A Multidimensional Review of Resilience: Resources, Processes, and Outcomes[i]

Marcus L. Snell[1], Daniel A. Eisenberg[1], Thomas P. Seager[1], Susan Spierre Clark[1], Young Joon Oh[2], John E. Thomas[1], and Lauren R. McBurnett[1]

[1]School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, AZ, USA
[2]Center for Behavior, Institutions and the Environment, Arizona State University, Tempe, AZ, USA

Contact: thomas.seager@asu.edu

Keywords: Resilience, Resilience metrics, Resilience process

While advocates for resilient infrastructure systems typically emphasize improving risk analysis and management (PPD-21, 2013; NRC, 2012; Hubbard, 2009), the necessity that risk places upon knowledge of the hazard means it is unequipped to deal with the emergent behavior of *surprise* (Anderson, 1999; Rinaldi, 2001; Mitleton-Kelly, 2003; Bekebrede, 2010; Hollnagel et al., 2011; Seager et al., 2011; Clark et al., 2016). Recent policy shifts have emphasized the development of resilience analysis as a complement to risk to prepare infrastructure systems for unforeseen, cascading, and complex failures that can cause catastrophic losses (Park et al., 2013; Clark & Seager, 2015). Nonetheless, there is disagreement among experts on what resilience means and how to measure resilience in engineered infrastructure systems. This paper reviews a sampling of resilience literature from a variety of disciplines and identifies at least three dimensions of resilience: *resources*, *processes*, and outcome *priorities* (Seager et al., 2008; Adger, 2009; Mathias et al., 2016; Christensen, 2012).

The first dimension measures resilience in system *resources* as material buffers, system redundancies, or internal capabilities (Linkov et al., 2013a; Linkov et al., 2013b; Eisenberg et al., 2014). For example, within an energy distribution system some resilient resources can be the inventory of emergency fuel or water stockpiles, number of backup generators, redundant power lines, workers, key replacement equipment, energy feedstock, or material composition available (Willis & Loa, 2015). Measuring resilience as a system or component property within an infrastructure system is one approach to understanding preparedness. For example, it may be important to know how many miles of oil spill containment boom are available to respond to a surprise spill in the same way that it is important to know how many life jackets are available on a boat. This dimension dominates the Department of Homeland Security's *National Infrastructure Protection Plan (NIPP)* (NIPP 2013), and discussions of resilience that rely on dynamic systems

[i] This paper is part of the IRGC Resource Guide on Resilience, available at: https://www.irgc.org/risk-governance/resilience/. Please cite like a book chapter including the following information: IRGC (2016). Resource Guide on Resilience. Lausanne: EPFL International Risk Governance Center. *v29-07-2016*

modeling (Han 2010), network theory and agent-based modeling (Baggio, 2011), and whole life cycle costing (Viavattene, 2012).

Nonetheless, it should be clear that resources alone are useless without a set of *processes* to deploy them effectively. In the process dimension, resilience is measured in actions, rather than system properties (Hollnagel et al., 2011; Park et al., 2013; Seager 2014; Seager 2016). Process-based resilience is an emergent behavior of a complex system (Holling, 1996; Rinaldi, 2001; Park et al., 2013) stemming from cross domain, technical-social-ecological interactions and connections that influence adaptive capacity. In this manner, resilience is measured by what the system does, such as the way a system senses, anticipates, adapts, learns, or functions at all times and specifically in response to stressors. For example, the observe-orient-decide-act (OODA) loop is utilized by the military for rapid risk assessment in a flexible environment (Willi, 2003). The Functional Resonance Analysis Method is a methodological approach to understanding the couplings and resonance of system functions resulting in emergent behavior (Hollnagel, 2012). Thus, process-based resilience emphasizes the capability of people to adapt infrastructure to manage surprise. Additionally, the implications of a process-based perspective are not merely technical, they are also ethical (Adger, 2009). Whereas risk-based decision-making often relegates failure to matters of chance and mitigates their consequences by socializing risks (e.g., insurance), adaptive response places additional burdens on decision-makers to consider the adverse consequences of failures on different impacted populations.

An outcomes-based perspective emphasizes the necessity of understanding competing resilience outcome *priorities* – such as determining when the system has begun to stabilize after an event and restore damaged resources (Seager et al, 2007; McDaniels, 2008). A National Institute of Standards and Technology funded project outlines resilience through the PEOPLES Framework (Renschler, 2010). This framework suggests community scale resilience can be evaluated in seven dimensions: population and demographics, environmental/ecosystem, organized governmental services, physical infrastructure, lifestyle and community competence, economic development, and social-cultural capital. These dimensions highlight areas within the technical, social, and ecological systems of communities whose functionality can be affected through stressors. Resilience is then characterized by measuring the retrospective performance of the infrastructure system from the time of initial loss of system functionality to the time it takes for the system to recover.

Although current resilience research often emphasizes one dimension at the expense of others, we argue that each of these three perspectives are critical in understanding a system's resilient response to an event. Unfortunately, the relationships between resources, processes, and outcomes are rarely explicit – especially in times of crisis – and the relationship between management intent and consequences is clouded by system complexity. Nonetheless, to achieve resilience policy goals, the influences and interactions between multiple resilience perspectives must be examined in greater detail. Comprehensive guidance regarding the types of resources, processes, and priorities that are supportive of resilient infrastructure systems, with consideration of ethical principles, for safeguarding the public under conditions of component failure must be developed.

Annotated Bibliography

On Resources

Baggio, J. A. (2011). Analyzing Social-Ecological Systems: Linking Resilience, Network theory, and Agent Based Modelling. *Networks*, (May).

Baggio explores analysis at the junction of the social-ecological systems. A theoretical model is constructed from the integration of network and resilience theory to analyze landscape properties effect on predator-prey system. Then a managing institution is added to the model which is allowed to alter the system landscape. Resilience is based upon the network metrics and modeled agents.

Eisenberg, D. A., Park, J., Bates, M. E., Fox-Lent, C., Seager, T. P., & Linkov, I. (2014). Resilience metrics: Lessons from military doctrines. *The Solutions Journal*.

Eisenberg *et al.* further applies the resilience matrix approach developed by Linkov et al. (2013a) to engineering, ecological, and cyber systems to demonstrate its value for developing resilience metrics across characteristically different system types. This paper also discusses how the “resilience processes” of sensing, anticipating, adapting, and learning may be considered alongside metrics developed with the resilience matrix framework.

Han, S., Lee, S., & Peña-Mora, F. (2010). System Dynamics Modeling of a Safety Culture Based on Resilience Engineering. In *Construction Research Congress* (pp. 389–397). doi:10.1061/41109(373)39

Han *et al.* present system dynamics modeling as a method for analyzing the resilience of a system. A practical application of theories on a safety culture is illustrated. With the derived model, managers can monitor the safety culture as arising from an interaction of resources among workers, managers, and the organization to interpret safety based on an organizational perspective.

Linkov, I., Eisenberg, D. A., Plourde, K., Seager, T. P., Allen, J., & Kott, A. (2013b). Resilience metrics for cyber systems. *Environment Systems and Decisions*, *33*(4), 471–476. doi:10.1007/s10669-013-9485-y

Linkov *et al.* applies the “resilience matrix” initially presented in Linkov et al. (2013a) to develop qualitative metrics for cyber system resilience. The resilience matrix combines the National Academies of Science resilient system abilities of planning and preparing for, absorbing, recovering from, and adapting to unforeseen events with the US Military Command and Control Research Program’s taxonomy of system components, specifically: physical, cyber, cognitive, and social. The four abilities and four component types form a 4x4 matrix of metrics useful for assessing the resilience of cyber infrastructure systems.

Viavattene, C., & Faulkner, H. (2012). An uncertainty index to measure the feasibility of Whole-Life Cycle Costing approach in flood risk management. *Journal of Flood Risk Management*, *5*(3), 215–225. doi:10.1111/j.1753-318X.2012.01140.x

Viavatte and Faulkner develop a qualitative method to assess the feasibility of utilizing Whole-Life Cycle Costing. A user interface tool utilizing Visual Studio.net 2003 was created to aid in

the feasibility decision and applied to flood management in a small residential and commercial area.

On Processes

Holling, C. S. (1996). Engineering Resilience versus Ecological Resilience. *Engineering within Ecological Constraints*, (1996), 31–44.

Holling presents resilience from the engineering and ecological perspectives. Engineering resilience is defined as resistance to change from steady state and the speed of return to equilibrium. Ecological resilience is defined as a systems ability to change to another regime of stability when far from equilibrium. An argument is made for the integration of knowledge at scale and the interrelation between perspectives.

Hollnagel, E., Paries, J., Woods, D. D., & Wreathall, J. (2011). *Resilience Engineering in Practice: A Guidebook*. *Ashgate studies in resilience engineering*.

Hollnagel *et al*. suggest the continued development of resilience engineering has focused on four abilities that are essential for resilience. These are the ability a) to respond to what happens, b) to monitor critical developments, c) to anticipate future threats and opportunities, and d) to learn from past experience. This book is divided into four main sections which describe issues relating to each of the four abilities. The chapters in each section emphasize practical ways of engineering resilience and feature case studies and real applications. The text is written to be easily accessible for readers who are more interested in solutions than in research, but will also be of interest to the latter group.

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), 356–67. doi:10.1111/j.1539-6924.2012.01885.x

Park *et al*. argues that current understandings of resilience improperly conflates resilience and risk perspectives by expressing resilience exclusively in risk terms. In contrast, the paper describes resilience as an emergent property of what an engineering system does, rather than a static property the system has. In this approach, resilience analysis can be understood as differentiable from, but complementary to, risk analysis, with important implications for the adaptive management of complex, coupled engineering systems. Management of the 2011 flooding in the Mississippi River Basin is discussed as an example of the successes and challenges of resilience-based management of complex natural systems that have been extensively altered by engineered structures.

Rinaldi, S. M., Peerenboom, J. P., & Kelly, T. K. (2001). Identifying, understanding, and analyzing critical infrastructure interdependencies. *IEEE Control Systems Magazine*, *21*(6), 11–25. doi:10.1109/37.969131

Rinaldi *et al*. present critical infrastructure as an interdependent, complex adaptive system. Emphasis is placed upon defining infrastructure, infrastructure dependencies, and infrastructure interdependencies. Examples are presented on the various ways interdependencies present themselves and a conceptual framework for interrogating them.

On Outcomes

Mathias, J.D., Clark, S. S., Onat, N., & Seager, T. P. (2016). *Reconciling outcome- and process-based approaches of resilience: Application to electric power generation*. Manuscript submitted for publication.
Mathias *et al.* propose a framework for integrating an outcome-based approach (based on a dynamical controlled system framework) and a process-based approach (based on the SAAL framework) to resilience under resource constraints. The framework is applied to a model of electric power generation to show the complementary aspects of outcome, resources and process approaches for analyzing infrastructure resilience.

Renschler, C. S., Frazier, A. E., Arendt, L. A., Cimellaro, G. P., Reinhorn, A. M., & Bruneau, M. (2010). *Developing the "PEOPLES" Resilience Framework for Defining and Measuring Disaster Resilience at the Community Scale* (pp. 1–10).
Renschler *et al*. present seven dimensions of community resilience: Population and Demographics, Environmental/ Ecosystem, Organized Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital. The proposed "PEOPLES" Resilience Framework provides the basis for the development of quantitative and qualitative models that measure continuously the resilience of communities against extreme events or disasters in any or a combination of the above-mentioned dimensions. Metrics of analysis are outlined for each dimension and are applied in subsequent papers by Renschler *et al*.

Citations/Other

Anderson, P. (1999). Complexity Theory and Organization Science. *Organizational Science*, *10*(3), 216–232.

Bekebrede, G. (2010). Experiencing Complexity: A gaming approach for understanding infrastructure systems. *Faculty TPM*, *PhD*, 362.

Christensen, C. M., Allworth, J., & Dillon, K. (2012). *How will you measure your life?* New York, NY: Harper Business.

Clark, S. S. & Seager, T. P. (2015). *A Socio-Technical Approach to Critical Infrastructure Resilience*. Center for Infrastructure Protection and Homeland Security Report. Available: http://cip.gmu.edu/2015/11/23/a-socio-techniure-resilience/#_ftn12
Clark and Seager describe the socio-technical approach to critical infrastructure resilience employed by researchers at Arizona State University (ASU). The report includes a brief explanation for the shift in public policy from risk analysis to resilience and identifies four barriers to creating resilient critical infrastructure systems. It concludes by describing several methodologies used at ASU to investigate and ideally overcome the identified resilience challenges.

Clark, S. S., Chester, M., & Seager, T. P. (2016). The Vulnerability of Interdependent Urban Infrastructure Systems to Climate Change: Could Phoenix be a Katrina of Extreme Heat?

Manuscript submitted for publication. Submitted for publication.
Clark, Chester and Seager indicate that we have a poor understanding of how vulnerability to climate change can be amplified through increasingly interdependent urban infrastructure systems. They explore the potential for a cascading failure of critical infrastructure systems in Phoenix, AZ during an extreme heat event to identify possible pathways of disruption in coupled energy, water, transportation and food systems. Their research illustrates the complexity of interdependent critical infrastructure systems and its implications for the impacts of climate change on society.

Department of Homeland Security. (2013). *NIPP 2013: Partnering for Critical Infrastructure Security and Resilience.*

Department of Homeland Security. (2015). *Dams Sector-Specific Plan*.

Eisenberg, D. A., Park, J., Bates, M. E., Fox-Lent, C., Seager, T. P., & Linkov, I. (2014). Resilience metrics: Lessons from military doctrines. *The Solutions Journal.*

Hollnagel, E. (2012). *FRAM: The Functional Resonance Analysis Method*. *Journal of Chemical Information and Modeling* (Vol. 53). doi:10.1017/CBO9781107415324.004

Hubbard, D. W. (2009). *The failure of risk management: Why it's broken and how to fix it.* Hoboken, NJ: Wiley.

Linkov, I., Eisenberg, D. A., Bates, M. E., Chang, D., Convertino, M., Allen, J. H., Flynn, S. E., & Seager, T. P. (2013a). Measurable resilience for actionable policy. *Environmental Science & Technology*, *47*(18), 10108-10110. doi: 10.1021/es403443n

Linkov, I., Eisenberg, D. A., Plourde, K., Seager, T. P., Allen, J., & Kott, A. (2013b). Resilience metrics for cyber systems. *Environment Systems and Decisions*, *33*(4), 471–476. doi:10.1007/s10669-013-9485-y

McDaniels, T., Chang, S., Cole, D., Mikawoz, J., & Longstaff, H. (2008). Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. *Global Environmental Change*, *18*(2), 310–318. doi:10.1016/j.gloenvcha.2008.03.001

Mitleton-Kelly, E. (2003). Ten principles of complexity and enabling infrastructures. In *Complex Systems and Evolutionary Perspectives on Organizations: The Application of Complexity Theory to Organisations*.

Morton, L. W., & Olson, K. R. (2013). Birds Point-New Madrid Floodway: Redesign, reconstruction, and restoration. *Journal of Soil and Water Conservation*, *68*(2), 35A–40A. doi:10.2489/jswc.68.2.35A

National Research Council (NRC) (2012). *Disaster Resilience: A National Imperative*. Washington, DC: The National Academies Press. doi:10.17226/13457.

Presidential Policy Directive—*Critical Infrastructure Security and Resilience* (PPD-21) (2013) http://www.whitehouse.gov/the-press- office/2013/02/12/presidential-policy-directive-critical-infrastructure- security-and-resil

Seager, T. P., Satterstrom, F. K., Linkov, I., Tuler, S. P., & Kay, R. (2007). Typological review of environmental performance metrics (with illustrative examples for oil spill response). *Integrated Environmental Assessment and Management*, *3*(3), 310–321. doi:10.1897/1551-3793(2007)3[310:TROEPM]2.0.CO;2

Seager, T. P., & Korhonen, J. (2008). Beyond Eco-Efficiency : a Resilience Perspective. *Business Strategy and the Environment*, *17*, 411–419. doi:10.1002/bse

Seager, T., Selinger, E., & Wiek, A. (2011). Sustainable Engineering Science for Resolving Wicked Problems. *Journal of Agricultural and Environmental Ethics*, *25*(4), 467–484. doi:10.1007/s10806-011-9342-2

Seater, T.P. [ISSST Network]. (2014, November 19) *Dr. Thomas P Seager - Resilient Infrastructure Requires New Thinking.* Retrieved from http://youtu.be/OxDpLdCBbW4

Seater, T.P. [ISSST Network]. (2016, April 19) *The Failure of Risk.* Retrieved from https://youtu.be/wYYoUTY9IA0

Willi, B. (2003). The OODA loop. *Flying Safety*, *59*(10), 12.

Willis, H. H., & Loa, K. (2015). *Measuring the Resilience of Energy Distribution Systems*.