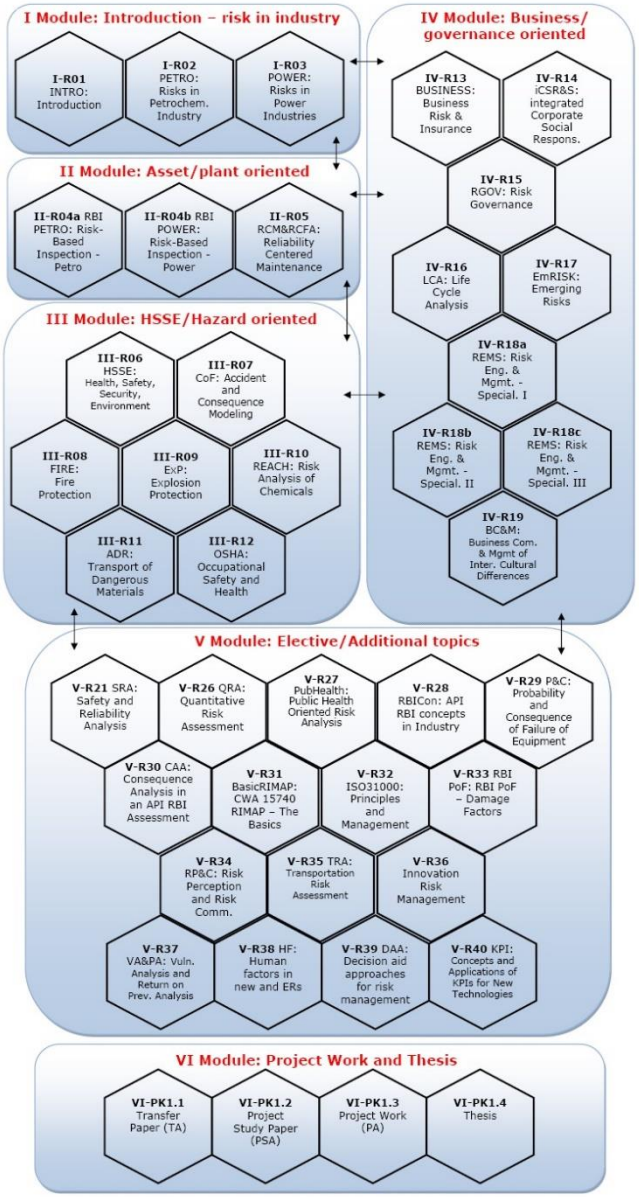
Course VC-R42 RoI:

Resilience of Infrastructures

Unit 1: State-of-the-art, basic principles, approaches



How do you define resilience?

Outline

- Definition
  - Ecology
  - Disaster resilience
  - Engineering and critical infrastructure
- Useful concept?
- Metrics and quantitative analysis
- Resilience as an operational tool

Resilience of ecological systems (Holling 1973)

- System property
- Ability of systems to absorb changes and still persist
- Relationships within a system
- Can be measured by the probability of extinction
- A system can fluctuate greatly and still be very resilient

Ecology and survivability (Carpenter et al. 2001)

- Amount of disturbance that can be tolerated before system moves to a different state space controlled by different processes
  - Need to specify a system's current configuration and which disturbances are of interest
  - Adaptive capacity

1. Amount of change system can undergo
2. Degree to which the system is capable of self-organization
3. Degree to which system can build capacity to learn and adapt

- Resilience Alliance

Disaster resilience

- United Nations International Strategy for Disaster Reduction (2005)
  - Capacity of a system, community, or society to resist or change to obtain an acceptable level of functioning
  - Degree to which system is capable of organizing itself to increase capacity for learning, adaptation, and recovery from a disaster
- Hyogo Framework for Action: Building the resilience of nations and communities to disasters
  - Substantial reduction of disaster losses, economic and environmental assets of communities and countries
  - Integration of disaster risk reduction into sustainable development
  - Development institutions and capacities to build resilience
  - Risk reduction into implement emergency preparedness, response and recovery
- European Union
  - Help communities withstand and recover from disasters
  - Focus on root causes

U.S. National Academy of Science (2012)

- Four components
  - Ability to prepare and plan for
  - Absorb
  - Recover from
  - Adapt to actual or potential adverse events
- Resilient measurement system should
  - Indicators to recover quickly
  - Social factors that enhance or inhibit a community's ability to recover
  - Indicators of ability for structures to withstand disasters
  - Factors that capture special needs of groups
- Investments in resilience will avoid the need for costly recovery later

Why is resilience important?

- Occurrence of disasters
- Population growth
- Aging public infrastructure
- Interdependent economic and social systems
- Impossibility of eliminating all risk
- Impact of climate change and degradation of natural defenses

Engineering resilience and critical infrastructure

- Lack of consensus but most definitions involve
  - Initial impact
  - Recovery time
- Four Rs (Bruneau et al. 2003, Tierney & Bruneau 2007)
  - Robustness: ability of system to withstand external shocks
  - Redundancy: extent to which system satisfy functional requirements in event of disturbance
  - Resourcefulness: ability to diagnose and initiate solutions
  - Rapidity: ability to recover and contain losses

- Scenario identification versus worst-case planning
- Does resilience include preventing a disruption?

Risk and resilience

- Park et al. (2013)
  - Risk analysis starts with identification of hazards
  - Resilience requires preparing for the unexpected
  - But resilience is a dynamic, emergent property that can only be observed in the context of a specific scenario
  - Resilience is an ongoing adaptive process for complex systems
- Haimes (2009)
  - Manifestation of states of systems
  - Time dependent

- A good risk analysis should incorporate the resilience of system
- Often risk analysis does not consider the time or recovery aspect in resilience and understanding how system responds or adapts to adverse consequences is a useful contribution of resilience thinking

Operational resilience

- Absorb impact without losing capacity to function (U.S. Homeland Security Council 2007)
- Can system (or an operator who manages the system) adapt behavior to maintain continuity of operations?
- Use of network theory and attacker-defender models (Alderson et al. 2015)
- Ignores recovery or time element

Other definitions

- Presidential Policy Directive on Critical Infrastructure Security and Resilience: ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions (The White House 2013)
- ASCE Committee on Critical Infrastructure:
  - Capability to mitigate against significant all-hazards risk and incidents
  - Recover and reconstitute critical service
- UK Civil Contingencies Secretariat of the Cabinet Office: ability of a system or organization to withstand and recover from adversity
- Infrastructure Security Partnership: holistic concept

Useful concept or just a buzzword?

- Resilience developed from a concept in mechanics to a word that is interpreted wildly and applied to many different areas
- Umbrella concept for many desirable attributes → leads to confusion and is not very helpful (Klein et al. 2004)
- Recognition of linkage and interdependence between humans and ecological and engineering systems
- Bouncing back: communities may not be able to bounce back to original state after a disruption, and it is may not be desirable to bounce back
- Concept is only as useful as it helps decision makers in the areas of disasters, security, and critical infrastructure

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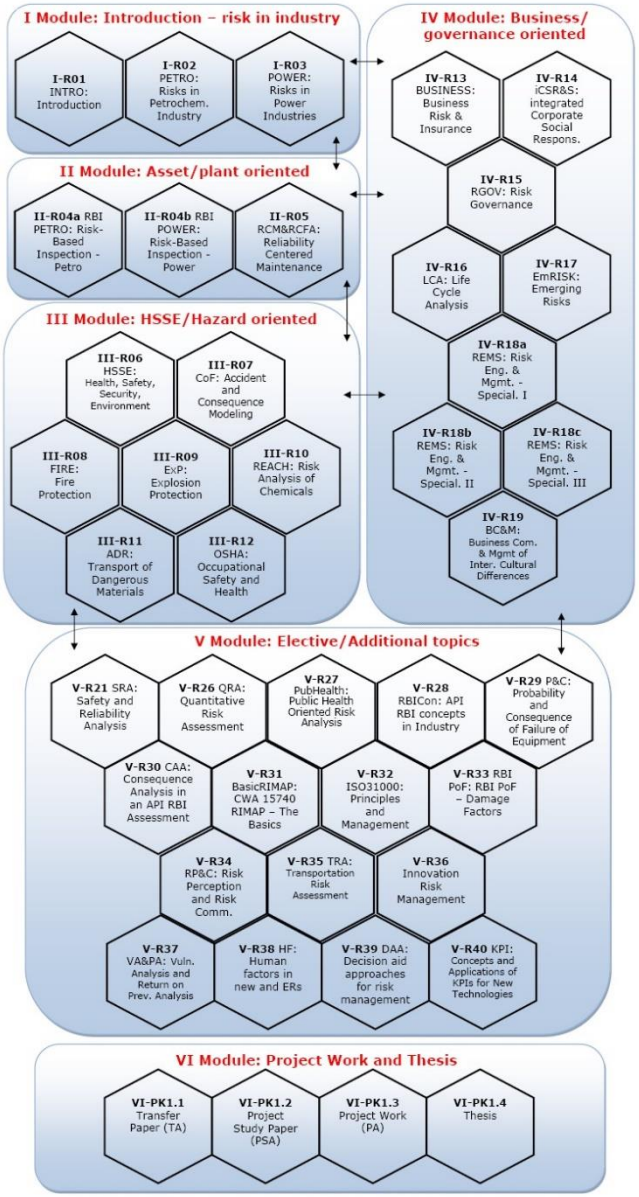
Unit 2: Theoretical background, methods, tools, indicators



Quantitative measurements for resilience

- Impossible to identify priority needs for investment without some sort of numerical measurement
- Need to monitor progress
- Compare costs and benefits

Single metric for resilience?

- Haimes (2009): resilience cannot be measured by a single metric
- Multidimensional outputs (consequences) for a specific input (threats)
- To answer what is the resilience of x requires knowledge about the attack and how x would recover from an attack
- Redundancy and robustness lead to a vector of resilience
- If a single resilience metric is used to compare two systems, need to assume that two systems will be subjected to same exact threats with the same probabilities

Multi-attribute resilience indices

- Coastal Resilience Index based on self-assessment
  - Communities think of a bad storm and a worst storm
  - Assess how well infrastructure survived and how long transportation recovered
  - Given a low, medium, and high then rolled up to an overall metric of resilience
- Argonne National Laboratory Resilience Index
  - Infrastructure survey tool focus on physical security, security management, security force, information sharing, protective measures assessment, and dependencies
  - Data reviewed by experts
  - Aggregated to Protective Measure Index
- Baseline Resilience Indicator for Communities (Cutter et al. 2010): mean of find indices related to social, economic, institutional, infrastructural and community resilience
- Carnegie Mellon Resiliency Engineering Framework—21 capability areas

National Resilience Scorecard

- Indicators of ability of critical infrastructure to recover
- Social factors that limit or enhance a community's ability to recover
- Ability of buildings and structures to withstand
- Special needs of individuals or groups

(U.S. National Academy of Science 2012).

UN Disaster Resilience Scorecard for Cities

- Organization, budget for disaster risk reduction, risk assessments, critical infrastructure, education and healthcare infrastructure, public awareness and capacity, ecosystem, warning systems and preparedness, recovery

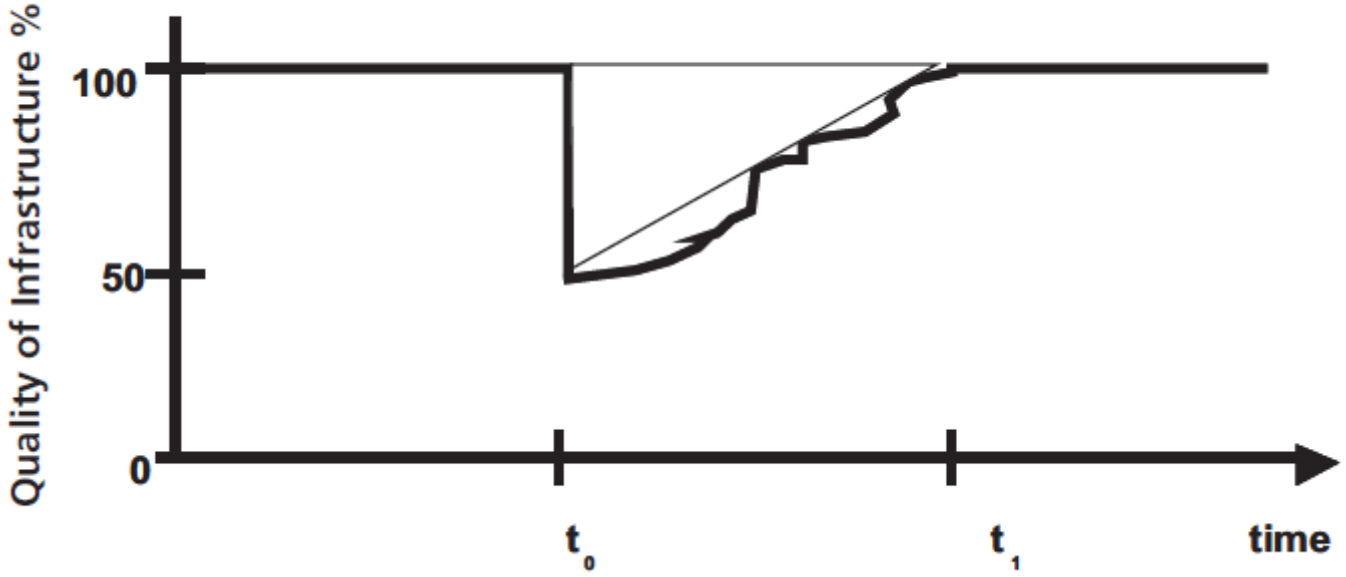
Resilience matrix

Linkov et al. 2013

	Plan / prepare	Absorb	Recover	Adapt
Physical	State and capability of system	Performance to maintain function	Recovery to system functionality	Improvement
Information	Data preparation and analysis	Real-time assessment of functionality	Data to track recovery progress	Data storage protocols
Cognitive	System design and operation decisions	Contingency protocols	Recovery decision making	Design of new system criteria
Social	Social network	Personnel and social institutions for response	Teamwork and knowledge sharing	Changes to institutions and policies

Resilience triangle

FIGURE 1 The Resilience Triangle

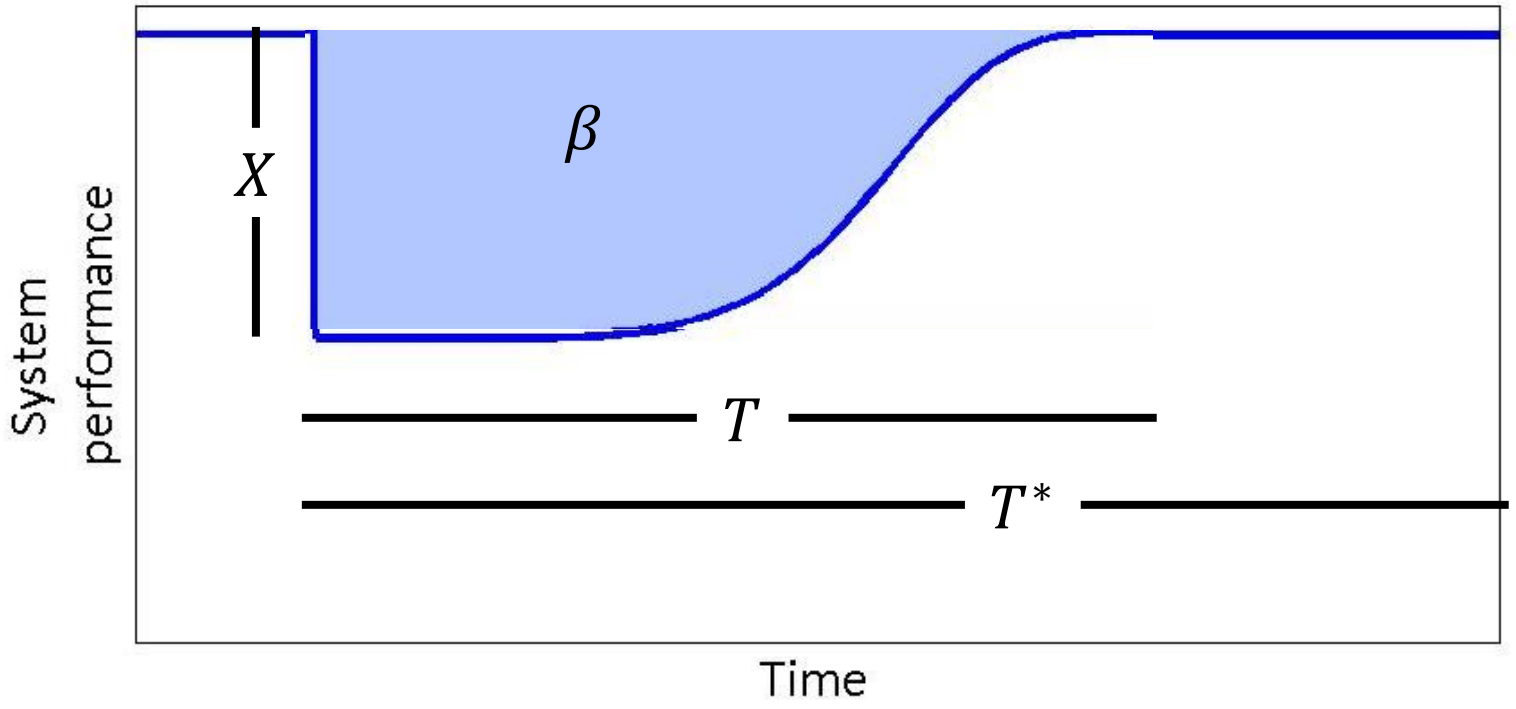


$$R_* = \int_{t_0}^{t_1} [100 - Q(t)]dt$$

Bruneau et al 2003, Tierney & Bruneau 2007

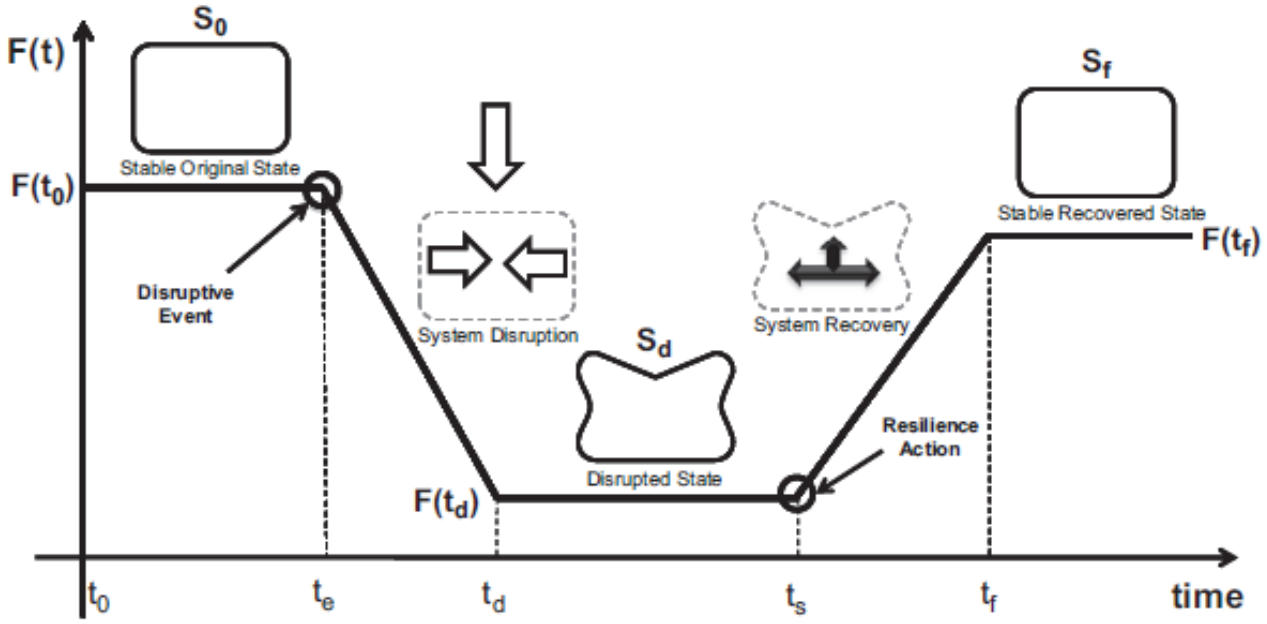
Nonlinear recovery

$$R_*(\beta, X, T) = 1 - \frac{\beta X T}{T^*}$$



Zobel 2014

Time-dependent resilience metric



$$R_*(t|e) = \frac{F(t|e) - F(t_d|e)}{F(t_0) - F(t_d|e)}$$

Henry and Ramirez-Marquez 2012

Extensions to time-dependent resilience

- Barker et al. (2013)
  - Component importance based on resilience (network model)
  - Each component prioritized by how resilient network is when component suffers disruption
  - Reliability, vulnerability, survivability, and recoverability
- Pant et al. (2014): Stochastic metrics of resilience

Economic resilience (Rose 2007)

- Measure economic impacts of disruptions (e.g., input-output models): translate physical disruption to economic or business interruption losses
- Static resilience: Ratio of economic losses to maximum economic loss (for both direct losses or total losses)

$$R_* = \frac{Estimated\ or\ actual\ economic\ loss\ avoided}{Maximum\ potential\ economic\ loss}$$

- Dynamic resilience: Loss-reducing effect of hastening repair and reconstruction

$$R_* = Output\ with\ enhanced\ recovery\ - Output\ with\ normal\ recovery$$

Other resilience metrics

- Li & Lence (2007): Probability that a system that failed a given time will recover by a future time
- Lian & Hames (2006), MacKenzie & Barker (2013)
  - Resilience defined as recovery
  - Recovery follows exponential curve
  - Used as model parameter for a dynamic economic model
- Omer et al. (2009):
  - Network topology for resilience of telecommunication cable system
  - Ratio of value delivery of the network after a disruption to value delivery of the network before a disruption
- McManus et al. (2007): 15 resilience indicators which are grouped into three attributes

Is resilience an operational tool?

- Many articles on resilience assert that the previous studies have not yet operationalized resilience or developed general enough metrics for resilience
- And then the article proposes its own method for operationalizing or measuring resilience

Potential solutions

- Multi-attribute approach (e.g., resilience scorecard, resilience matrix)
- Determine a measure of system performance (could be economic losses) and model and/or gather data on system performance during a disruption → resilience triangle
- Use worst-case scenarios
  - Increasing resilience makes worst-case scenarios less bad (Alderson et al. 2015)
  - System's actual performance compared to worst-case (Rose 2007)

If you are a decision maker, do you feel comfortable using this approach to help you make decisions about resource allocation and emergency preparation?

References

- Alderson, D.L., Brown, G.G., & Carlyle, W.M. (2015). Operational models of infrastructure resilience. *Risk Analysis*, 35(4), 562-586.
- Barker, K., Ramirez-Marquez, J.E., & Rocco, C. (2013). Resilience-based network component importance measures. *Reliability Engineering and System Safety*, 117, 89-97.
- Bruneau, M., Chang, S.E., Eguchi, R.T., Lee, G.C., O'Rourke, T.D., Reinhorn, A.M., Shinozuka, M., Tierney, K., Wallace, W.A., & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4), 733-752.
- Carpenter, S., Walker, B., Anderies, J.M., & Abel, N. (2001). From metaphor to measurement: Resilience of what to what? *Ecosystems*, 4, 765-781.
- Cutter, S.L., Burton, C.G., & C. T. Emrich, C.T. (2010). Disaster resilience indicators for benchmarking baseline conditions. *Journal of Homeland Security and Emergency Management*, 7(1).
- Haimes, Y.Y. (2009). On the definition of resilience in systems. *Risk Analysis*, 4(29), 498-501.

References

- Henry, D. & Ramirez-Marquez, J.E. (2012). Generic metrics and quantitative approaches for system resilience as a function of time. *Reliability Engineering and System Safety*, 99, 114-122.
- Holling, C.S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1-23.
- Klein, R.J.T., Nicholls, R.J., & Thomalla, F. (2004). Resilience to natural hazards: How useful is this concept? EVA working paper no. 9, DINAS-COAST working paper no. 14. Potsdam Institute for Climate Impact Research.
- Li, Y. & Lence, B.J. (2007). Estimating resilience for water resources systems. *Water Resources Research*, 43(7), W07422, doi/10.1029/2006WR005636
- Lian, C. & Haimes, Y.Y. (2006). Managing the risk of terrorism to interdependent infrastructure systems through the dynamic inoperability input-output model. *Systems Engineering*, 9(3), 241-258.

References

- Linkov, I., Eisenberg, D.A., Bates, M.E., Chang, D., Convertino, M., Allen, J.H., Flynn, S.E., & Seager, T.P. (2013). Measurable resilience for actionable policy. *Environmental Science & Technology*, 47(18), 10108-10110.
- MacKenzie, C.A., & Barker, K. (2013). Empirical data and regression analysis for estimation of infrastructure resilience with application to electric power outages. *Journal of Infrastructure Systems*, 19, 25-33.
- McManus, S., Seville, E., Brunsdon, D., & Vargo, J. (2007). *Resilience Management: A Framework for Assessing and Improving the Resilience of Organisations*. Research Organisations Research Report 2007/01.
- Omer, M., Nilchiani, R., & Mostashari, A. (2009). Measuring the resilience of the global internet infrastructure system. *Proceedings of the 3rd Annual IEEE Systems Conference*, Vancouver, B.C.
- Pant, R., Barker, K., Ramirez-Marquez, J.E., & Rocco, C.M. (2014). Stochastic measures of resilience and their application to container terminals. *Computers & Industrial Engineering*, 70, 183-194.
- Park, J., Seager, T.P., Rao, P.S.C., Convertino, M., & Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis*, 33(3), 356-367.

References

- Rose, A. (2007). Economic resilience to natural and man-made disasters: Multidisciplinary origins and contextual dimensions. *Environmental Hazards*, 7, 383-398.
- Tierney, K. & Bruneau, M. (2007). Conceptualizing and measuring resilience: A key to disaster loss reduction. *TR News*, May-June, 14-17.
- United Nations International Strategy for Disaster Reduction. (2005). *Hyogo Framework for Action 2005-2015: Building the Resilience and Communities to Disasters*. Geneva: UN/ISDR-07-2007.
- U.S. Homeland Security Council. (2007). National Strategy for Homeland Security. Washingtion, D.C.: White House.
- U.S. National Academy of Science. (2012). *Disaster Resilience: A National Imperative*. Committee on Increasing National Resilience to Hazards and Disasters, Committee on Science, Engineering, and Public Policy. Washington D.C.: The National Academies Press.
- The White House. (2013). Presidential Policy Directive: Critical Infrastructure Security and Resilience. Washington, D.C.
- Zobel, C.W. (2014). Quantitatively representing nonlinear disaster recovery. *Decision Sciences*, 43(4), 687-710.