Smart and Resilient Energy Systems: Metrics and Evaluation

Igor Linkov and Matthew Bates

Risk and Decision Sciences Team, US Army

6172339869

Igor.Linkov@usace.army.mil

US Army Corps of Engineers.

- 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 possible should the storm impact its service area.

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."

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.

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

BUILDING STRONG®

ENVIRONMENTAL Science & Technology

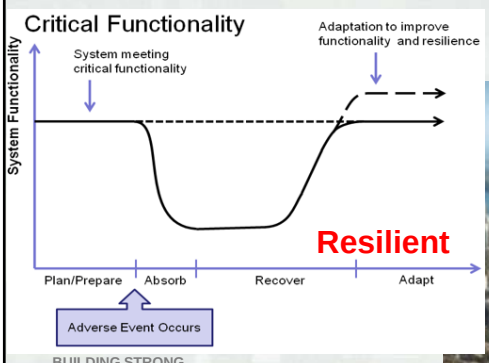
Viewpoint

pubs.acs.org/es

Can You Be Smart and Resilient at the Same Time?

Dayton Marchese and Igor Linkov*

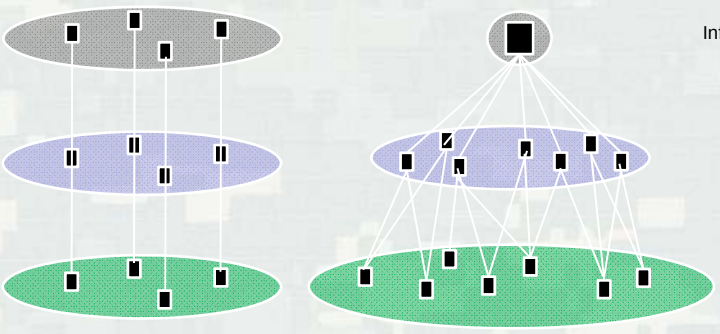
DOI: 10.1021/acs.est.7b01912
Environ. Sci. Technol. 2017, 51, 5867−5868



Smart

BUILDING STRONG®

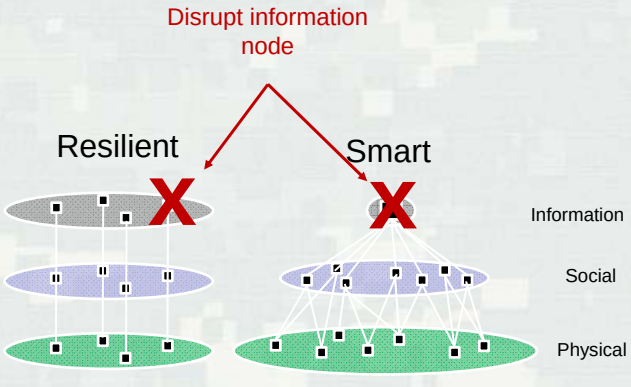
Smart vs Resilient



BUILDING STRONG®

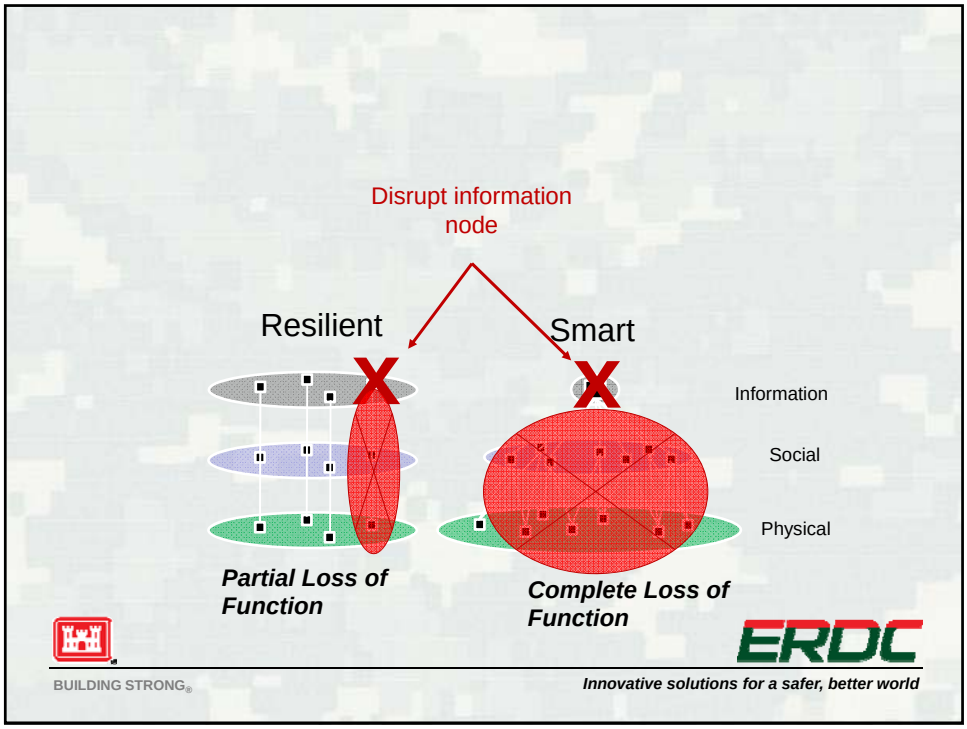
Innovative solutions for a safer, better world

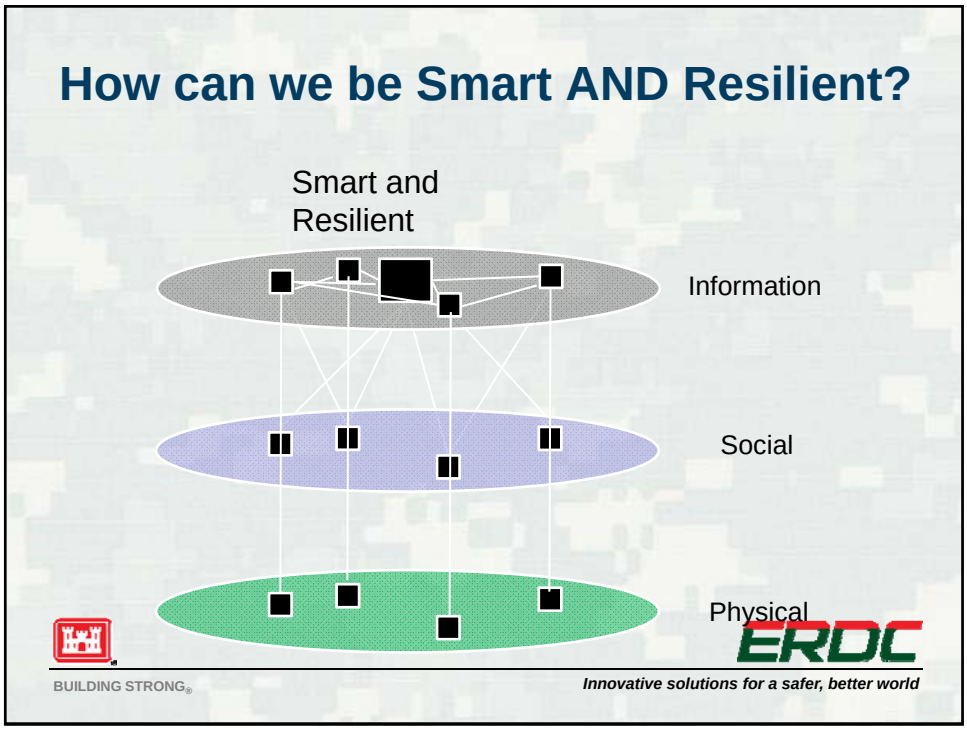
Smart vs Resilient under Attack



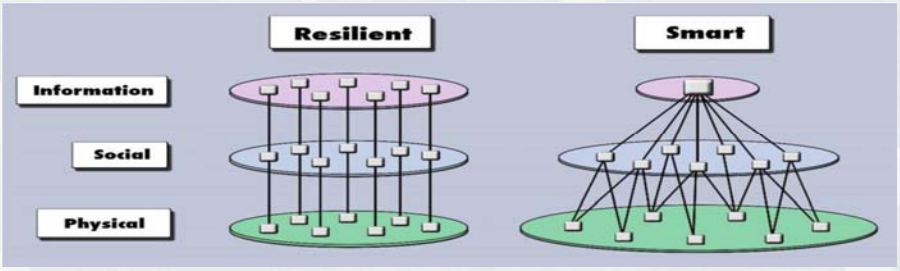
BUILDING STRONG®

Innovative solutions for a safer, better world


Disrupt information node
Resilient
Smart
Information
Social
Physical
Partial Loss of Function
Complete Loss of Function
BUILDING STRONG®
Innovative solutions for a safer, better world


How can we be Smart AND Resilient?
Smart and Resilient
Information
Social
Physical
BUILDING STRONG®
Innovative solutions for a safer, better world

Difference in Smartness and Resilience



- 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**

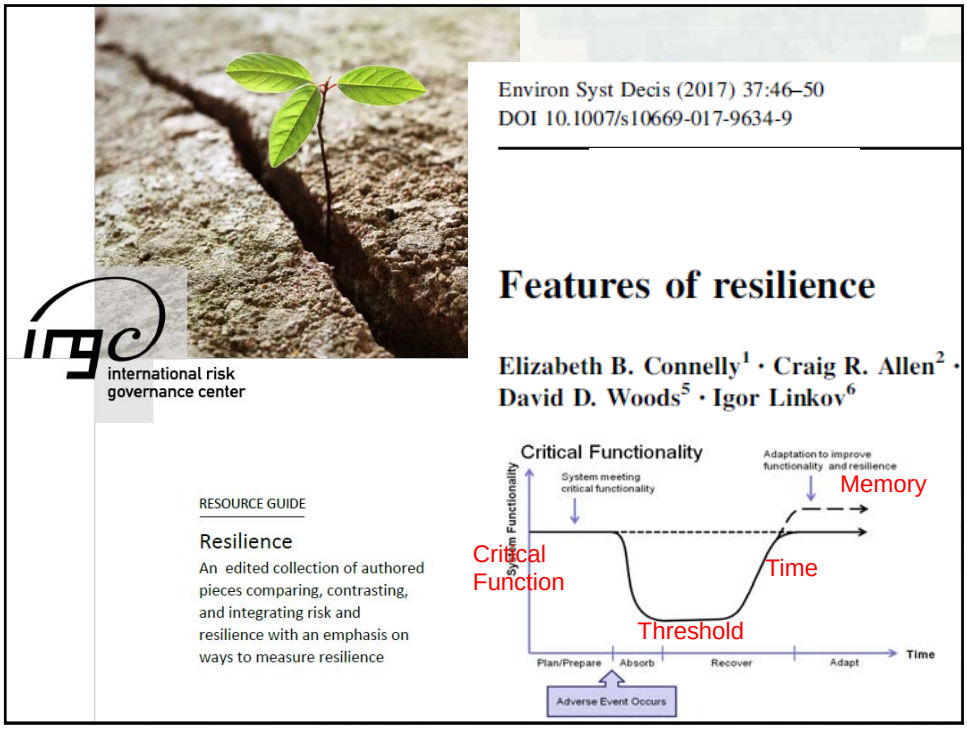
How to Quantify Resilience and do Tradeoffs?

Marchese and Linkov, 2017

Measuring the "Smartness" of the Electricity Grid

B. Dupont, *Student Member, IEEE*, L. Meeus, and R. Belmans, *Fellow, IEEE*

Enable informed participation by customers	
Advanced Meters	1A: Number of advanced meters installed
	1B: Percentage of total demand served by advanced meters
Dynamic Pricing Signals	2A: The fraction of customers served by RTP tariffs
	2B: The fraction of load served by RTP tariffs
Smart Appliances	3A: Total yearly retail sales volume for purchases of smart appliances [€]
	3B: Total load capacity in each consumer category that is actually or potentially modified by behaviours of smart appliances [MW]
Demand Side Management	4A: Fraction of consumers contributing in DSM [%]
	4B: Percentage of consumer load capacity participating in DSM [MW/MW]
	4C: Potential for time shift (before start-up and during operation) [h]
Prosumer	5A: Total electrical energy locally (decentralised) produced versus total electrical energy consumed [MWh/MWh]
	5B: Minimal demand from grid (maximal own production) versus maximal demand from the grid (own production is zero) [MW/MW]
	5C: Fraction of time prosumer is net producer and consumer [h/h]
Accommodate all generation and storage options	
Distributed Generation and Storage	6A: Amount of production generated by local, distributed generation (MW/MW)
	6B: Potential for direct electrical energy storage relative to daily demand for electrical energy [MWh_{el}/MWh_{el}]
	6C: Indirect electrical energy storage through the use of heat pumps: time shift allowed for heating/cooling [h]
PHEVs	7A: The total number and percentage shares of on-road light-duty vehicles, comprising PHEVs
	7B: Percentage of the charging capacity of the vehicles that can be controlled (versus the charging capacity of the vehicles or the total power capacity of the grid) [MW/MW]
	7C: Percentage of the stored energy in vehicles that can be controlled (versus the available energy in the vehicles or the total energy consumption in the grid) [MWh/MWh]
	7D: Number of charging points that are provided to charge the vehicles
DER Interconnection	8A: The percentage of grid operators with standard distributed resource interconnection policies
Sell more than kWhs	
New Energy Services	9A: Number of customers served by ESCO's
	9B: Number of additional energy services offered to the consumer
	9C: Number of kWh that the consumer saves in comparison to the consumption before the energy service
Flexibility	10A: The number of customers offering flexibility to aggregators
	10B: The flexibility that aggregators can offer to other market players [MWh]
	10C: The time that aggregators can offer a certain flexibility [h]
	10D: To what extent are storage and DG able to provide ancillary services as a percentage of the total offered ancillary services
	10E: Percentage of storage and DG that can be modified vs. total storage and DG [MW/MW]
Customer Choice	11A: Number of tariff plans available to end consumers
Support Mechanisms	12A: The average percentage of smart grid investment that can be recovered through rates or subsidies
	12B: The percentage of smart grid investment covered by external financing
Interoperability Maturity Level	13A: The weighted average maturity level of interoperability realised among electricity system stakeholders
Provide power quality for the 21st Century	
Power Quality	14A: Amount of voltage variations in the grid [RMS]



international risk governance center

RESOURCE GUIDE

Resilience

An edited collection of authored pieces comparing, contrasting, and integrating risk and resilience with an emphasis on ways to measure resilience

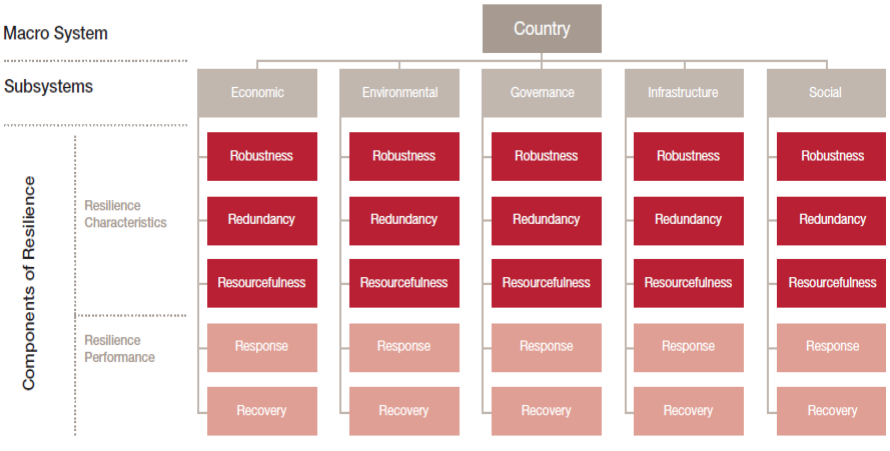
Environ Syst Decis (2017) 37:46–50
DOI 10.1007/s10669-017-9634-9

Features of resilience

Elizabeth B. Connelly[1] · Craig R. Allen[2] · David D. Woods[5] · Igor Linkov[6]

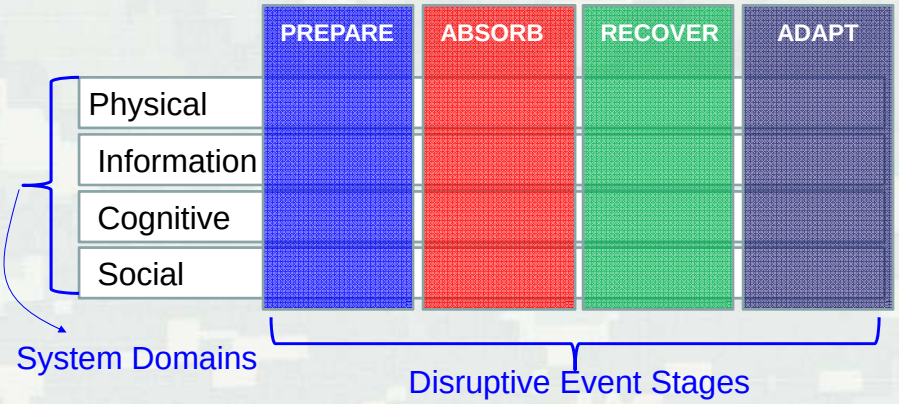
Resilience -- 3R, 4R, 5R?

Figure 1 What is resilience?



Source: World Economic Forum

2. Metrics-Based Resilience Approaches



Linkov et al., 2013

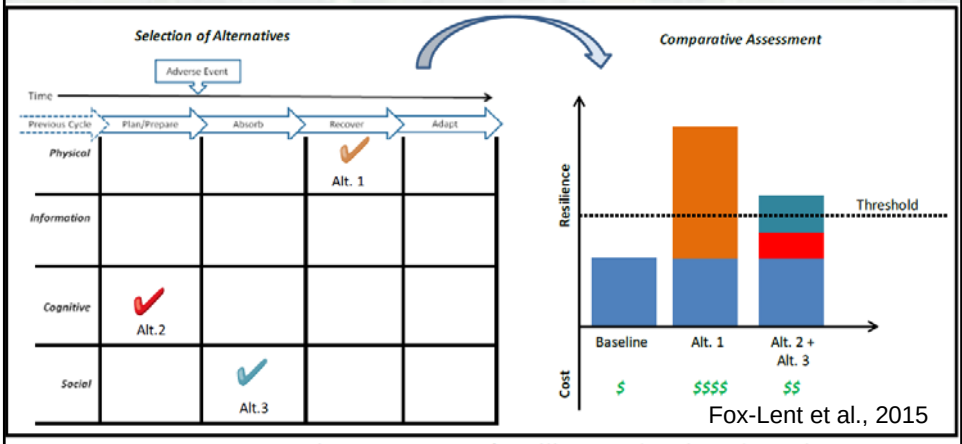
Scale

Home | Neighborhood | Town | County | Region | State | Country

BUILDING STRONG®

Innovative solutions for a safer, better world

Assessment using Decision Analysis



Fox-Lent et al., 2015

Figure 5: Comparative Assessment of Resilience-Enhancing Alternatives

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

solutions for a safer, better world

How it works: Project Evaluation

- Baseline assessment can be used to evaluate proposed projects

	Prepare	Absorb	Recover	Adapt	
Physical	71	16	60	10	
Information	63	45	21	18	
Cognitive	90	49	38	27	
Social	82	54	12	52	43

Project 1

	Prepare	Absorb	Recover	Adapt
Physical	+10	+18	+9	+32
Information	+8		+17	
Cognitive				
Social				

	Prepare	Absorb	Recover	Adapt	
Physical	81	34	69	42	
Information	71	45	38	18	
Cognitive	90	49	38	27	
Social	82	54	12	52	51

Project 2

	Prepare	Absorb	Recover	Adapt
Physical				
Information		+5	+15	+22
Cognitive				
Social	+3		+12	+21

	Prepare	Absorb	Recover	Adapt	
Physical	71	6	60	10	
Information	63	50	36	40	
Cognitive	90	49	38	27	
Social	85	54	24	73	47

*Projects may have (+) or (-) in other matrices

Problems with Metrics-Based Approaches

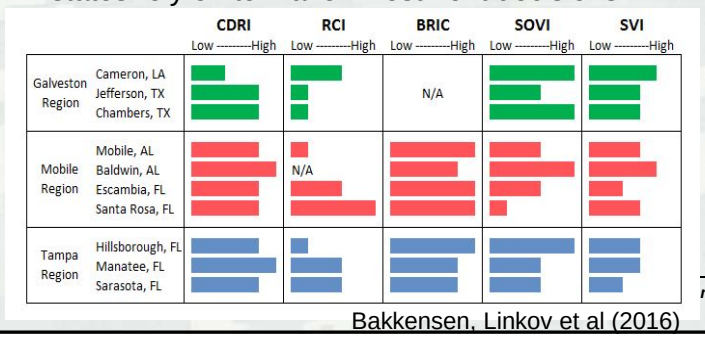
•Measuring for emerging threats remains difficult: the gap between measures and increased vulnerabilities can be hard to close

•Many measurement programs utilize data that does not contribute to informing decisions or changing behavior.

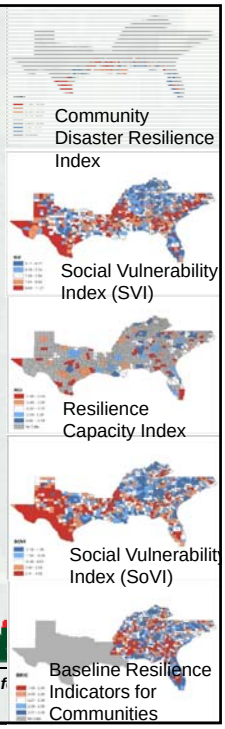
Not everything that counts can be counted, and not everything that can be counted counts.
Albert Einstein

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?



Bakkensen, Linkov et al (2016)



Emerging Science of Resilience

- Integration of Eco, Engineering and Psychological legs of Resilience
- Resilience Matrix and Visualization Tool
- Tiered Approach to Resilience Assessment
- Network Science Methodology
- Smartness vs. Resilience

Table 1 Resilience features common to socio-ecology, psychology, organizations, and engineering and infrastructure, which are related to the temporal phases from the National Academy of Sciences definition of resilience

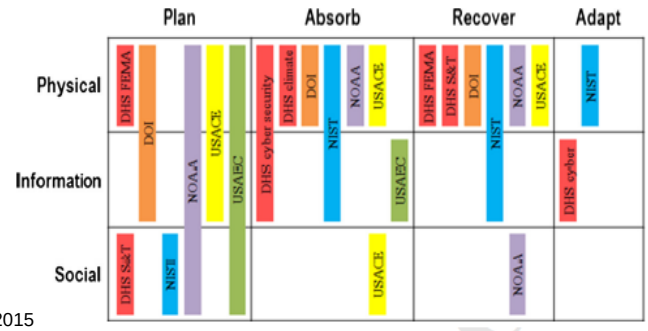
NAS phase of resilience	Resilience feature	Description by application domain			
		Socio-ecological	Psychological	Organizational	Engineering and infrastructure
Plan	Critical functions (services)	A system function identified by stakeholders as an important dimension by which to assess system performance			
		Ecosystem services provided to society	Human psychological well-being	Goods and services provided to society	Services provided by physical and technical engineered systems
Absorb	Thresholds	Intrinsic tolerance to stress or changes in conditions where exceeding a threshold perpetuates a regime shift			
		Used to identify natural breaks in scale	Based on sense of community and personal attributes	Linked to organizational adaptive capacity and to brittleness when close to threshold	Based on sensitivity of system functioning to changes in input variables
Recover	Time (and scale)	Duration of degraded system performance			
		Emphasis on dynamics over time	Emphasis on time of disruption (i.e., developmental stage: childhood vs adulthood)	Emphasis on time until recovery	Emphasis on time until recovery
Adapt	Memory/ adaptive management	Change in management approach or other responses in anticipation of or enabled by learning from previous disruptions, events, or experiences			
		Ecological memory guides how ecosystem reorganizes after a disruption, which is maintained if the system has high modularity	Human and social memory can enhance (through learning) or diminish (e.g., post-traumatic stress) psychological resilience	Corporate memory of challenges posed to the organization and management that enable modification and building of responsiveness to events	Re-designing of engineering systems designs based on past and potential future stressors

Connelly et al., 2017

2. Resilience of Complex Organizations

Environ Syst Decis

Fig. 1 Agency resilience actions addressed (relative to NAS definition) in physical, information, and social domains



Larkin, Fox-Lent, Linkov et al., 2015

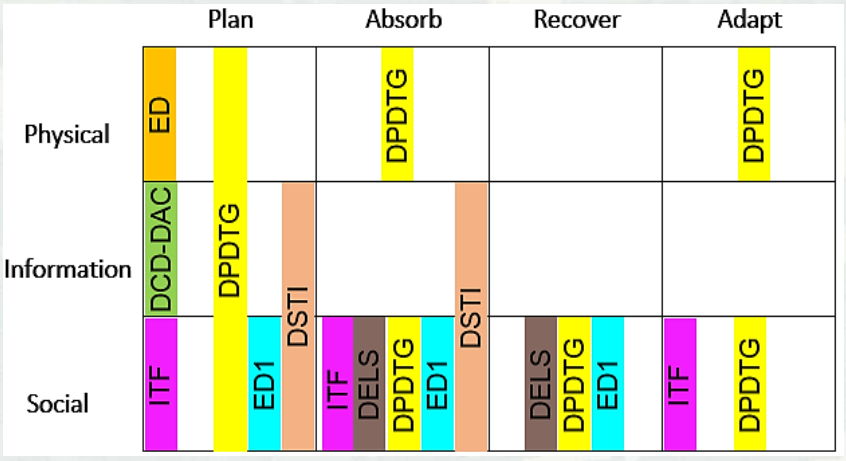
BUILDING STRONG®

ERDC

Innovative solutions for a safer, better world

20

Resilience: OECD



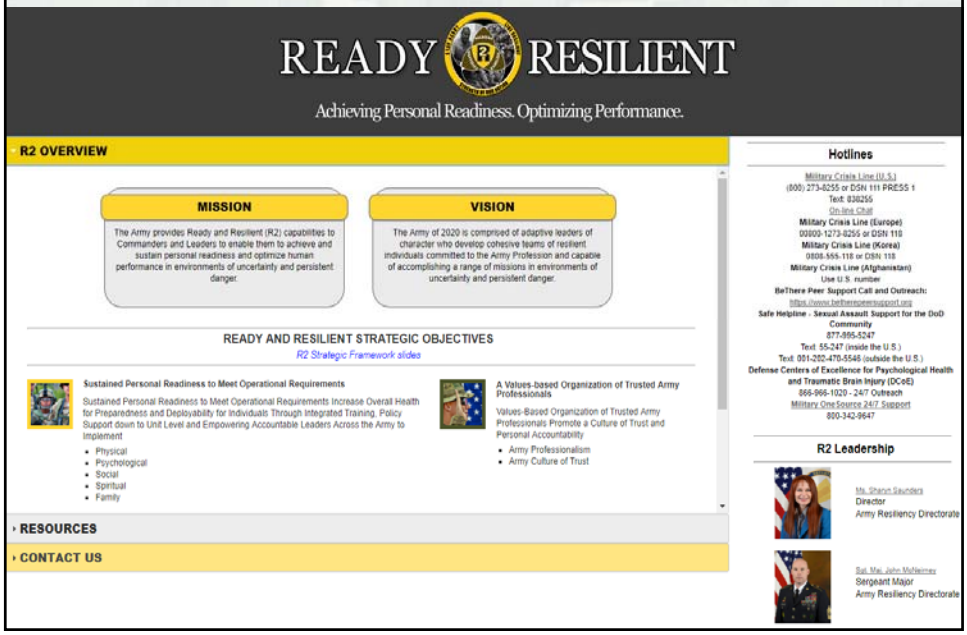
, Linkov, 2017

BUILDING STRONG®

Innovative solutions for a safer, better world

21

US Army



Resilience: US Army

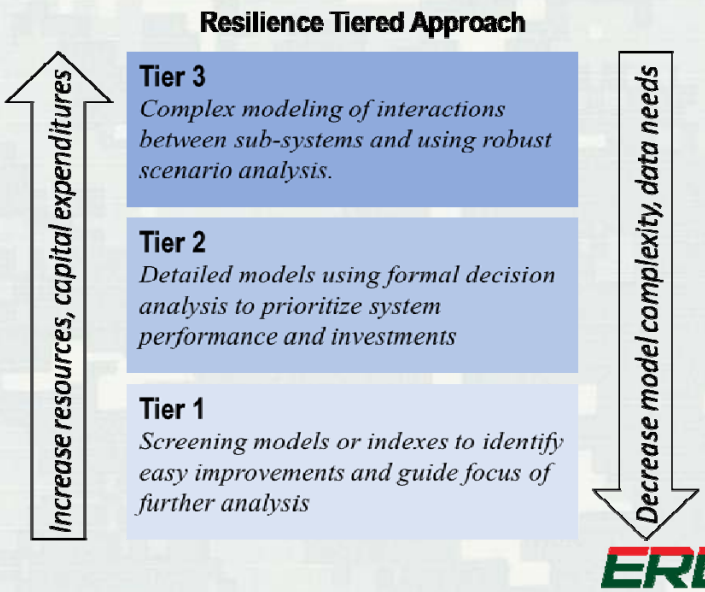
AFTER WOOD ET AL, 2018

BUILDING STRONG®

Innovative solutions for a safer, better world

23

3. Tiered Approach to Resilience Assessment



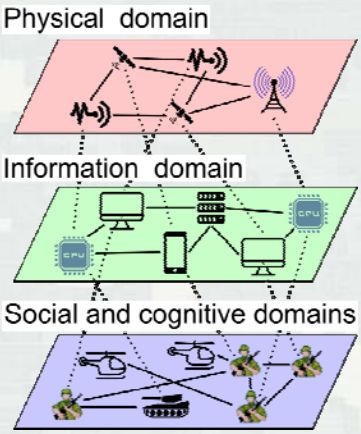
BUILDING STRONG®

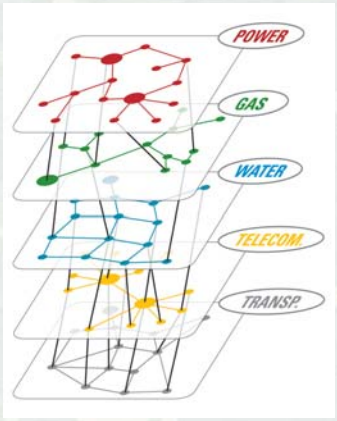
After Linkov et al., 2017

Innovative solutions for a safer, better world

4. Future: Network-based Approaches

We quantify resilience by using network science approach by considering the different domains as interdependent multiplex networks.





BUILDING STRONG®

Innovative solutions for a safer, better world

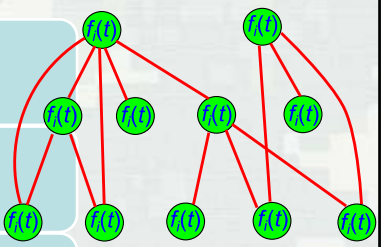
Network-based Resilience Theory?

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 ($\boldsymbol{E}$)



Ganin et al., 2016

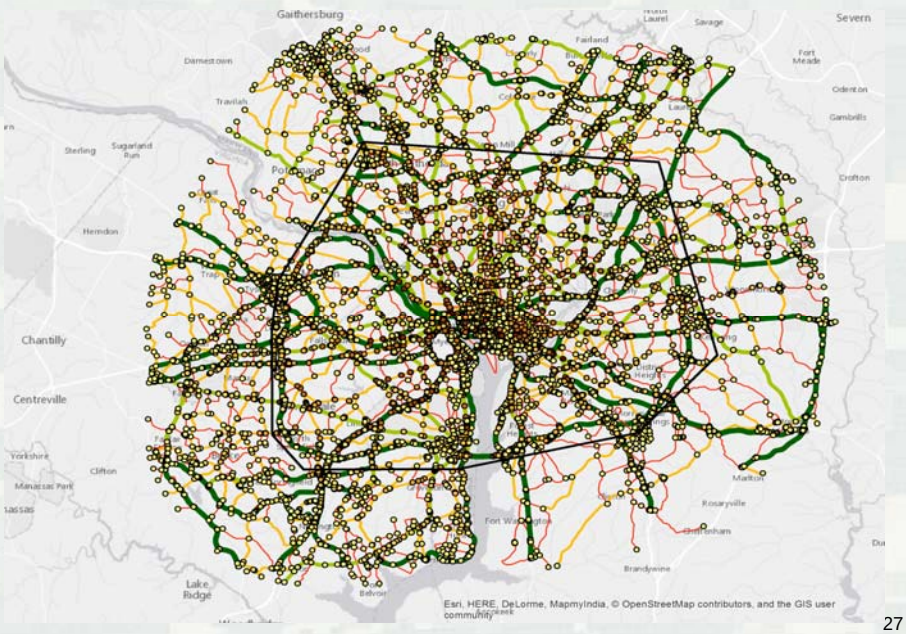
$$R = f(\mathcal{N}, \mathcal{L}, \mathcal{C}, \boldsymbol{E})$$

BUILDING STRONG®

Innovative solutions for a safer, better world

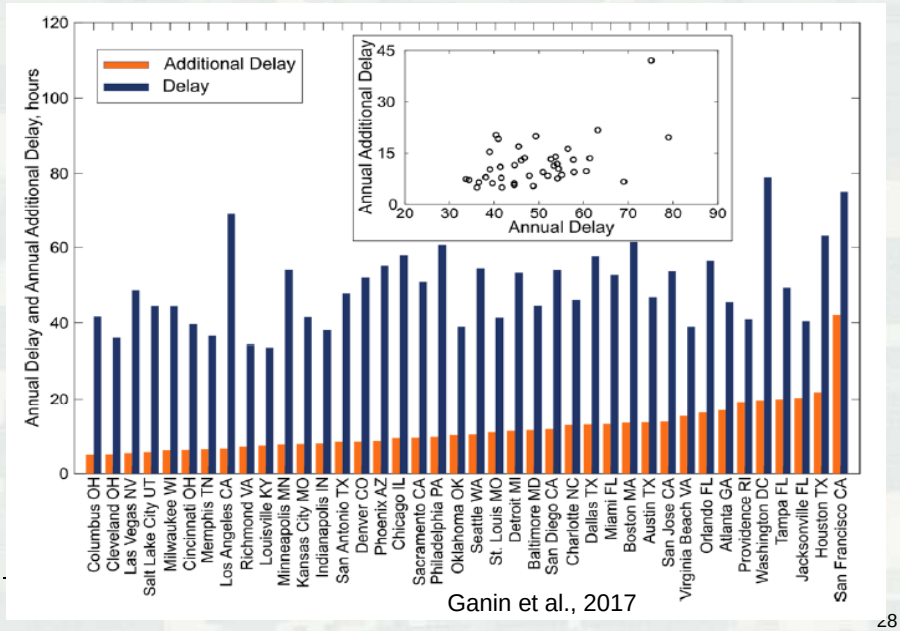
26

Transportation Networks in 40 Cities



27

Smartness/Efficiency vs. Resilience



Ganin et al., 2017

28

References

1) Linkov, I., Palma-Oliveira, J.M., eds (2017). **Risk and Resilience**. Springer, Amsterdam.
2) Florin, M.V., Linkov, I., eds. (2016). **International Risk Governance Council (IRGC) Resource Guide on Resilience**. International Risk Governance Center, 2016
3) Ganin, A., Kitsak, M., Keisler, J., Seager, T., Linkov, I., (2017, accepted for publication). Resilience and efficiency in transportation networks. Science Advances.
4) Marchese, D., & Linkov, I. (2017). **Can You Be Smart and Resilient at the Same Time?** *Environ. Sci. Technol.* 2017, 51, 5867−5868
5) 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.
6) Collier ZA, Kott A, Linkov I. (2016). **Security metrics in industrial control systems**. Cyber-Security of SCADA and Other Industrial Control Systems. New York, NY: Springer; 2016.
7) Allen, C.R., Bartlett-Hunt, S., Bevans, R.A., Linkov, I. (2016). **Avoiding decline: fostering resilience and sustainability in midsize cities**. Sustainability 8:844
8) DiMase D, Collier ZA, Linkov I (2016, on-line) **Traceability and Risk Analysis Strategies for Addressing Counterfeit Electronics in Supply Chains**. Risk Analysis.
9) Thorisson, H., Lambert, J.H., Cardenas, J.J., Linkov, I., (2016, on-line). **Resilience Analytics with Application to Power Grid of a Developing Region**. Risk Analysis
10) Gisladottir, V., Ganin, A., Keisler, J.M., Kepner, J., Linkov, I., (2016, on-line). **Resilience of Cyber Systems with Over- and Under-regulation** Risk Analysis
11) Bakkensen, L., Fox-Lent, C., Read, L., and Linkov, I. (2016, on-line). **Validating Resilience and Vulnerability Indices in the Context of Natural Disasters**. Risk Analysi
12) Linkov, I., Larkin, S., Lambert, J.H. (2015). **Concepts and approaches to resilience in governance**. Environment, Systems, and Decisions 35:219-228.
13) Ganin, A., Massaro, E., Keisler, J., Kott, A., Linkov, I. (2016). **Resilient Complex Systems and Networks**. Nature Scientific Reports 6,19540.
14) Fox-Lent, C., Bates, M. E., Linkov, I. (2015). **A Matrix Approach to Community Resilience Assessment**.. Environment, Systems, and Decisions 35(2):205-219.
15) Larkin, S., Fox-Lent C., Linkov, I. (2015). **Benchmarking Agency and Organizational Practices in Resilience Decision Making**. Environ., Syst., & Dec. 35(2):185-195.
16) DiMase D, Collier ZA, Linkov I (2015). **Systems Engineering Framework for Cyber Physical Security and Resilience**. Environment, Systems, and Decisions 35:291.
17) Sikula, N.R., Linkov, I., (2015). **Risk Management Isn't Enough: A Conceptual Model for Resilience**. Environ., Syst., & Dec. 35:219-228.
18) Linkov, I., Fox-Lent, C., Keisler, J., Della-Sala, S., Siweke, J. (2014). **Plagued by Problems: Resilience Lessons from Venice**.
19) Collier, Z.A., Linkov, I., DiMase, D., Walters, S., Lambert, J.(2014). **Risk-Based Cybersecurity Standards: Policy Challenges and Opportunities**. *Computer* 47:70
20) Linkov, I, Kröger, W., Levermann, A., Renn, O. et al. (2014). **Changing the Resilience Paradigm**. *Nature Climate Change* 4:407
21) Roege, P., Collier, Z.A., Mancillas, J., McDonagh, J., Linkov, I. (2014). **Metrics for Energy Resilience**. *Energy Policy* Energy Policy 72:249
22) Eisenberg, D.A., Linkov, I., Park, J., Chang, D., Bates, M.E., Seager, T., (2014). **Resilience Metrics: Lessons from Military Doctrines**. *Solutions* 5:76
23) 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
24) Park, J., Seager, T, Linkov, I., (2013). **"Integrating risk and resilience approaches to catastrophe management in engineering systems,"** *Risk Analy.*, 33(3), pp. 356.
25) Linkov, I., Eisenberg, D. A., Bates, M. E.,., Flynn, S. E., Seager, T. P. (2013). **Managing resilience to meet national needs**. *Environ. Science & Technology* 47:10108

Springer

Call for Papers:
Special Issue on
Disruptions, Adaptation, and Resilience:
Analysis, Data, and Validation

BUILDING STRONG®

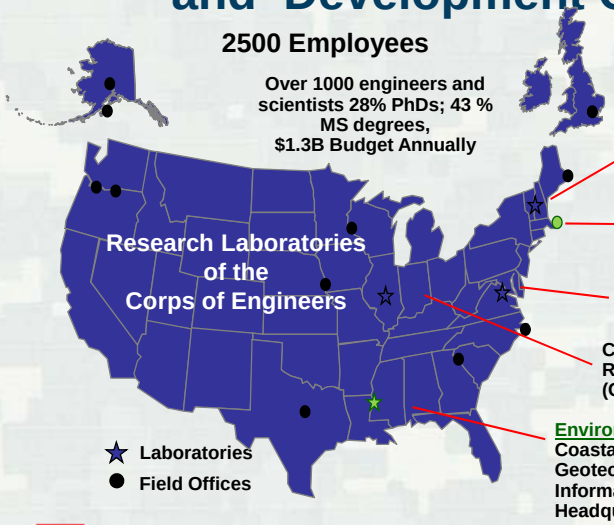
ERDC

Innovative solutions for a safer, better world

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)

BUILDING STRONG®

ERDC

Innovative solutions for a safer, better world

32