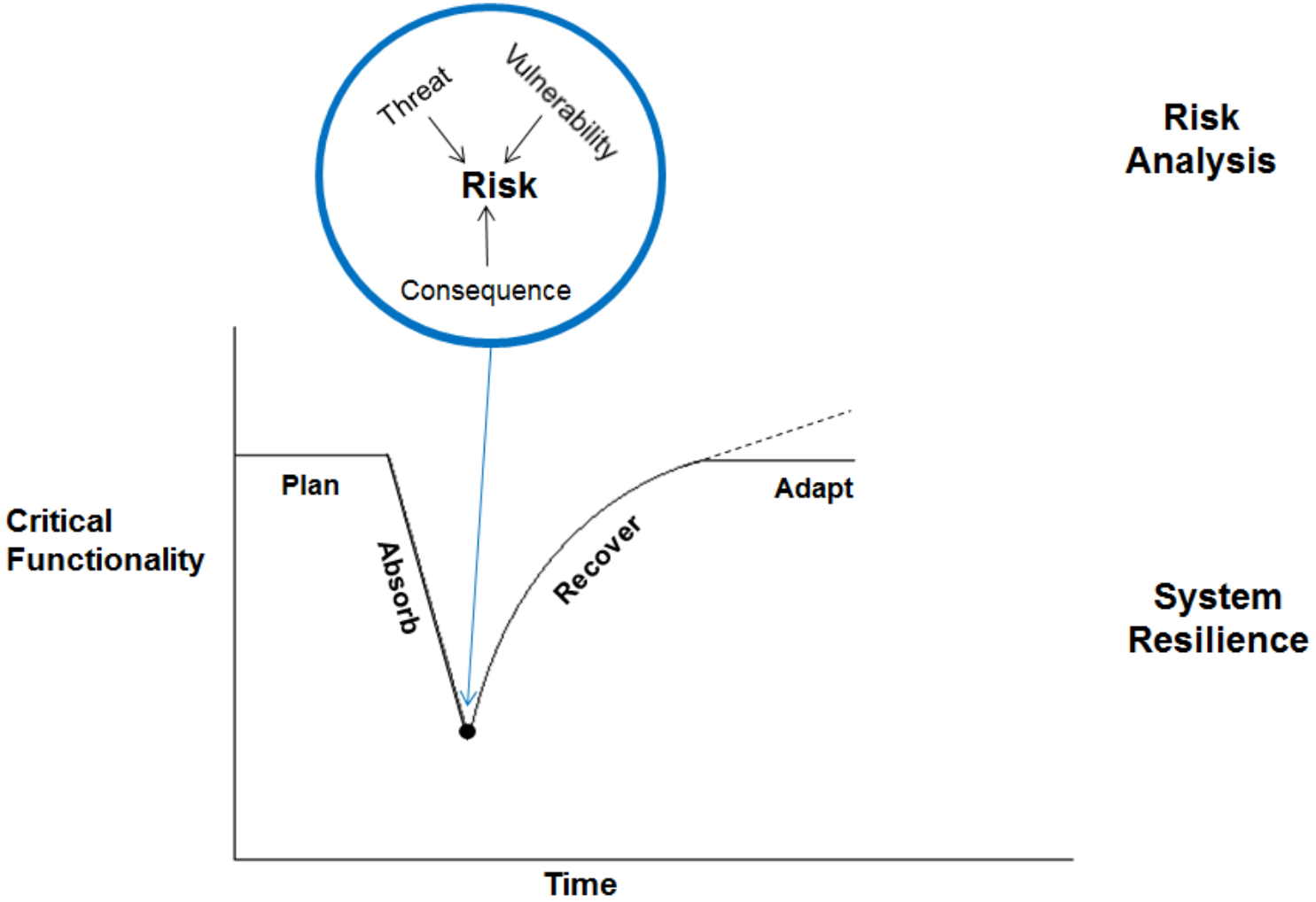
30 | NATURE | VOL 555 | 1 MARCH 2018

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

Igor Linkov, Benjamin D. Trump
US Army Corps of Engineers, Concord, Massachusetts, USA.
Jeffrey Keisler *University of Massachusetts Boston, USA.*
igor.linkov@usace.army.mil

System Risk/Security and Resilience



After Linkov et al, Nature Climate Change 2014

From World Economic Forum

Failure of Relatively Simple System: Northeast blackout of 2003

- How can a software bug of an energy company in Ohio lead to a blackout in New York City?
  - August 14-16, 2003
  - A software bug in the energy company's alarm system left causing operators to remain unaware of the need to re-distribute load after overloaded transmission lines drooped into foliage.
  - What should have been a manageable local blackout cascaded into collapse of the Northeast US electric grid

Can Digitalization Help?

- While FPL has invested nearly $3 billion to build a stronger, smarter energy grid, with this powerful of a storm, customers should prepare for potentially prolonged power outages

Sep 5, 2017

JUNO BEACH, Fla., Sept. 5, 2017 /PRNewswire/ -- Florida Power & Light Company (FPL) today announced that it is closely monitoring the path of Hurricane Irma and preparing to respond safely and as quickly as possi

FPL

More Than 10 Million People Lost Power in Florida

Thanks to Hurricane Irma, the southwest of the state's electrical grid will need a "wholesale rebuild."

L | SEP 11, 2017 | TECHNOLOGY

ERDC

Innovative solutions for a safer, better world

FPL spent $3 billion preparing for a storm. So why did Irma knock out the lights?

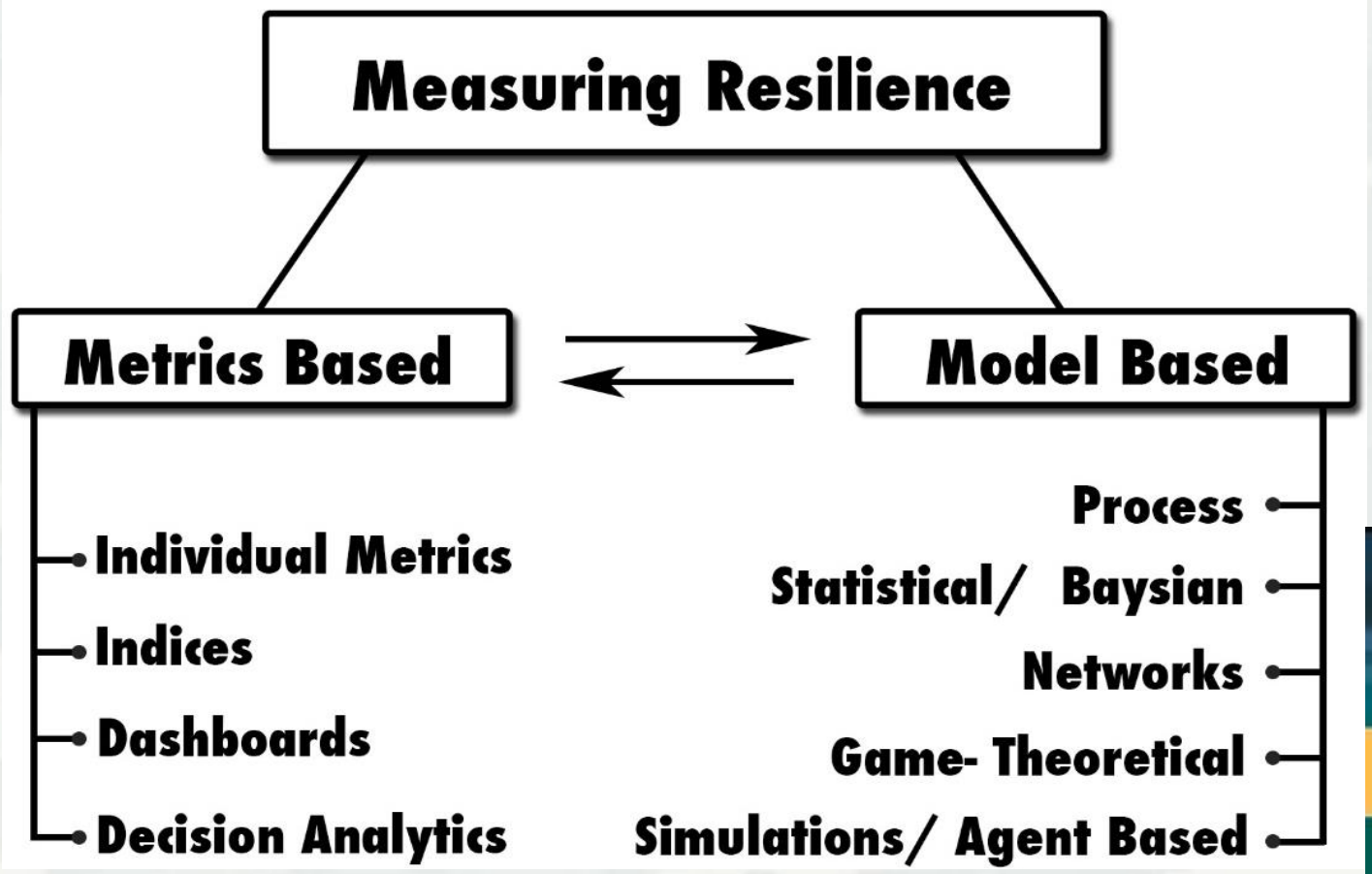
BY NICHOLAS NEHAMAS AND NANCY DAHLBERG
nnehamas@miamiherald.com
SEPTEMBER 21, 2017 8:00 AM

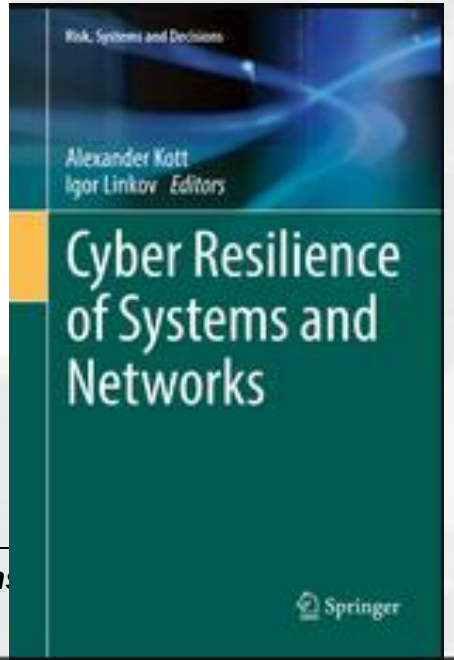
An electrical worker repairs stoplights the morning after Hurricane Irma swept through Naples, Florida.

The Slatest | YOUR NEWS COMPANION | SEPT. 11 2017 4:56 PM

After Irma, Florida's Smart Grid Needs the Longest and Most Complex Restoration in U.S. History

How to Measure Resilience?

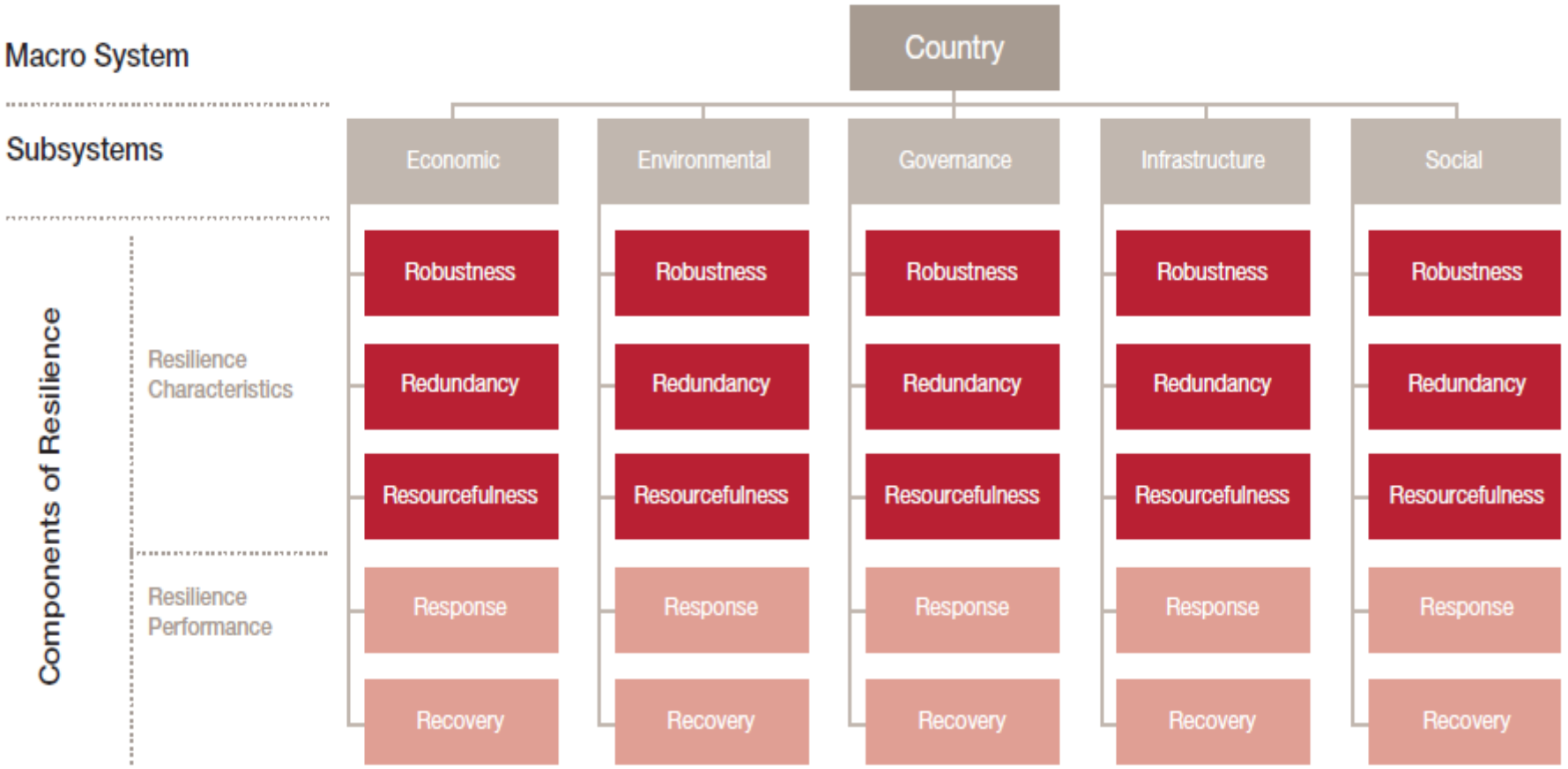




After 2019

State of Resilience Assessment

Figure 1 What is resilience?



Source: World Economic Forum

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

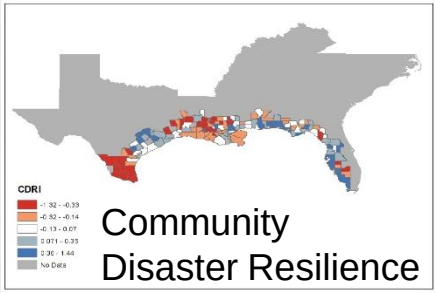
Not everything that counts can be counted, and not everything that can be counted counts.
Albert Einstein

Validating Resilience Indices

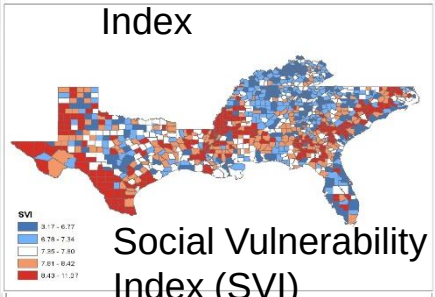
- 5 county-level resilience and vulnerability indices
- Relative rather than absolute scores
- Different aggregations of much the same data –
  - (Gini, poverty rate, vehicle access, hospitals, workforce composition, etc.)
- Adjacent counties show different patterns of relative resilience/vulnerability. What should states rely on to make investment decisions?

		CDRI	RCI	BRIC	SOVI	SVI
		Low --------High	Low --------High	Low --------High	Low --------High	Low --------High
Galveston Region	Cameron, LA			N/A		
	Jefferson, TX					
	Chambers, TX					
Mobile Region	Mobile, AL					
	Baldwin, AL		N/A			
	Escambia, FL					
	Santa Rosa, FL					
Tampa Region	Hillsborough, FL					
	Manatee, FL					
	Sarasota, FL					

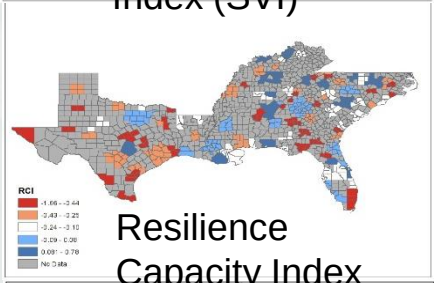
Bakkensen, Linkov et al (2016)



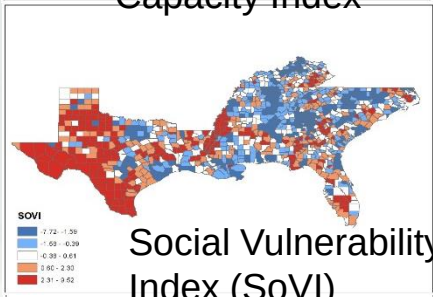
Community Disaster Resilience Index



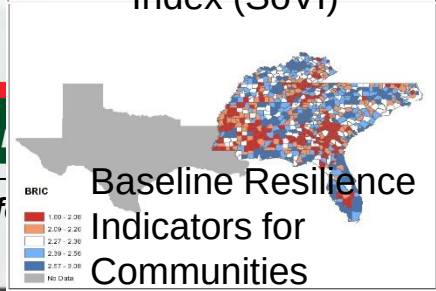
Social Vulnerability Index (SVI)



Resilience Capacity Index

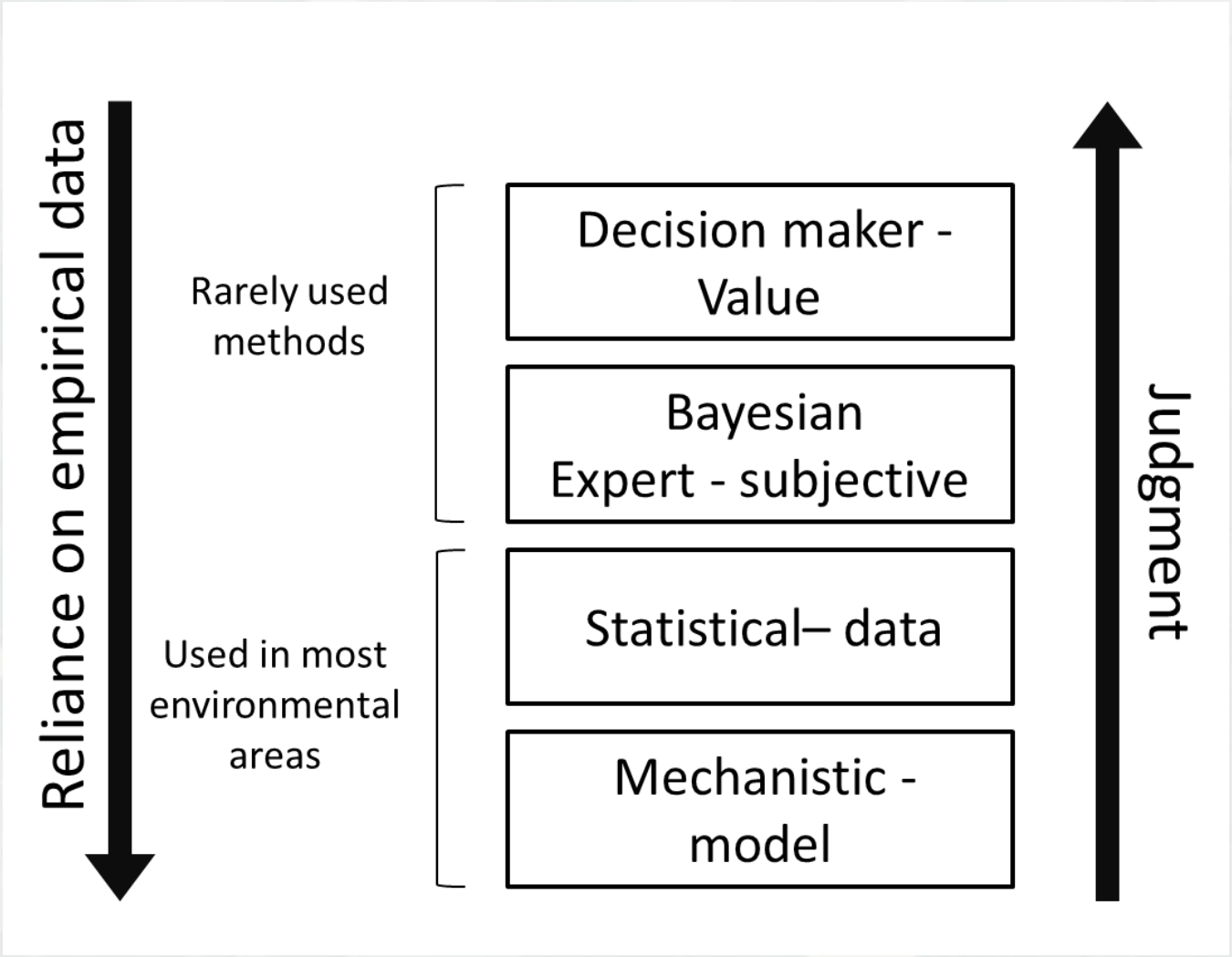


Social Vulnerability Index (SoVI)



Baseline Resilience Indicators for Communities

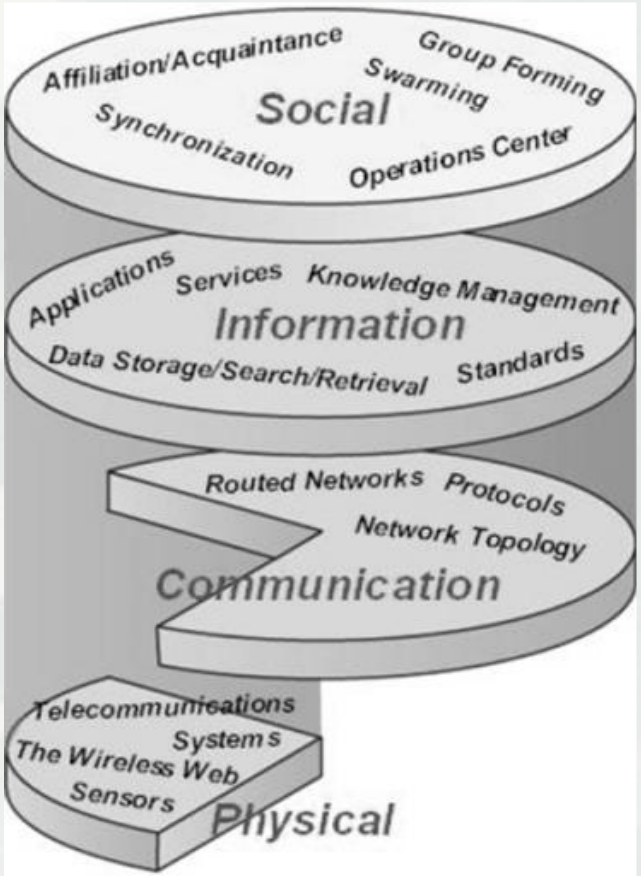
Ways to Model



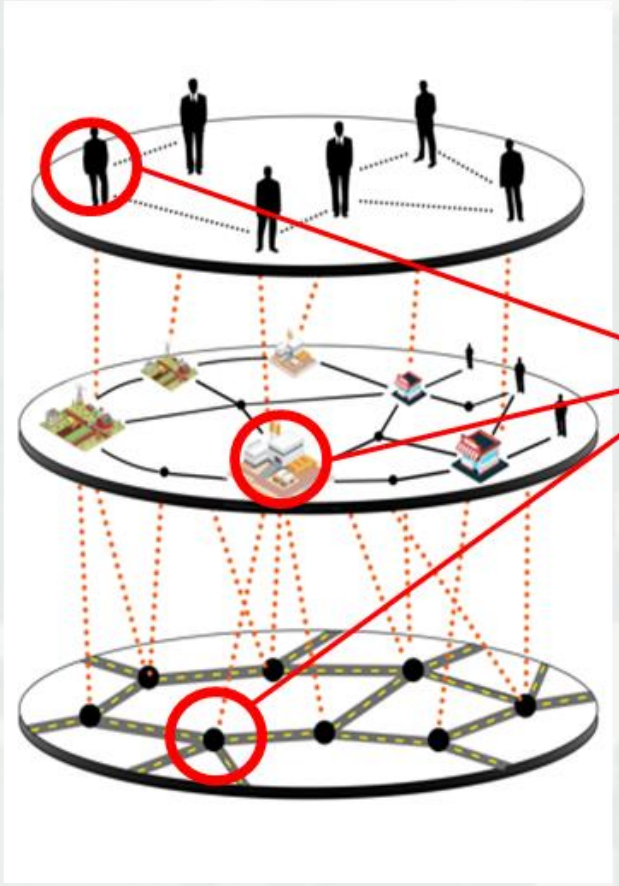
From Keisler and Linkov, 2014

Vision for Systems Resilience

Real World



Model



Operations

Management Alternatives

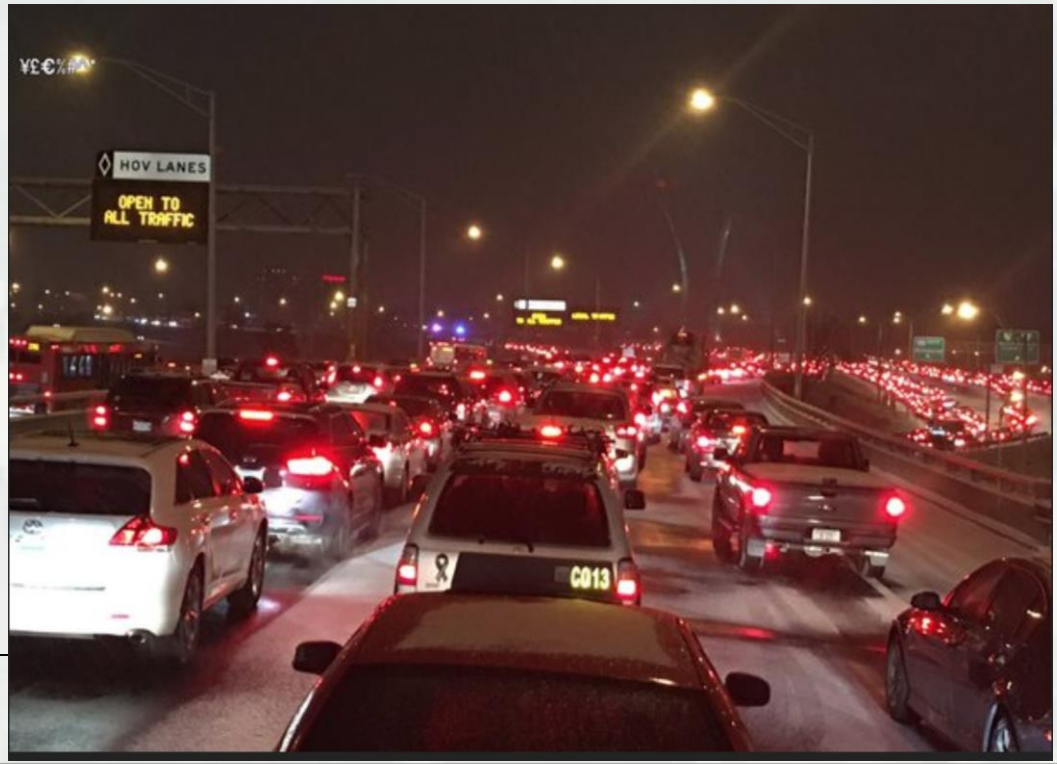
Example: Resilience Quantification in Transportation Network

Washington, DC 1937

Washington, DC January 20, 2016

1 inch of snow melted and turned into ice.

- 767 car accidents.
- Hours of traffice delays
- Traffic jams took days to disentangle!



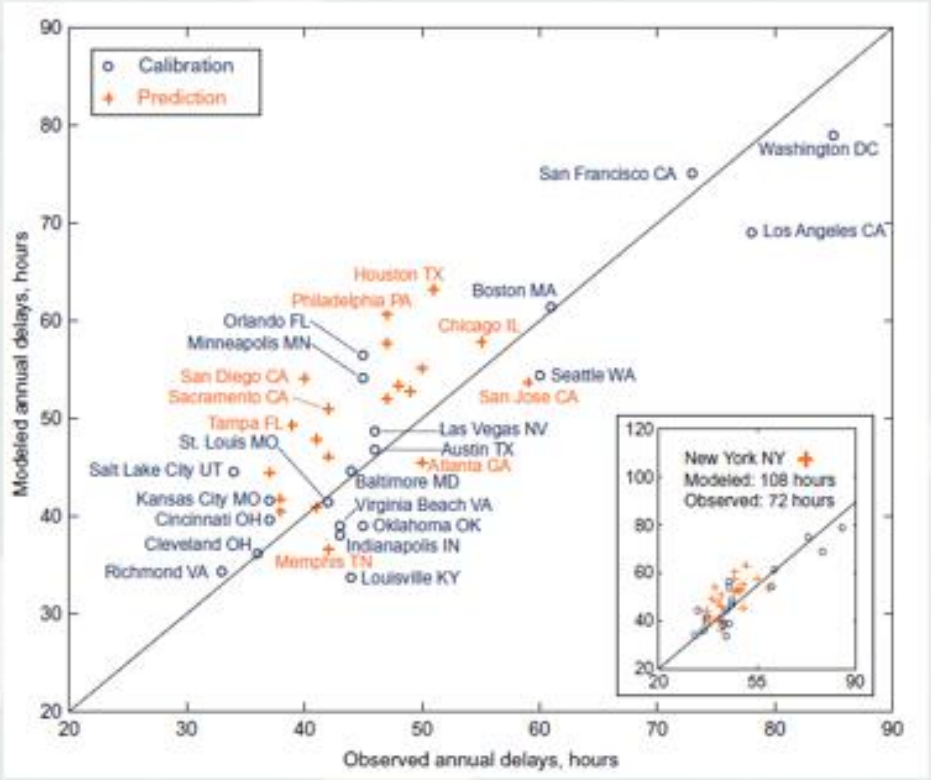
SCIENCE ADVANCES | RESEARCH ARTICLE v. 3, Dec 2017

NETWORK SCIENCE

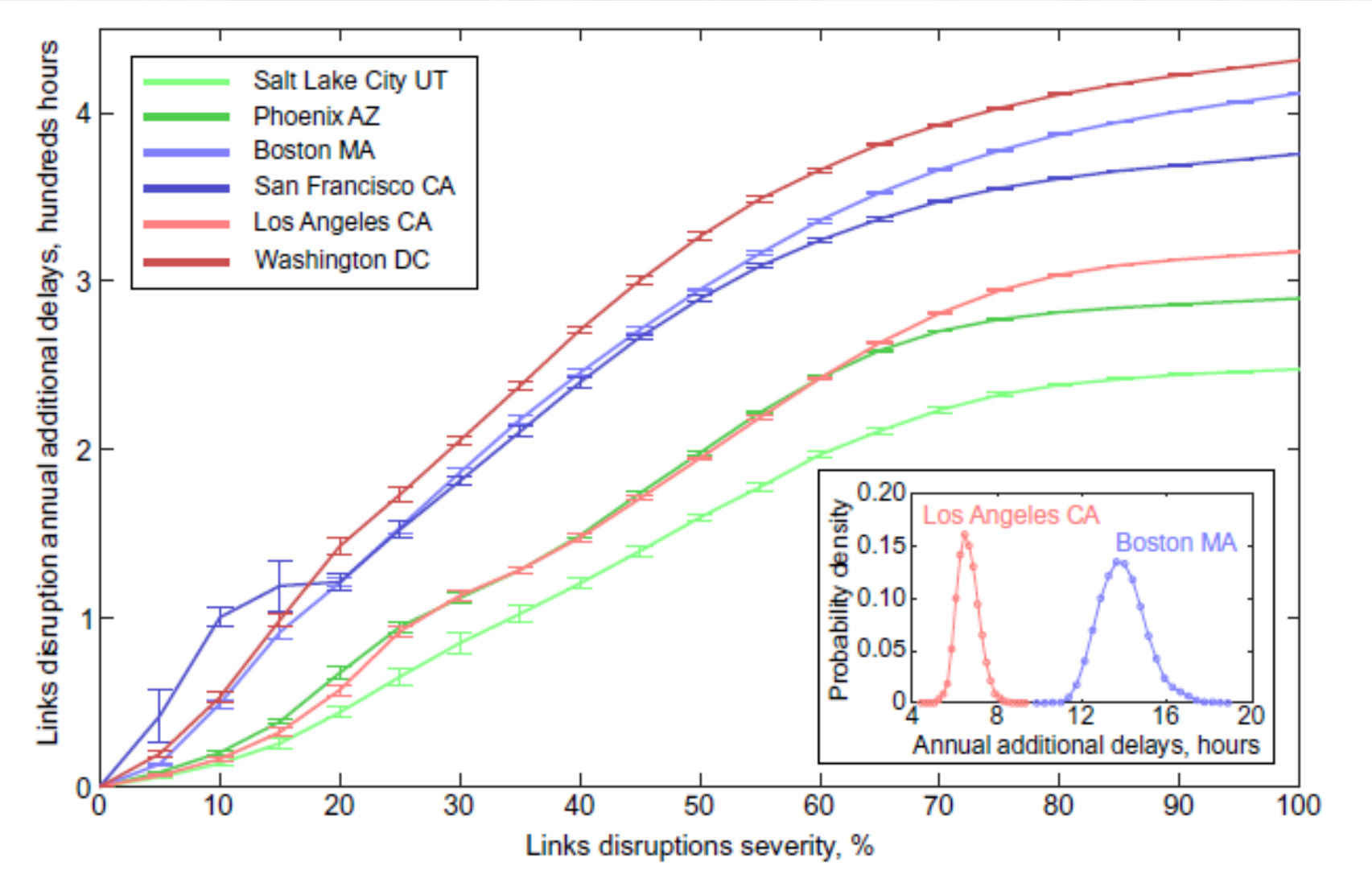
Resilience and efficiency in transportation networks

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

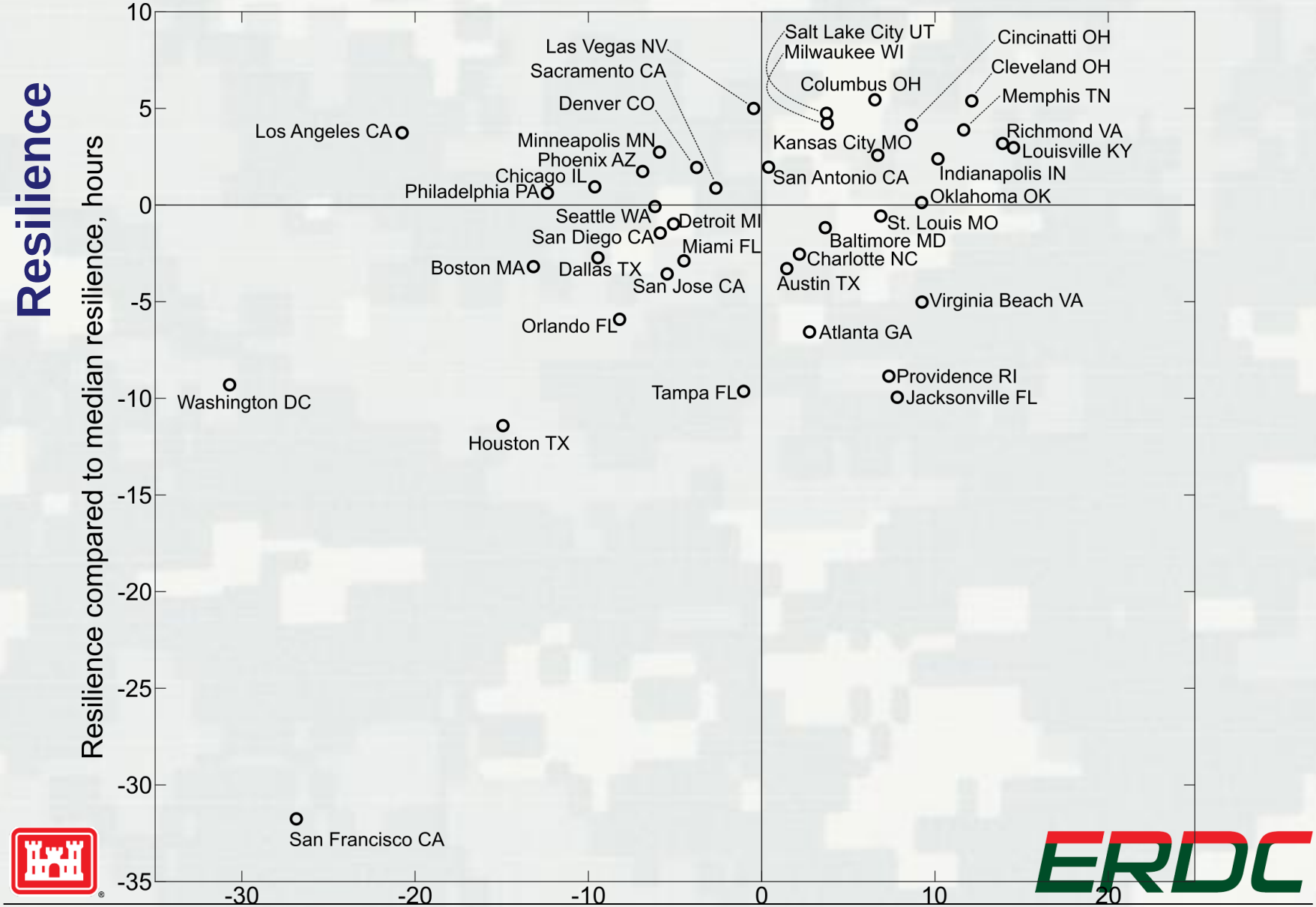
40 US Cities with Different Traffic Delays



Transportation Networks in 40 Cities



Efficiency and Resilience do not Correlate



BUILDING STRONG®

ERDC

Innovative solutions for a safer, better world

Lack of Resilience: Financial Implications

Regional Economic Modeling (REMI)

Input-Output

Close analysis of inter-industry relationships

General Equilibrium

Estimate of long-run stability of the economy allows for analysis of policy decisions

Econometrics

Advanced statistical analyses underpinning the model

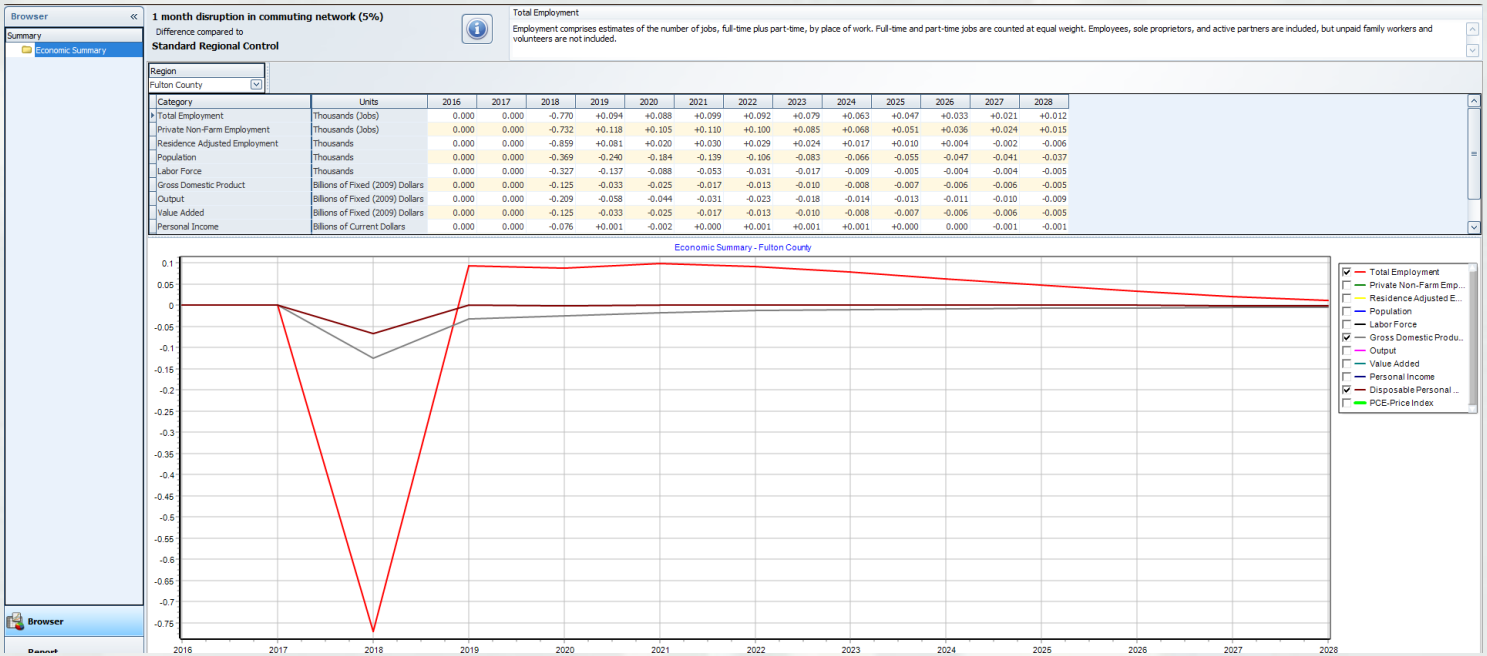
Economic Geography

Effects of geographic concentration of labor and industry

Integrated REMI economic modelling approach

Atlanta

One Month of 5% Network Disruption

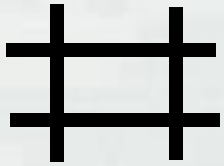


Category	Units	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028
Total Employment	Thousands (Jobs)	0.000	0.000	-0.770	+0.094	+0.088	+0.099	+0.092	+0.079	+0.063	+0.047	+0.033	+0.021	+0.012
Private Non-Farm Employment	Thousands (Jobs)	0.000	0.000	-0.732	+0.118	+0.105	+0.110	+0.100	+0.085	+0.068	+0.051	+0.036	+0.024	+0.015
Residence Adjusted Employment	Thousands	0.000	0.000	-0.859	+0.081	+0.020	+0.030	+0.029	+0.024	+0.017	+0.010	+0.004	-0.002	-0.006
Population	Thousands	0.000	0.000	-0.369	-0.240	-0.184	-0.139	-0.106	-0.083	-0.066	-0.055	-0.047	-0.041	-0.037
Labor Force	Thousands	0.000	0.000	-0.327	-0.137	-0.088	-0.053	-0.031	-0.017	-0.009	-0.005	-0.004	-0.004	-0.005
Gross Domestic Product	Billions of Fixed (2009) Dollars	0.000	0.000	-0.125	-0.033	-0.025	-0.017	-0.013	-0.010	-0.008	-0.007	-0.006	-0.006	-0.005
Output	Billions of Fixed (2009) Dollars	0.000	0.000	-0.209	-0.058	-0.044	-0.031	-0.023	-0.018	-0.014	-0.013	-0.011	-0.010	-0.009
Value Added	Billions of Fixed (2009) Dollars	0.000	0.000	-0.125	-0.033	-0.025	-0.017	-0.013	-0.010	-0.008	-0.007	-0.006	-0.006	-0.005
Personal Income	Billions of Current Dollars	0.000	0.000	-0.076	+0.001	-0.002	+0.000	+0.001	+0.001	+0.001	+0.000	0.000	-0.001	-0.001

- **770 jobs lost (0.07%)**
- **$125 million 2009 dollars in GDP lost (0.09%)**
- **$66 million current dollars in disposable personal income lost (0.09%)**

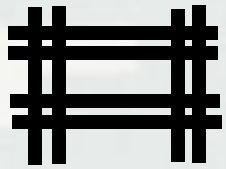
Why Bother?

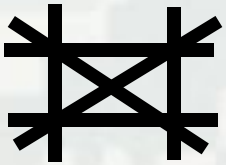
Managing Resilience is Different than Efficiency



Current System

Design to Maximize Efficiency





Design to Maximize Resilience

Transportation Research Part C 100 (2019) 318–329

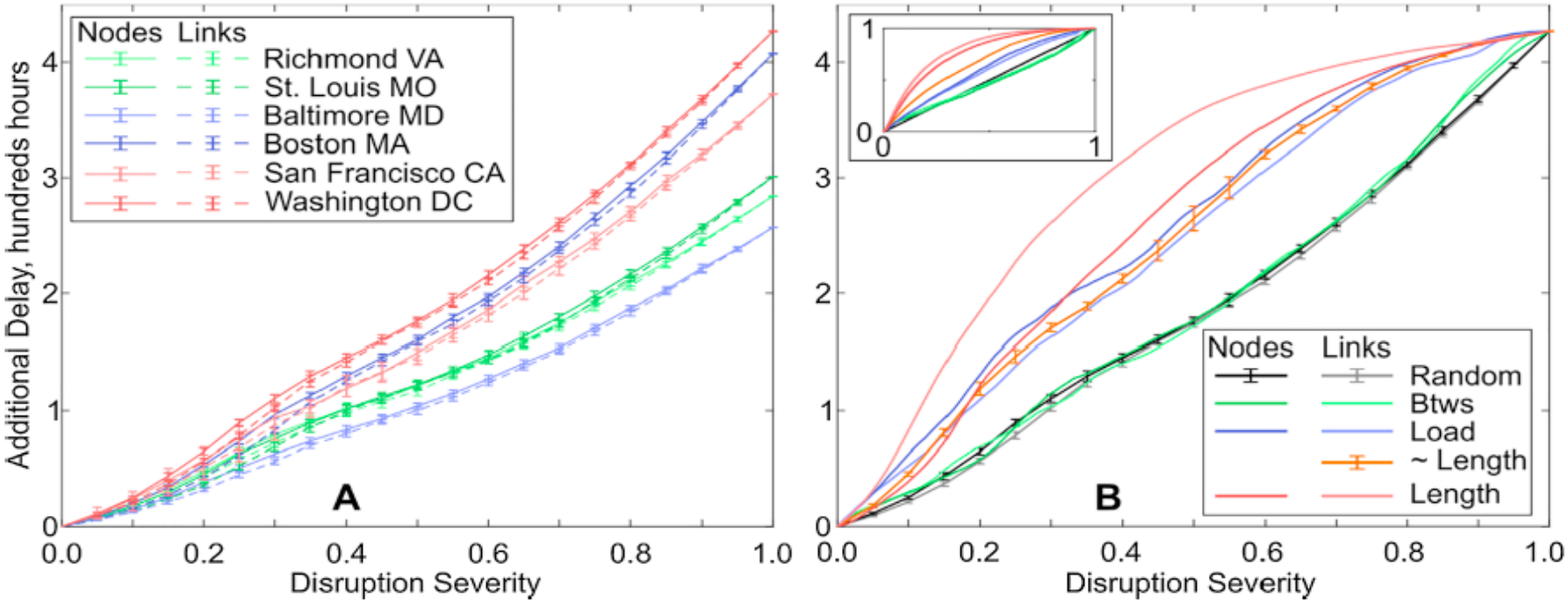
Contents lists available at ScienceDirect

Transportation Research Part C

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

Resilience in Intelligent Transportation Systems (ITS)

Alexander A. Ganin[a,b], Avi C. Mersky[a], Andrew S. Jin[c], Maksim Kitsak[d],



Resilience and Sustainability

Contents lists available at ScienceDirect

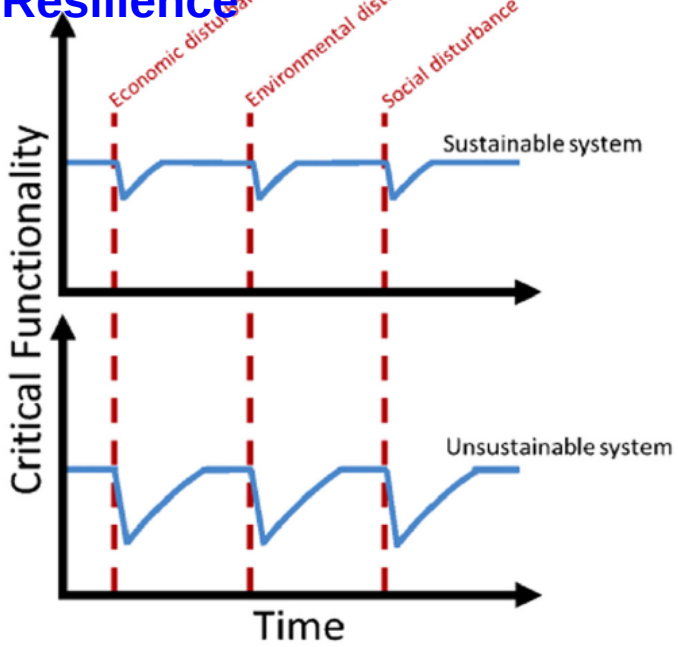
Science of the Total Environment

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

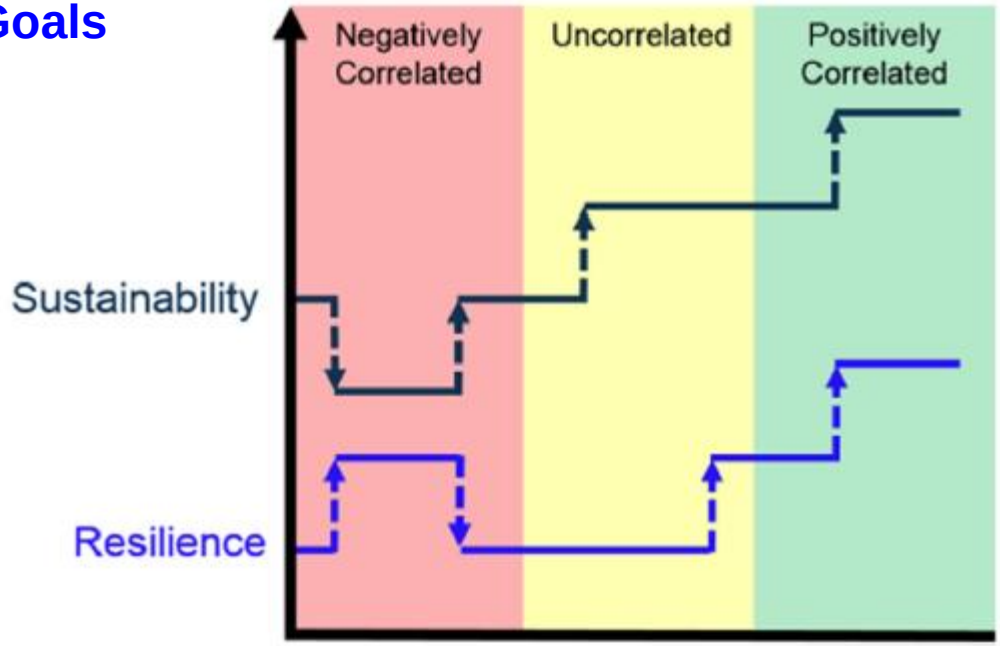
Resilience and sustainability: Similarities and differences in environmental management applications

Dayton Marchese [a], Erin Reynolds [a], Matthew E. Bates [a], Heather Morgan [b], Susan Spierre Clark [c], Igor Linkov [a,*]

Sustainability as component of Resilience



Sustainability and Resilience as Separate Goals



Resilience and Smartness

Environmental Science & Technology

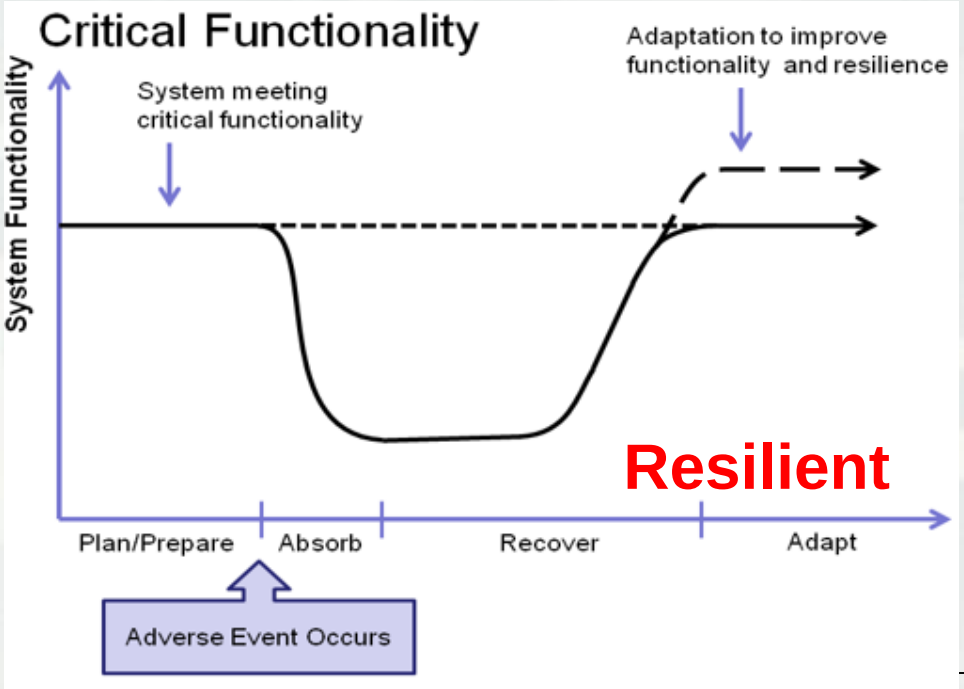
Viewpoint

pubs.acs.org/es

Can You Be Smart and Resilient at the Same Time?

Dayton Marchese and Igor Linkov*

DOI: 10.1021/acs.est.7b01912
Environ. Sci. Technol. 2017, 51, 5867−5868

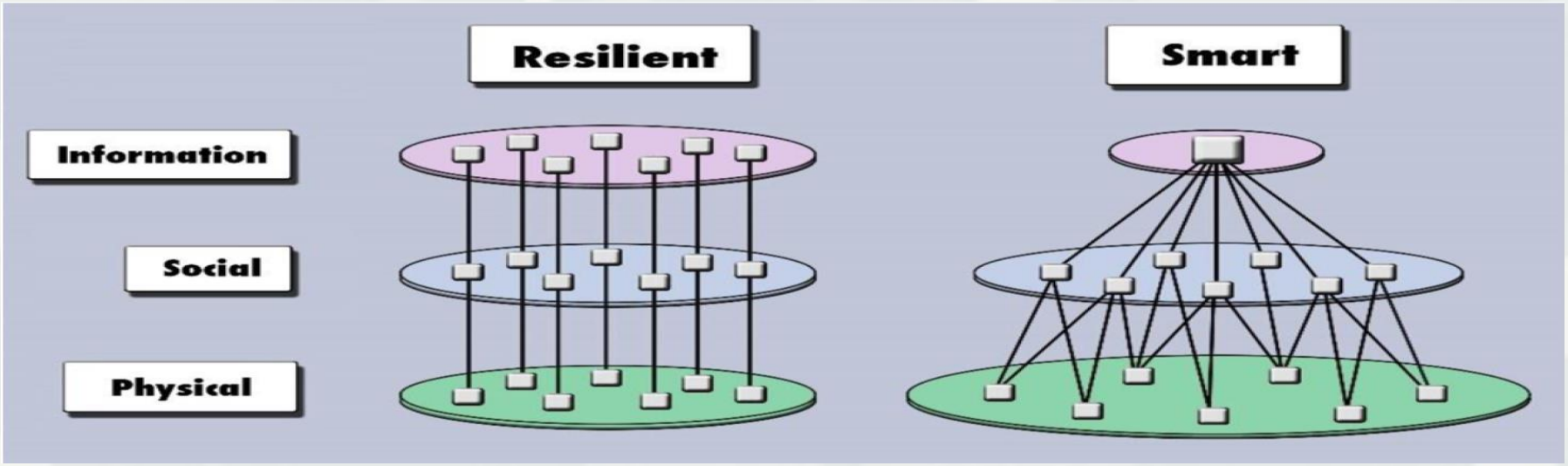


Smart

ERDC

Innovative solutions for a safer, better world

Smart vs. Resilient

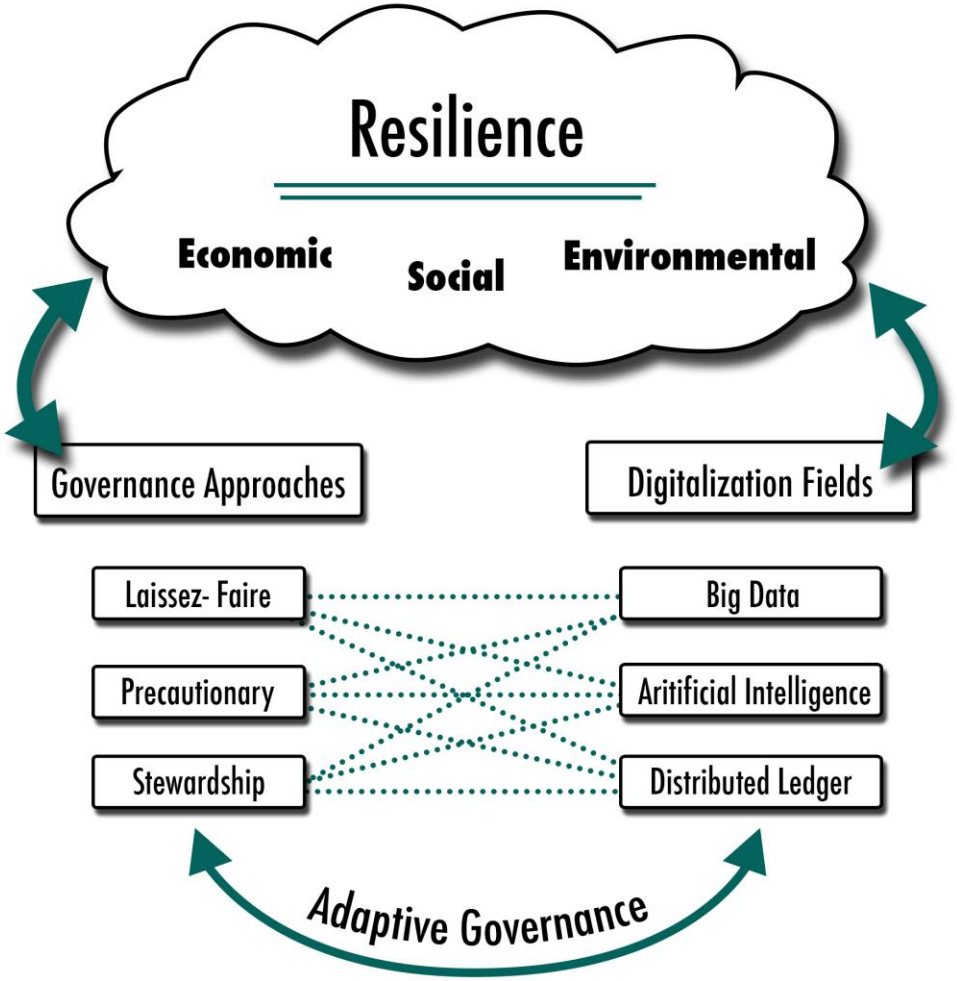


- Fully Redundant
- Greater maintenance requirements
- Functional during disruption
- **Less efficient during random attacks**

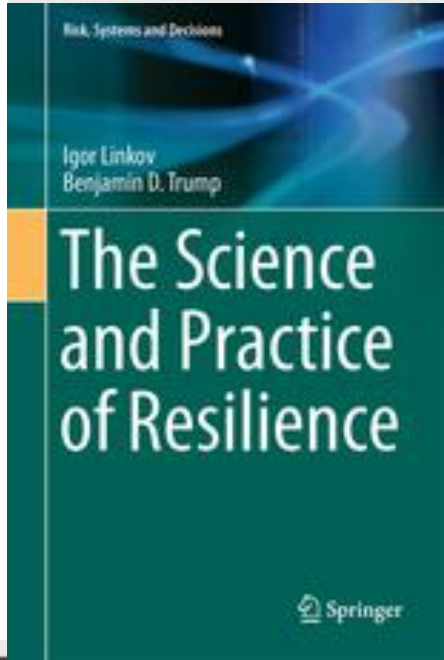
- Observe emergent patterns
- Centralized decision making
- No redundancy
- **Prone to targeted attacks**

Marchese and Linkov, 2017

Resilience, Digitalization and Governance

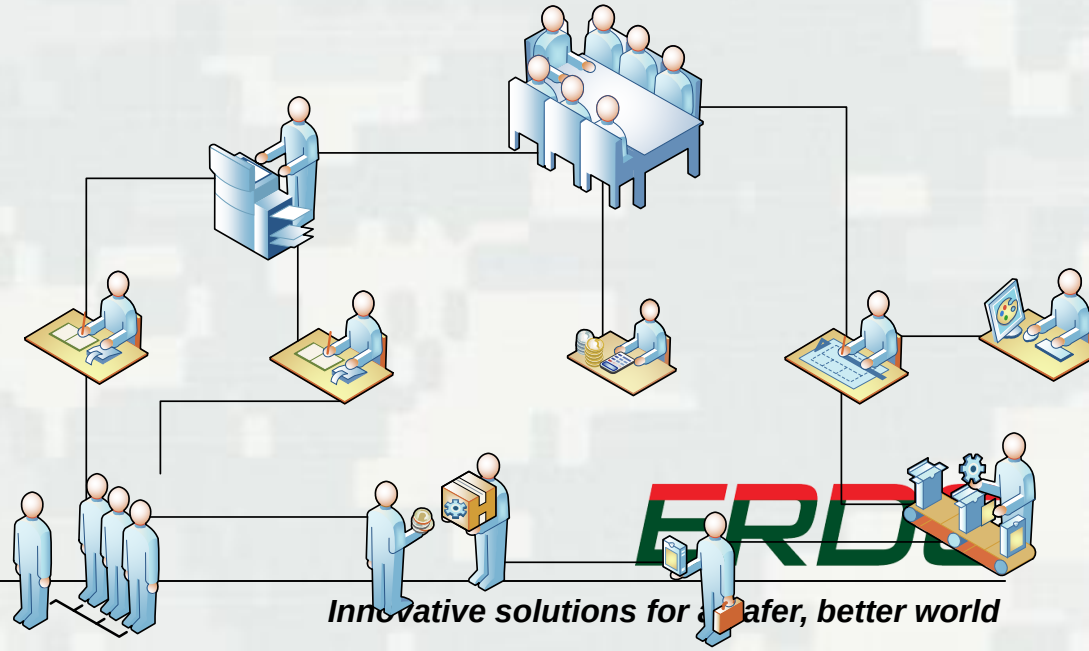


After 2019



Business and Resilience Value Chain

Business Value Chain



After

THE RESILIENCE SHIFT

Lloyd's Register Foundation

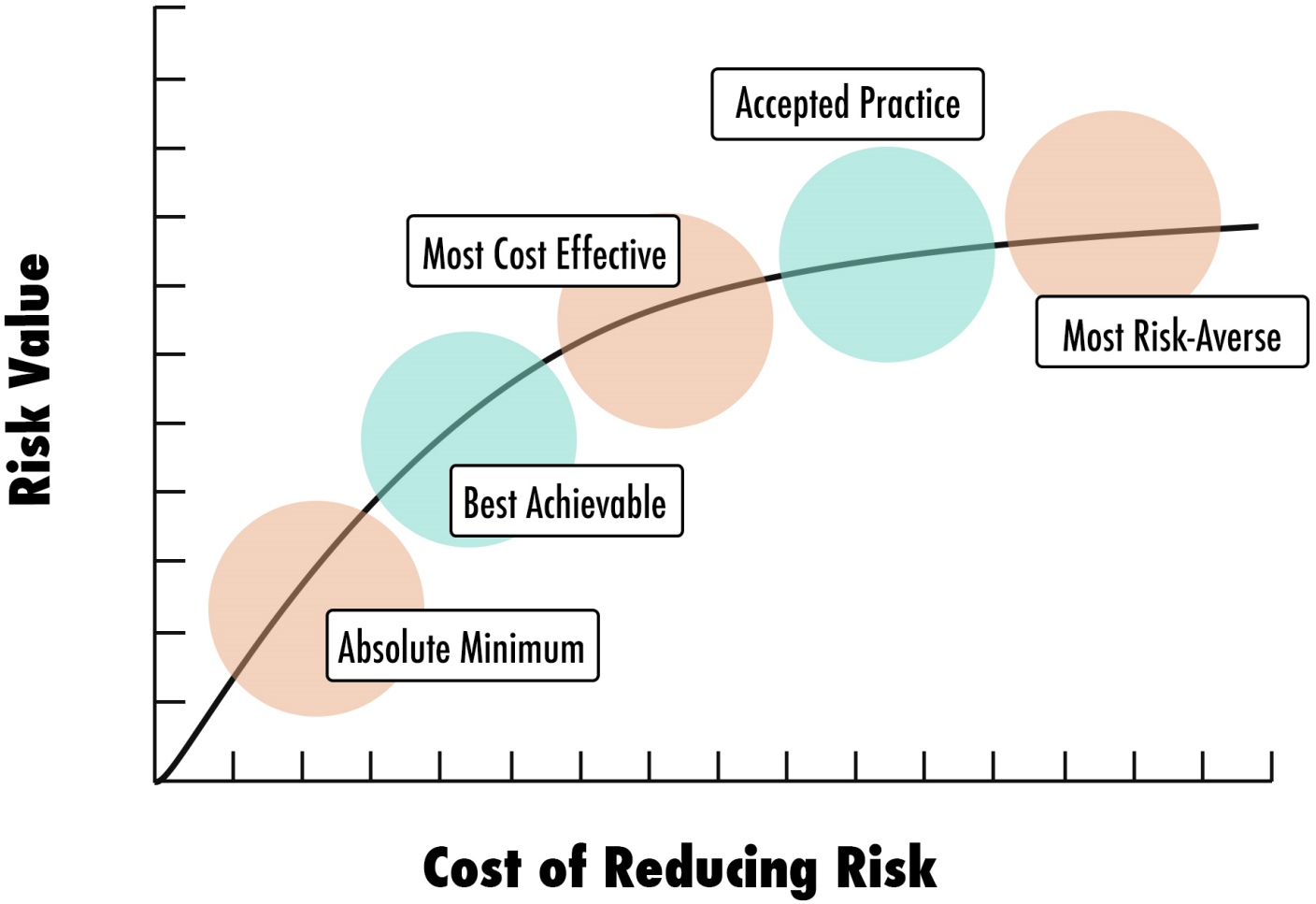
ARUP

ERDC

BUILDING STRONG®

Innovative solutions for a safer, better world

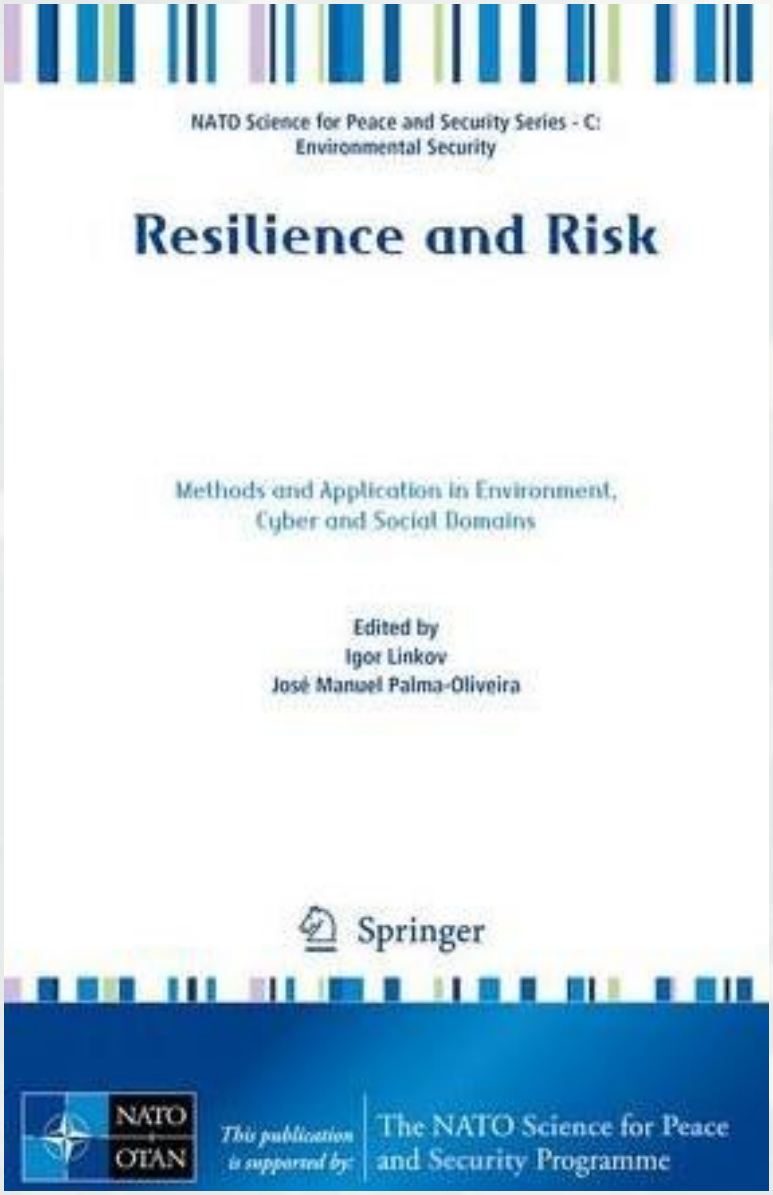
Buying Down Risk vs Managing Resilience?

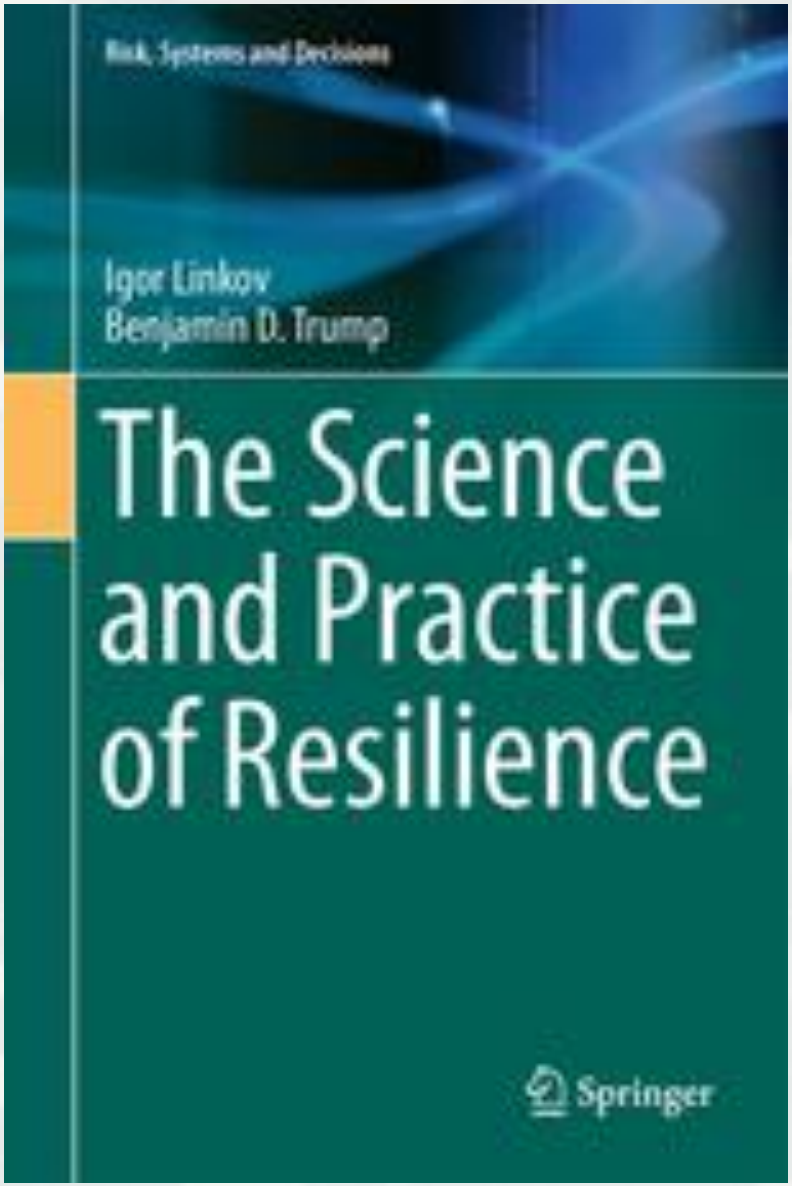


After Bostick et al 2018

References

1) Kott, A., Linkov, I. eds (2019). **Cyber Resilience in Systems and Networks.** Springer, Amsterdam.
2) Linkov, I., Palma-Oliveira, J.M., eds (2017). **Risk and Resilience.** Springer, Amsterdam.
3) Florin, M.V., Linkov, I., eds. (2017). **International Risk Governance Council (IRGC) Resource Guide on Resilience**. International Risk Governance Center, Switzerland
4) Linkov, I., Trump, B.D., Keisler, J.M. (2018). **Risk and resilience must be independently managed**. Nature 555:30
5) Kurth, M., Keenan, J.M., Sasani, M., Linkov, I. (2018, in press). **Defining resilience for the US building industry**. Building Research and Innovation.
6) Bostick, T.P., Lambert, J.H., Linkov, I. (2018). **Resilience Science, Policy and Investment for Civil Infrastructure**. Reliability Engineering & System Safety **175:**19-23.
7) Massaro, E., Ganin, A., Linkov, I., Vespignani, A. (2018). **Resilience management of networks during large-scale epidemic outbreaks**. Science Reports **8:**1859.
8) Ganin, A., Kitsak, M., Keisler, J., Seager, T., Linkov, I., (2017). **Resilience and efficiency in transportation networks**. Science Advances **3**:e1701079.
9) Marchese, D., Reynolds, E., Bates, M.E., Clark, S.S., Linkov, I. (2018). **Resilience and sustainability: similarities and differences.** Sci Total Environ. 613-614:1275-83.
10) Marchese, D., & Linkov, I. (2017). **Can You Be Smart and Resilient at the Same Time?** *Environ. Sci. Technol.* 2017, 51, 5867−5868
11) Connelly, E. B., Allen, C. R., Hatfield, K., Palma-Oliveira, J. M., Woods, D. D., & Linkov, I. (2017). **Features of resilience**. *Environ Systems and Decisions*, 37(1), 46-50.
12) Allen, C.R., Bartlett-Hunt, S., Bevans, R.A., Linkov, I. (2016). **Avoiding decline: fostering resilience and sustainability in midsize cities**. Sustainability 8:844
13) DiMase D, Collier ZA, Linkov I (2016, on-line) **Traceability and Risk Analysis Strategies for Addressing Counterfeit Electronics in Supply Chains.** Risk Analysis.
14) Thorisson, H., Lambert, J.H., Cardenas, J.J., Linkov, I., (2017). **Resilience Analytics with Application to Power Grid of a Developing Region**. Risk Analysis 37:1268
15) Gisladottir, V., Ganin, A., Keisler, J.M., Kepner, J., Linkov, I., (2017). **Resilience of Cyber Systems with Over- and Under-regulation** Risk Analysis 37:1644
16) Bakkensen, L., Fox-Lent, C., Read, L., and Linkov, I. (2016). **Validating Resilience and Vulnerability Indices in the Context of Natural Disasters**. Risk Analysis 37:982
17) Linkov, I., Larkin, S., Lambert, J.H. (2015). **Concepts and approaches to resilience in governance.** Environment, Systems, and Decisions 35:219-228.
18) Ganin, A., Massaro, E., Keisler, J., Kott, A., Linkov, I. (2016). **Resilient Complex Systems and Networks**. Nature Scientific Reports 6,19540.
19) Fox-Lent, C., Bates, M. E., Linkov, I. (2015). **A Matrix Approach to Community Resilience Assessment.**. Environment, Systems, and Decisions 35(2):205-219.
20) Larkin, S., Fox-Lent C., Linkov, I. (2015). **Benchmarking Agency and Organizational Practices in Resilience Decision Making**. Environ., Syst., & Dec. 35(2):185-195.
21) DiMase D, Collier ZA, Linkov I (2015). **Systems Engineering Framework for Cyber Physical Security and Resilience.** Environment, Systems, and Decisions 35:291.
22) Sikula, N.R., Linkov, I., (2015). **Risk Management Isn't Enough: A Conceptual Model for Resilience.** Environ., Syst., & Dec. 35:219-228.
23) Linkov, I., Fox-Lent, C., Keisler, J., Della-Sala, S., Siweke, J. (2014). **Plagued by Problems: Resilience Lessons from Venice** .Environment, Systems, Decision 34:378
24) Collier, Z.A., Linkov, I., DiMase, D., Walters, S., Lambert, J.(2014). **Risk-Based Cybersecurity Standards: Policy Challenges and Opportunities**. *Computer* 47:70
25) Linkov, I, Kröger, W., Levermann, A., Renn, O. et al. (2014). **Changing the Resilience Paradigm**. *Nature Climate Change* 4:407
26) Roege, P., Collier, Z.A., Mancillas, J., McDonagh, J., Linkov, I. (2014). **Metrics for Energy Resilience**. *Energy Policy* Energy Policy 72:249
27) Eisenberg, D.A., Linkov, I., Park, J., Chang, D., Bates, M.E., Seager, T., (2014). **Resilience Metrics: Lessons from Military Doctrines**. *Solutions* 5:76
28) Linkov, I., Eisenberg, D. A., Plourde, K., Seager, T. P., Allen, J., Kott, A (2014). **Resilience Metrics for Cyber Systems**. *Environment, Systems and Decisions* 33:471
29) Park, J., Seager, T, Linkov, I., (2013). "**Integrating risk and resilience approaches to catastrophe management in engineering systems**," *Risk Analy.*, 33(3), pp. 356.
30) Linkov, I., Eisenberg, D. A., Bates, M. E., Flynn, S. E., Seager, T. P. (2013). **Measurable Resilience for Actionable Policy**. *Environ. Science & Technology* 47:10108


NATO Science for Peace and Security Series - C:
Environmental Security
Resilience and Risk
Methods and Application in Environment,
Cyber and Social Domains
Edited by
Igor Linkov
José Manuel Palma-Oliveira
Springer
NATO
OTAN
This publication is supported by:
The NATO Science for Peace and Security Programme

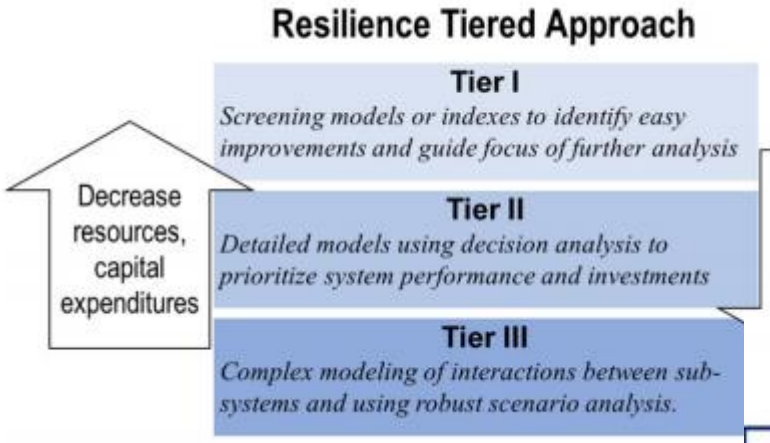

Risk, Systems and Decisions
Igor Linkov
Benjamin D. Trump
The Science and Practice of Resilience
Springer

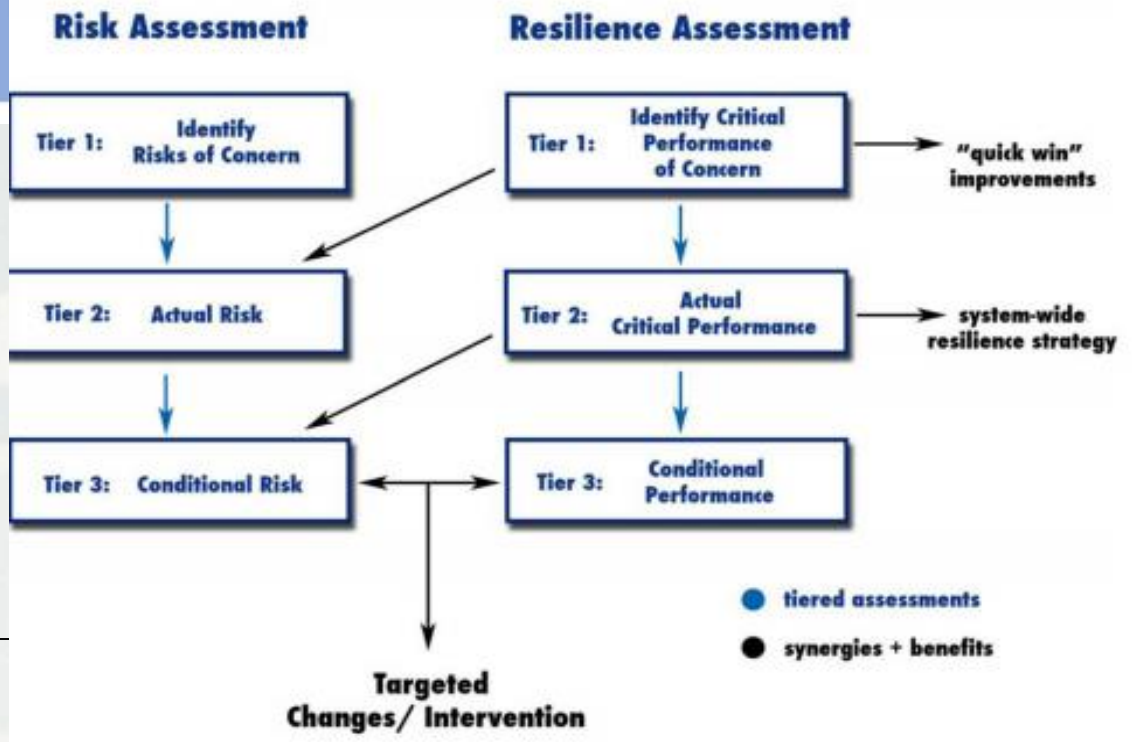
Risk Analysis DOI: 10.1111/risa.12

Perspective

Tiered Approach to Resilience Assessment

Igor Linkov,[1,*] Cate Fox-Lent,[1] Laura Read,[1] Craig R. Allen,[2] James C. Arnott,[3,11]
ı Coaffee,[5] Marie-Valentine Florin,[6] Kirk Hatfield,[7] Iain Hyde,[21]
ɜandar Jovanovic,[9] Roger Kasperson,[10] John Katzenberger,[11]
ames H. Lambert,[13] Richard Moss,[14] Peter S. Murdoch,[15]
Roger S. Pulwarty,[17] Dale Sands,[23] Edward A. Thomas,[18]
vid Woods[20]





Contents lists available at ScienceDirect

Omega

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

Quantifying and mapping resilience within large organizations☆

Matthew Wood, Emily Wells, Glenn Rice, Igor Linkov*

Army

Ready and Resilient