Aligning Different Schools of Thought on Resilience of Complex Systems and Networks[i]

David J. Yu[1,*], P. Suresh C. Rao[1,*], Christopher J. Klinkhamer[1], Elisabeth H. Krueger[1,2], Nikhil Sangwan[1], Kyungmin Sung[1]

[1]Purdue University, [2]Helmholtz Centre for Environmental Research - UFZ Germany

Contact: davidyu@purdue.edu, SureshRao@purdue.edu

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Multiple schools of thought have emerged on how complex systems persist or reorganize in response to change. A first step towards resilience management should be clarifying how these different schools of thought fit together. With this aim, we synthesize the following four concepts: resilience thinking as developed in the fields of ecology and social-ecological systems (SESs) research, resilience engineering as developed in the safety management research of engineered systems, robust control as developed in control theory of feedback systems, and spatial resilience as developed in the fields of geomorphology, landscape ecology, or complex network studies.

Resilience thinking is a cluster of concepts that has been expanded to represent how complex self-organized systems persist or reorganize among multiple regimes of reinforcing processes (or multiple stable attractors or basins of attraction). It focuses on three emergent system-level features: resilience as persistence, adaptability, and transformability (Walker et al., 2004; Folke et al., 2010).

- Resilience is the ability to respond to external (or internal) disturbances while undergoing change so as to still preserve essentially the same functions of the current regime. Resilience can be further classified into specified and general resilience. Specified resilience is specific about "resilience of what to what" (Carpenter et al., 2001). It refers to the capacity of a system to maintain a specific set of functions in relation to a well-defined set of disturbances. General resilience, in contrast, relates to the capacity of a system to deal with all kinds of disturbances, both expected and unexpected ones (Folke et al., 2010). Many resilience studies focus on the aspects of self-organization that generate multiple regimes, thresholds that form the boundaries of these regimes, and how a system may suddenly flip between such regimes from a seemingly small change in a condition (regime shift). Finally, resilience by itself does not address normative considerations; a resilient regime can be either good or bad to human welfare.
- Adaptability is the ability of a system to learn and adjust its responses to changing conditions and continue operating within the current regime. Hence, adaptability

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enhances resilience. Adaptability is aided by structural and functional diversity and redundancy of components, connections, and processes. Loss of such features, either through natural or anthropogenic changes, contributes to decreased adaptability and thus resilience loss.

- Transformability is the ability to create a fundamentally new system when the existing system becomes untenable because of great change. In a complex system with nested or multi-level hierarchy (e.g., households make up neighbourhoods, neighbourhoods comprise districts, districts make up a city, etc.), transformability at a lower level can help the resilience at a higher level. For example, periodic district-level water supply failures and the resulting rehabilitation of pipes in these districts can make the whole city resilient to a major water supply failure. Therefore, it is crucial to understand that multi-level interactions drive the interplay among resilience, adaptability, and transformability. Adaptive cycle and panarchy of nested adaptive cycles are useful heuristics about how such interplays unfold across multiple levels (Allen et al., 2014).

In the field of robust control, robustness relates to the sensitivity of a designed system's performance to a well-defined set of disturbances (Csete & Doyle, 2002). Unlike resilience, aspects of multiple regimes are not explicitly covered by robustness. Robustness represents a degree of resistance relative to a particular set of disturbances with known and anticipated (with some probability) frequency and intensity that are identified through risk analysis. Hence, robustness and specified resilience are analogous when the focus of analysis is on system dynamics in the vicinity of a regime's steady-state. When the focus of analysis is expanded to cover potential regime shifts, robustness and specified resilience mean different things. Further, a fundamental property of all feedback systems is that designed features that confer robustness to certain kinds of disturbances necessarily lead to hidden fragilities to some other set of disturbances (Carlson & Doyle, 2002). This so-called robustness-fragility trade-off has been observed in SESs (Janssen & Anderies, 2007). In coupled engineered-social systems, this debate is focused on balancing fail-safe designs (robustness-based) with safe-fail (resilience-based) design paradigms; that is, there is a need for an integration of both risk and resilience approaches for design and operations of coupled systems (Park et al., 2013).

Safety management engineers have traditionally focused on robustness through risk analysis. They have begun to embrace resilience ideas (Fiksel, 2003), and termed their approach as "resilience engineering." They define resilience as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions" (Hollnagel, 2014). This definition is essentially the same as that of general resilience. Hollnagel (2014) outlines four main traits of resilience engineering: the ability to respond to various kinds of disturbances (both familiar and unfamiliar ones), the ability to monitor system states, the ability to learn from the consequences of past decision-making, and the ability to anticipate and proactively adapt to changing conditions. Engineered complex systems, such as urban infrastructure networks, indeed are designed to monitor system state and performance, and re-rout flows of traffic or water, etc. when necessary. Yet, these systems are not inherently resilient, because they do not have the ability to adapt or transform structure and functions through self-organization, as do ecological and social systems/networks. Further, when engineered systems fail, either through long-term erosion of physical structures or suddenly from major shocks, they do not re-emerge or re-organize by themselves; rather, it is the urban communities that use and depend on them that actively invest to repair and rehabilitate the failed infrastructure.

Resilience characterization of a complex system needs to incorporate processes and feedbacks, not only over different time scales but also across the spatial domains of the system. It is important to observe and model changes in spatial heterogeneity (statistical spatial moments), spatial structure and patterns (geo-statistical analyses), flows (of matter, energy, etc.) across gradients and interfaces, connectivity (network topological metrics) among spatial elements, and dispersal (diffusion of matter, information, organisms, etc.). Such spatiotemporal attributes respond dynamically to both internal and external forcing, whether deterministic or stochastic, to maintain local (specific) or overall (general) resilience. Just as cumulative adverse impacts of sequences of internal and external disturbances can lead to either gradual erosion of system functions (performance) over time or experience a sudden collapse, so too do spatial cascades of losses of diversity, patterns, connectivity, and flows lead to propagation of regime shifts across space. Thus, spatial resilience can be understood as the ability to maintain the appropriate combination of spatial attributes required to enable emergence of asymmetries, heterogeneity, patterns, connectivity, flows, and feedbacks (Allen et al., 2016). Spatial resilience is linked to the "preservation of a system's structure", which does not necessarily refer to the spatial layout of a system, but rather the "functional map" and topology of the system. Such functional mapping of urban infrastructure networks has been suggested by several authors (Porta et al., 2006; Masucci et al., 2014).

Strategies for Resilience Improvement

How do these schools of thought fit together? How can we use them in concert as instruments for resilience management of coupled complex systems? It is important to realize that resilience and robustness are not conflicting concepts as shown in Figure 1. When the time scale of analysis is in the units of decades or longer, resilience may be more fitting because it incorporates aspects such as adaptability and transformability that begin to matter in such longer time scales (Anderies et al., 2013). When the time scale is shorter (i.e., in the units of few hours or days) and system boundaries are more narrowly defined, robustness (resistance) may be more fitting because it explicitly deals with the sensitivity of a system output to a well-defined set of disturbances. In a similar manner, when specificity or predictability of key outputs and system dynamics is high, risk analysis can still be useful and planned adaptation or deliberate transformation can be possible. When the opposite is true, learning-by-doing may be necessary and unplanned adaptation or forced transformation is more likely. Hence, resilience and robustness are complementary concepts—the choice between the two concepts ultimately depends on the nature of the spatial boundary, time-scale, and specificity or predictability of key variables that one is considering. However, continuously applying robustness as the sole basis for ensuring persistent performance is dangerous: It can lead to catastrophic failures when another type of hazard co-occurs, as illustrated by the examples of Park et al. (2013) and the notion of robustness-fragility trade-offs.

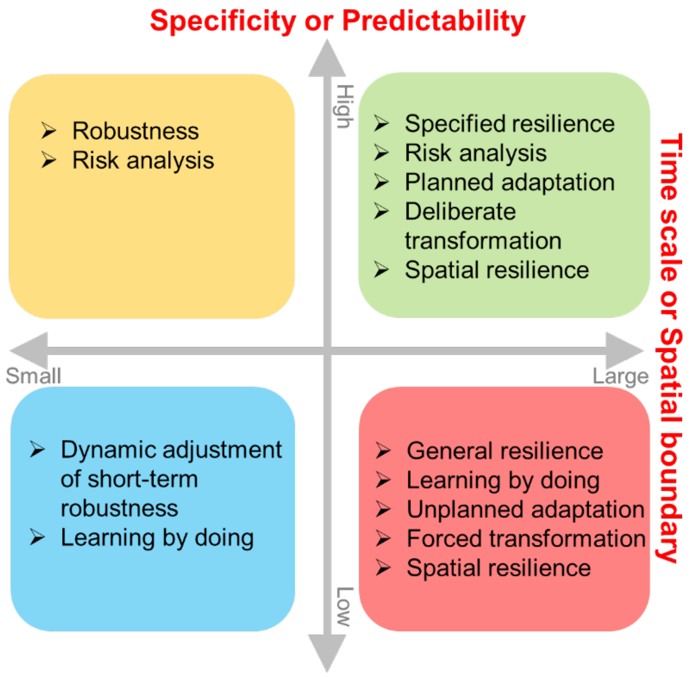

Figure 1: Relevance of the resilience-related concepts discussed along four analytical dimensions (time scale, spatial boundary, specificity of key variables, and predictability).

In the short term, robustness can be achieved by deciding which disturbances will be controlled and which ones will be tolerated at a particular point in time. Robustness ideas facilitate this process by forcing analysts to consider a precise system boundary and output measure and potential robustness-fragility trade-offs associated with design choices. When predictability is low and the time scale is longer, general resilience can be achieved by taking short-term and local robustness to the global scale with dynamically changing conditions and disturbances. This requires moving from the idea of protecting the system from failure ("fail-safe"), which is achievable only to expected risks, to embracing the potential of failure and creating a "safe-fail" environment in the event of unknown or unexpected shocks (Park et al., 2013). Implementation of this dynamic adjustment requires learning-by-doing, i.e., an iterative cycle of experimentation, monitoring, learning, and adaptation (Hollnagel, 2014; Yu et al., 2016). Similarly, resilience engineering scholars suggest that resilience ideas do not replace the conventional risk-based engineering approach. The basic idea is that risk analysis alone is insufficient for dealing with irreducible uncertainties associated with complex systems and thus should be accompanied by improved adaptability. Hence, practitioners should use robustness (through risk analysis) and general resilience (through learning-by-doing and dynamic adaptation) in concert to operationalize resilience management.

Quantifying Resilience

Quantifying resilience has received increasing attention in recent years, both from systems and networks modeling and composite indicators construction perspectives (Angeler & Allen, 2016), and is moving beyond earlier work defining terminology, concepts, and conceptual frameworks (Park et al., 2013; Ayyub, 2014). More recent attempts at quantifying resilience of technological systems were based on performance recovery from a single shock, or used an aggregate measure (average level of service provision) computed from system responses to multiple events over multiple years (Ganin et al., 2016).

New modeling approaches are based on either systems analyses perspectives or complex network analyses based on graph theory and acknowledge increasing vulnerability to unexpected shocks, or combinations of series of chronic, low-intensity and infrequent acute shocks (Moore et al., 2015; Klammler et al., 2016). Two key state variables of interest, aggregated at the system or network level, are: (1) the "system performance" ("functions", e.g., ecological or infrastructure or social services) and (2) “adaptive capacity”, which defines the ability of the system to cope with disturbances, recover from losses, learn from, and improve the process. While it is easy to monitor system performance, it has been much more challenging to quantify and monitor “adaptive capacity”; this gap remains the focus of current and future research efforts.

Klammler et al. (2016) developed a model to quantify resilience using multiple metrics of coupled systems performance under a stochastic disturbance regime. Here, resilience is modeled as a dynamic and emergent property of the coupled system with respect to regime shifts between a desirable regime (full service) and limited service conditions or complete system collapse. They also showed that resilience is a non-stationary (i.e., memory- or path-dependent) and emergent phenomenon under stresses, contingent on initial conditions, and the nature of the stochastic disturbance regime. However, lack of required long-term data for engineering system (infrastructure) performance under a series of stochastic shock (i.e., disturbances of varying frequency and intensity), and how to measure and monitor the dynamics of social system’s “adaptive capacity” remains a major obstacle to model testing and applications

Representation of the systems of interest as interdependent networks has also been examined. Examples include engineered and natural networks (e.g., river) and engineered networks (e.g., roads, pipes, power) and social networks (e.g., communities) in urban settings. Recent work (Newman, 2006; Barzel & Barabasi, 2013) has shown that many engineered and natural networks have topological similarities in that they all exhibit distinct features of functional self-similarity and scale-independence. Such networks have few well-connected critical nodes (hubs) and a large number poorly connected (terminal) nodes. Such networks are known to be vulnerable to structural fragmentation, and functional disruptions with the loss of only a few hubs, but robust to the loss of other less-connected nodes (Barabasi, 2016). Interdependent networks generally tend to be less robust, and more likely to be vulnerable to cascading failures initiated in other networks. Several quantitative measures of network topology, interconnectedness, and resilience have been recently proposed (Gao et al., 2016).

Closure

Despite continued advances in understanding and quantifying resilience, accurately measuring resilience remains an ongoing challenge, often only possible after system failure has already occurred and the recovery is underway. As a result, the design and management of engineered systems follow fail-safe strategies rooted in robustness and risk analysis. These strategies, however, often fail to recognize the importance of people, i.e., social capacity in imbuing resilience within an engineering system that is otherwise designed, built and operated on robustness, resistance, and redundancy, but does not inherently has resilience (as in adaptation and transformation) (Klammler et al., 2016). Recognizing the community's contributions to adaptive capacity should be a principal component of any future quantitative measure of coupled systems resilience.

Annotated Bibliography

Allen, C. R., Angeler, D. G., Garmestani, A. S., Gunderson, L. H., & Holling, C. S. (2014). Panarchy: Theory and Application. Ecosystems 17(4):578–589.

The article reviews the panarchy theory which has been used in various field, especially in complex systems. Also, it emphasizes the needs for testing hypothesis, regarding quantifying and measuring panarchy, to support the theory.

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The article provides an overview of current work on resilience, its quantification, and knowledge gaps in the field.

Anderies, J. M., Ostrom, E., Folke, C., & Walker, B. (2013). Aligning Key Concepts for Global Change Policy: Robustness, Resilience, and Sustainability. Ecology and Society 18(2):8.

Authors look closely at three similar and hence often confounding concepts of global change policy: robustness, resilience and sustainability. This paper provides explicit definitions of these concepts and highlights the similarities, distinctions and linkages between them. It points out their relevance at different time-scales and how they complement each other in different contexts.

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In this article, a resilience definition is provided that meets a set of requirements with clear relationships to the metrics of the relevant abstract notions of reliability and risk.

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This book provides a comprehensive overview of the present state of network science. Modular in design, the book includes sections on network evolution, robustness, and spreading phenomena, among other topics integral to network science and graph theory.

Barzel, B., & Barabasi, A. (2013). Universality in Network Dynamics. Nature Physics 9:673-681.

The authors develop a theory of the effects of perturbations to the dynamics of complex systems, and predicts several archetypes of universality in complex social and biological systems. Predictions of system response to perturbations are provided and supported by experimental data.

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This paper contrasts two different perspectives on complexity: Highly Optimized Tolerance (HOT) and Self-Organized Criticality (SOC). HOT framework considers the complex systems to

have highly structured, self-dissimilar internal configurations and robust-yet-fragile external behaviour.

Carpenter, S., Walker, B., Anderies, J. M., & Abel, N. (2001). From Metaphor to Measurement: Resilience of What to What? Ecosystems 4(8):765–781.
The article actually measures "which variable is resilient to which disturbance" in two different social-ecological systems. It is found that the adaptive capacity is evolved by novelty or learning.

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Taking cues from the engineering theory of complexity, authors explore biological complexity and highlight that spiraling complexity, feedback regulation, robustness, fragility and cascading failures are highly intertwined. This work also illustrates how fragility is conserved in complex systems through feedback interconnection resulting in robustness-fragility tradeoffs.

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To develop truly sustainable industrial product and design systems, the author proposes a broader systems thinking with explicit consideration of resilience in the core engineering systems as well as the larger systems in which they are embedded. A design protocol incorporating the related systems and their resilience is also presented in the paper.

Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., & Chapin, T. (2010). Resilience Thinking: Integrating Resilience, Adaptability and Transformability. Ecology And Society 15(4):20.
Folke et al. define and discuss three concepts-resilience, adaptability and transformability- which are central to resilience thinking of SES. Concepts such as adaptability and transformability are needed to enhance the SES resilience and better manage these intertwined systems across multiple scales. Authors also contrast general resilience vs specified resilience, and forced vs deliberate transformations in this work.

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Hollnagel, E. (2014). Resilience engineering and the built environment. Building Research & Information 42(2):221–228.
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Janssen, M., &Anderies, J. (2007). Robustness trade-offs in social-ecological systems. International Journal of the Commons, 1(1):43–65.
The article explains the concept of robustness in social-ecological systems, and provides a framework for robustness-fragility trade-offs with examples. It argues that absolute robustness doesn’t exist: a system can only be robust to specific disturbances.

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The article presents a systems model of the interdependence between urban technological systems (infrastructure) and socio-economic systems (institutions). Each system is characterized by a single state variable - service deficit resulting from insufficient infrastructure services to meet customer demands, and adaptive capacity of the institutions to maintain services. Resilience is identified as an emergent property of the system in response to stochastic shocks, and with respect to regime shifts between a desirable regime, limited service conditions or complete system collapse.

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Moore, C., Grewar, J., & Cumming, G. S. (2015). Quantifying Network Resilience: comparison before and after a major perturbation shows strengths and limitations of network metrics. Journal of Applied Ecology 53:636-645.
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Newman, M. E. J. (2006). Networks—An Introduction. Oxford University Press.
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Park, J., Seager, T. P., Rao, P. S. C., & Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineered systems. Risk Analysis, 33(3), 356-367.
The authors describe resilience analysis as complementary to risk analysis with important implications for the adaptive management of complex, coupled engineering systems. Resilience is defined as an emergent property resulting from a recursive process of sensing, anticipation, learning, and adaptation.

Porta, S., Crucitti, P., Latora, V., (2006). The network analysis of urban streets : A dual approach. Physica A 369, 853–866. doi:10.1016/j.physa.2005.12.063
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The article explains future trajectories of social-ecological systems (SESs) are determined by an interplay of their resilience, adaptability, and the transformability.

Yu, D. J., Shin, H. C., Pérez, I., Anderies, J. M., & Janssen, M. A. (2016). Learning for resilience-based management: Generating hypotheses from a behavioral study. Global Environmental Change 37:69–78.
The article emphasizes that learning enhances adaptive capacity for resilience. Authors examined how learning is encouraged for resilience by analysing empirical data from a behavioral experiment on SES.