Resilience: Approaches to Risk Analysis and Governance

An introduction to the IRGC Resource Guide on Resilience[i]

Igor Linkov, Benjamin D. Trump, and Cate Fox-Lent

Wide ranging and uncertain threats to public health, energy networks, cybersecurity, and many other interconnected facets of infrastructure and human activity, are driving governments, including those of the United States, European Union and elsewhere to further efforts to bolster national resilience and security. Concerns arise from the increasingly interconnectedness of the world, where infrastructure systems rely on novel technologies that, while expanding services and promoting system maturation and growth, expose such systems to new and cascading risks that could devastate the normal functioning of important systems. Such risks – ranging from cybersecurity to loss of biodiversity to important ecosystem services – represent growing challenges for risk managers in the 21st century. They require development of conventional risk management strategies, but also resilience-driven strategies to adequately protect against undesirable consequences of uncertain, unexpected and often dramatic events.

The National Academy of Sciences (NAS) defines disaster resilience as "the ability to plan and prepare for, absorb, recover from, and adapt to adverse events" (NAS 2012). The NAS definition highlights a societal need to address highly uncertain and consequential risk events that are not easily addressed through traditional approaches of risk management. With this in mind, the paragraph above defines a scientific challenge about complexity, interdependencies, forms of adaptation, scale that requires a new synthesis across complexity, biology, computers, social and cognitive sciences. Connecting the science challenge to the societal need will require engineering advances —advances that will bridge the traditional divide between engineering disciplines and social sciences.

With this in mind, decision-makers and policymakers have utilized the concept of resilience to evaluate the capability of various complex systems to maintain safety, security and flexibility, and recover from a range of potential adverse events. Further, resilience offers the capability to better review how systems may continually adjust to changing information, relationships, goals, threats, and other factors in order to adapt in the face of change – particularly those potential changes that could yield negative outcomes. Preparation for reducing the negative consequences of such events when they occur is generally thought to include enhancing resilience of systems in desirable states, and has been described as including considerations of risk assessment as well as necessary resilience actions before, during, and after a hazardous event takes place. As such, resilience efforts inherently consider the passage of time and shifting capabilities and risks that may accrue due to changes in system performance and capacity to absorb shocks. Resilience strategies have the potential to radically change how a nation prepares itself for the potential disruptions of key services such as energy, water, transportation, healthcare, communication and financial services. When nations

---

[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*

prepare for recovery from external shocks of a significant magnitude, resilience strategies must be considered.

Despite the promise of resilience analysis to improve the safety and security of the variety of industries mentioned and others, the field remains relatively new to the risk management community. Some risk managers oppose risk and resilience, some articulate the two concepts for their complementarity, some say that risk is part of resilience, others say that resilience is part of risk. One recurring complication is the lack of standardization in the field. Practitioners employ a variety of definitions, metrics, and tools to assess and manage resilience in differing applications. Another complication includes the sheer breadth of what resilience analysis implies, both from the standpoint of methodology as well as case applications. These issues motivate the need to provide an overview of various perspectives on the definitions, interpretations, and methodological underpinnings of resilience analysis and thinking as it relates to more traditional risk management. Such an exercise is necessary for, and vital to, the future of the field, where further structure will be needed to facilitate a more common set of definitions and working tools that practitioners can use to deploy resilience into various fields in the future.

Here we introduce a series of papers from thinkers and practitioners in the field of resilience. It offers a view on some of the common streams of thought discussed by disciplinary experts. Specifically, this paper includes (I) a comparison of risk and resilience management strategies, (II) a description of common features within resilience analysis and thinking, and (III) a discussion of the benefits that resilience management brings to the field of risk management.

I - Comparison of Risk and Resilience Management Strategies

Resilience analysis fundamentally maintains much of the same philosophical background as traditional risk assessment. However, resilience analysis additionally delves into the unknown, uncertain and unexpected at the scale of systems rather than individual components. Resilience thinking requires practitioners to ponder potential future threats to system stability and develop countermeasures or safeguards to prevent longstanding losses. Resilience analysis maintains one primary difference in the sense that it primarily focuses on outcomes: practitioners are directly concerned by the ability of the impacted organization, infrastructure, or environment to rebound from external shocks, recover and adapt to new conditions. In other words, where traditional risk assessment methods seek to harden a vulnerable component of the system based upon a snapshot in time, resilience analysis instead seeks to offer a ‘soft landing’ for the system at hand. Resilience management is the systematic process to ensure that a significant external shock – i.e. climate change to the environment, hackers to cybersecurity, or a virulent disease to population health – does not exhibit lasting damage to the functionality and efficiency of a given system. This philosophical difference is complex yet necessary in the face of the growing challenges and uncertainties of an increasingly global and interconnected world.

In reviewing the similarities and differences in the fields of risk and resilience (approaches and methodologies), it is necessary to consider the philosophical, analytical, and temporal factors involved in each field’s deployment (Aven 2011). Philosophical factors include the general attitude and outlook that a risk or resilience analyst expresses when understanding and preparing for risks in a given model. Analytical factors include those quantitative models and qualitative practices deployed to formally assess risk in a particular model. Lastly, temporal factors include the timeframe over which risk is traditionally considered using the analytical models available. Overall, consideration of these and other factors will demonstrate that, while resilience analysis does differ somewhat from more conventionally utilized risk assessment, resilience thinking is highly compatible with existing methods and are synergistic with traditional risk analysis approaches.

Philosophically, risk and resilience analysis are grounded in a similar mindset of (a) avoiding negative consequences of bad things happening and (b) reviewing systems for weaknesses and identifying policies or actions that could best mitigate or resolve such weaknesses. Risk is the operative term for both methodologies, and the overall goal is to lessen as much as possible the damages that could accrue from a hazardous external shock or other undesirable event. As such, practitioners of both mindsets are explicitly required to identify and categorize those events that could generate hazardous outcomes to humans, the environment, or society in general (i.e. commerce, infrastructure, health services, etc.), and subsequently identify countermeasures to meet such hazards.

However, the two methodologies contrast on two key aspects: how to assess and understand uncertainty, and how to judge outcomes of hazardous events (Scholz et al 2012; Fekete et al 2014; Aven and Krohn 2014). For the former, a traditional risk analysis approach would seek to identify the range of possible scenarios in an ad hoc or formalized manner, and protect against negative consequences of an event based upon the event's likelihood, consequences and availability of funding, to cover an array of issues for a given piece of infrastructure or construct. In this way, conventional risk assessors generally construct a conservative framework centered upon system hardness, such as with system protections, failsafe mechanisms, and/or response measures to protect against and respond to adverse events. Such a framework has its benefits, but as we discuss in the next section, if the risk philosophy that supports the analysis is too rigid and inflexible, this can hinder event response efforts to rebound from a severe or catastrophic event.

When judging outcomes of hazardous events, resilience analysis fundamentally seeks to provide the groundwork for a 'soft landing', or the ability to reduce harms while helping the targeted system rebound to full functionality as quickly and efficiently as possible, which may imply adaption to new conditions. This is consistent with The National Academy of Sciences (NAS) definition of resilience, which denotes the field as "the ability to plan and prepare for, absorb, recover from, and adapt to adverse events." While this difference may appear subtle, it carries a significantly different operating statement that causes resilience analysts to focus more on 'flexibility' and 'adaptation' within their targeted systems. This differs from the conventional approach commonly deployed by traditional risk analysis, which instead seeks to identify a system that is fail-safe in nature yet inherently conservative. However, the intrinsic uncertainty of the world, the various actors and forces at work, and the systemic nature of many risks, make it significantly unlikely that inflexible systems would prevent all risks in the long run, or would adequately protect against severe events that could cause lasting and sweeping damage to society and the environment. This is particularly true for low-probability events, which have a significant chance of being written off in a traditional risk assessment report as being excessively unlikely enough to not warrant the proper resources to hedge against (Park et al 2013; Merz et al 2009). Even high-consequences events are often written off of many decision-makers' agendas, when they have a low probability of occurrence.

Analytical differences between traditional risk analysis and resilience analysis are less understood and developed due to the relatively recent attention to resilience. However, it is possible to derive some understanding based upon the philosophical frameworks that underlie the risk management process. Both risk analysis and resilience analysis permit the use of both quantitative data and qualitative assessment, which allows for greater overall flexibility in applications ranging from well-known hazards to highly uncertain and futuristic hazards through the utilization of subject expert insight where quantitative data is limited. Such information is generally integrated into a specific index or model in order to translate the findings into a meaningful result for the risk analyst, who is then able to offer either an improved understanding of the real risk that certain hazards pose against targeted infrastructure and/or an improved review of which alternative actions or policy options may be taken to mitigate the harms presented by such risks.

Quantitative data may be derived from engineering tests in the field, climate models, design specifications, historical data, or experiments in a laboratory, among others, where policymakers and stakeholders are able to view and assess the likelihood and consequence of certain risks against identified anthropologic or natural infrastructure. Likewise, qualitative assessment is generally derived from meetings with subject experts, community leaders, or the lay public, and can be can be used for narrative streamlined assessment such as with content analysis. In most cases, it is optimal to include both sources of information due to the ability of quantitative field data to indicate more accurate consequences and likelihoods of hazard alongside qualitative assessment's ability yield greater context to an existing understanding of risk data. However, it is often not possible for both sets of information to be generated with full confidence, either because of a lack of reliability within qualitative sources of assessment or because of lack or insufficience of quantitative data (due to the rarity of the situation that is studied, or concerns of ethical experimentation, and/or cost and time issues), leaving policymakers and stakeholders to make the best decisions with what is available to them. This is universally true for both traditional risk analysis and its fledgling partner in resilience analysis, and is likely to be the case for any risk assessment methodology to be developed in the future.

However, conceptualizations of risk and resilience are different. Resilience quantification is less mature than its peer methodology in traditional risk assessment, which otherwise has decades of practical use. This is because resilience is particularly relevant for dealing with uncertain threats, which are always difficult, if not impossible, to quantify. Nonetheless, several quantitative, semi-quantitative, and qualitative approaches have been proposed and deployed to measure systemic resilience at local, national, and international levels for a variety of catastrophic events (generally those with low-probability, high-consequences). Some of these approaches could be relatively simplistic, for example with a qualitative classification system. Others are more complex, for example with resilience matrices or highly complex network analysis, where the availability of information and user preferences determines the level of sophistication deployed for a given resilience case. Despite these differences, however, resilience thinking and analysis will be similarly dogged by the potential for 'garbage-in, garbage-out' analysis, where resilience practitioners must be vigilant, rigorous and robust in their use of relevant and valid quantitative data or qualitative information for whichever risk classification they to employ (Hulett et al 2000).

Temporally, risk analysis and resilience analysis are required to consider the near-term risks that have the potential to arise and wreak havoc upon complex systems (Hughes et al 2005). Both engage in exercises that identify and chart out those potential dangers that threaten to damage the infrastructure in question. This exercise can range from being unstructured and ad hoc to organized and iterative, yet ultimately analysts consider a series of threats or hazards that can have some measurable impact upon natural or man-made structures. These hazards are then reviewed based on their likelihood of occurrence and consequences on outcome, which is another iterative process. Lastly, risk analysts are required to assess the immediate aftermath of the various adverse events that were initially identified, and gain a greater understanding into how different components of infrastructure may be damaged and what the consequences of this may be.

Resilience analysis differs in a temporal sense from traditional risk analysis by also considering recovery of the system once damage is done. Thus, in addition to considering system decline immediately after an event (i.e. risk), resilience adds consideration of longer term horizons that include system recovery and adaptation. Traditional risk analysis *can* integrate recovery and adaptation (for example, by considering probability of system to recover by specific time after event or likelihood that it will be able to adapt), yet this is not necessarily the prime focus of the overall risk analytic effort. Instead, a traditional risk analysis project constructs the ideal set of policies that, given available money and resources, would offer the best path forward for risk prevention and management. Attention to longer term and lower probability threats is often neglected in favor of more intermediate and likely dangers, with only limited emphasis or focus on the need for infrastructural and organizational resilience building, in the face of uncertain and unexpected harms. In this way, traditional risk assessment may not accurately or adequately prepare for those low-probability yet high-consequence events that could dramatically impact human and environmental health or various social, ecological, and/or economic systems that have become ubiquitous within modern life.

II - Features of Resilience

Globalization is increasing and strengthening the connectivity and interdependencies between social, ecological, and technical systems. At the same time, increasing system complexity has led to new uncertainties, surprising combinations of events, and more extreme stressors. Confronted by new challenges, the concept of resilience, as an emergent outcome of complex systems, has become the touchstone for system managers and decision-makers as they attempt to ensure the sustained functioning of key societal systems subject to new kinds of internal and external threats. Ecological, social, psychological, organizational, and engineering perspectives all contribute to resilience as a challenge for society. However, there are weak linkages between concepts and methods across these diverse lines of inquiry. Useful ideas and results accumulate and partially overlap but it is often difficult to find the common areas. Further, the different technical languages hamper communication of ideas about resilience across of the different contributing disciplines and application problems.

Connelly et al. (2016) identified features of resilience that are common across conceptualizations of resilience in various fields including (i) critical functions (services), (ii) thresholds, (iii) recovery through cross-scale (both space and time) interactions, and (iv) memory and adaptive management. These features are related to the National Academy of Science definition of resilience through the temporal phases of resilience (Table 1). The concept of *critical functionality* is important to understanding and planning for resilience to some shock or disturbance. *Thresholds* play a role in whether a system is able to absorb a shock, and whether recovery time or alternative stable states are most salient. *Recovery time* is essential in assessing system resilience after a disturbance where a threshold is not exceeded. Finally, the concepts of *memory* describe the degree of self-organization in the system, and adaptive management provides an approach to managing and learning about a system's resilience opportunities and limits, in a safe-to-fail manner.

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 Science definition of resilience (discussed in Connelly et al 2016 – forthcoming).

NAS phase of resilience	Resilience Feature	Description by Application Domain			
		Socio-Ecological	Psychological	Organizational	Engineering & Infrastructure
Plan	Critical function	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	Threshold	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	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

Critical Functions (Services). Understanding the resilience of systems focuses on assessing how a system responds to sustained functioning or performance of critical services while under stress from an adverse event. In assessing resilience, it is necessary to define the critical functions of the system. Stakeholders play a key role in defining critical functions. Operationalizing resilience concepts depends on identifying the resilience of what, to what, and for whom. In addition, system resilience depends on how the boundaries of the system are drawn (i.e., the chosen scale of interest) and the temporal span of interest. Scale is often dictated by the social organizations responsible for managing the system based on temporal and spatial dimension (Cumming et al 2006). Thus, stakeholders influence how resilience is assessed both in terms of defining critical functions and system scale. For example, the Resilience Alliance workbooks for practitioners assessing resilience in socio-ecological systems asks stakeholder groups to envision the system and scale of interest, possible disturbances, and to identify vulnerabilities (Resilience Alliance 2010). Further, with respect to psychological resilience, individuals are responsible for assessing resilience through self-reported inventories of protective factors (e.g., adaptable personality, supportive environment, fewer stressors, and compensating experiences) (Baruth and Caroll 2002). It is common practice to use questionnaire responses of stakeholders to assess resilience in psychological and organizational systems.

Thresholds. The concept of resilience involves the idea of stable states or regimes in which a system exists prior to a disruptive event. Systems are able to absorb changes in conditions to a certain extent. Further, resilient systems have higher ability to anticipate and use other forms of information and have different ways to synchronize over multiple players (Woods 2003). However, if a shock perpetuates changes in conditions that exceed some intrinsic threshold, the system changes regimes such that the structure or function of the system is fundamentally different. It is the balance of positive and negative feedbacks that can cause a system trajectory to exceed a threshold and degrade system performance (leading to the "collapse" phase of the adaptive cycle) (Fath et al 2015). The nested nature of systems contributes to the possibility of cascading effects when a threshold at one scale is crossed and causes disruptions at other scales (Kinzig et al 2006). The sensitivity of system and sub-system performance to changes in inputs can be used to determine resilience thresholds. Resilience thresholds within organizations are linked to the adaptive capacity of the organization and of the management scheme utilized. Identifying thresholds prior to exceeding them is difficult and an area of intense research (Angeler and Allen 2016). When a threshold is crossed, return is difficult, especially where hysteresis is present. Where or when a threshold is not exceeded, resilience is still relevant, but measures of return time are more appropriate. These concepts are interlinked, and return time may slow as the resilience limits of a system are approached (i.e., critical slowing) (Dakos et al 2008; Gao et al 2016).

Scale. Resilience is often considered with respect to the duration of time from a disruptive event until recovery (or until the system has stabilized in an alternate regime), and the spatial extent of the system of interest. We consider space and time scales as inextricably linked. Changes in critical functionalities are highly correlated in time and space. It is a flawed approach when one aspect of scale is considered without co-varying the other. There is frequently an emphasis on minimizing time to recovery where full or critical levels of services or functions are regained. *Engineering resilience*, in particular, has a focus on the speed of return to equilibrium, but this measure of resilience does not adequately consider the possibility of multiple stable states, nor account for non-stationarity (Walker et al 2004). However, return to equilibrium provides important information about the resilience of a system to perturbations that don't cause the system to exceed a threshold and enter into an alternative regime. In the psychological domain, there is also a consideration for the timing of disruptive events within an individual's lifetime. For example, children might be more susceptible than adults to negative psychological impacts from an event, though this is not always the case. Further, resilience requires an appreciation for system dynamics over time. It is thought that resilience is linked to the dynamics of certain key variables, some of which are considered "slow" changing and constitute the underlying structure of the system while others are "fast" changing representing present-day dynamics. Panarchy theory captures this cross-scale structure in complex systems (Allen et al. 2014).

Memory. Memory of previous disruptions and the subsequent system response to a shock can facilitate adaptation and make systems more resilient. For example, Allen et al. (2016) observe that ecological memory aids in reorganization after a disruptive event. It has also been noted that socio-ecological resilience is enhanced by a diversity of memories related to the knowledge, experience, and practice of how to manage a local ecosystem (Barthel et al. 2010). Institutional memory can extend beyond individuals. For example, institutional memory is responsible for maintaining lessons learned from previous challenges to the organization or to similar organizations (Crichton et al 2009). In each case system-wide sensing or monitoring is essential to capture changes in salient driving conditions and critical functions. Memory of an event in the short term often results in increased safety or resilience through anticipation of a shock or disruptive event through enhanced resistance or adaptive capacity, though in the long-term the memory of the event fades (Woods 2003). Memory tends to be maintained if the system has high modularity or diversity.

In human physiology, responding to repeated stressors produces long run changes in the physiological systems affected by the series of events that evoke stress responses. Although memory of a past experience can have a negative impact on an individual, in some cases, memory can enable positive adaptation whereby these individuals are better able to cope with future stressors. Social memories tend to influence individuals' interpretations of reality, and thus maladaptive social memories can decrease individual and societal resilience.

Adaptive Management. Under changing conditions, however, memory of past disturbances and responses may not be sufficient for maintaining system performance or critical functionality. The concept of adaptive management acknowledges uncertainty in knowledge about the system, whereby no single management policy can be selected with certainty in the impact. Instead, alternative management policies should be considered and dynamically tracked as new information and conditions arise over time. Accordingly, management is able to adapt to emergent conditions, reduce uncertainty, and enhance learning in a safe-to-fail manner. By adjusting response strategies in advance to disruptive events, management is able to build a readiness to respond to future challenges. Anticipation and foresight lead organizations to invest in capabilities to deal with future disruptions and prepare for multi-jurisdictional coordination and synchronization of efforts such that the system adapts prior to disturbances. Thus, system-wide sensing (and monitoring), anticipating disruptions, adapting and learning (from both success and failure) occur proactively and in a perpetual cycle, or until key uncertainties are reduced (Park et al 2013).

There are a number of common features of resilience linked to the planning, absorbing, recovering and adapting phases identified in the NAS definition. Preparing or planning for resilience involves stakeholder identification of critical functions of the system and the strategic monitoring of those functions. Intrinsic thresholds or boundaries determine the amount of disturbance a system can absorb before the system enters an alternate regime, whereby the structure and/or critical functions of the system are different. Whether the system transitions to a new regime or remains the same, the time until the system (performance and critical functionality) recovers from a disturbance is used to assess resilience. Finally, memory and adaptive management facilitate system coping to changing conditions and stressors, even in an anticipatory sense. These features, along with stakeholders and scale, are important across domains in understanding and communicating resilience concepts.

III - Benefits of Resilience Thinking Over Traditional Risk Analysis

Traditional risk analysis and resilience analysis differ, yet overall they must be considered complementary approaches to dealing with risk (Figure 1). One way to assess how they are complementary is to consider Risk Assessment as bottom-up approach starting from data and resilience as Top-Down approach starting with mission and decision-maker needs with obvious need for integration. Risk assessment process starts with data collection and progresses through modelling to characterization and visualization of risks for management while resilience starts with assessing values of stakeholders and critical function and through decision models progresses towards generation of metrics and data that ultimately can inform risk assessments.

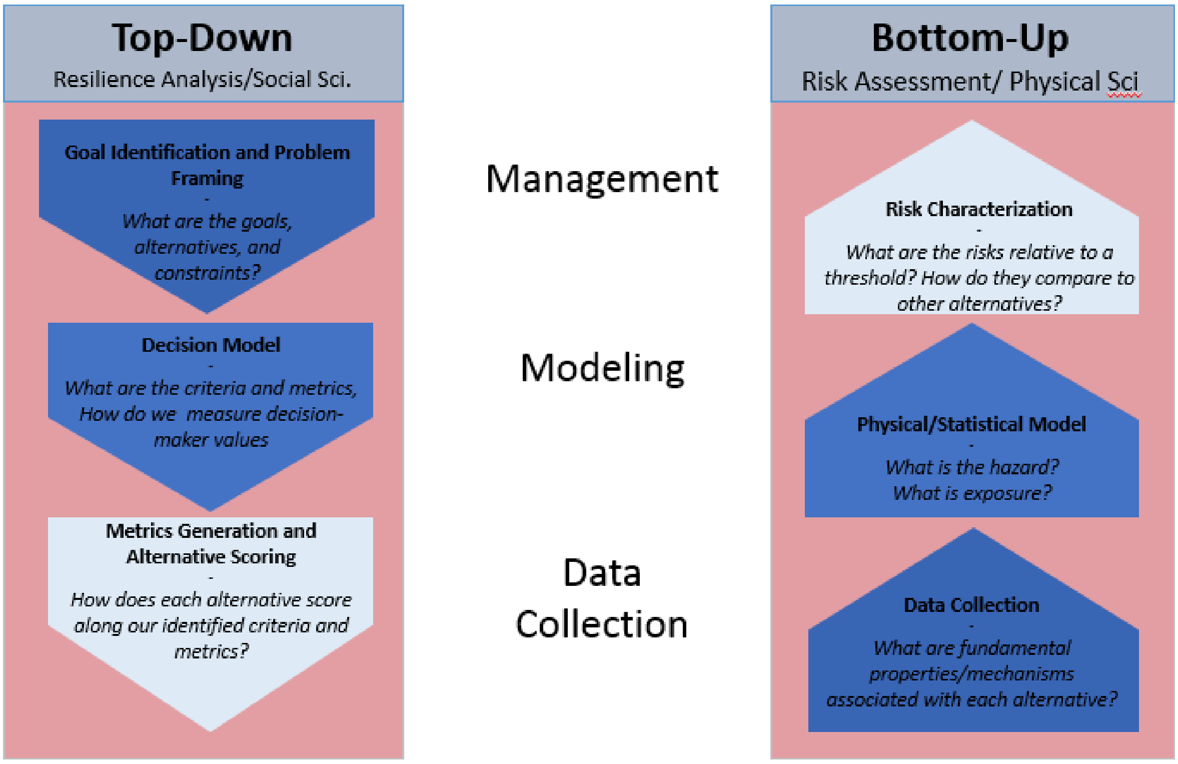

Figure 1: Risk and Resilience Integration (after Linkov et al., 2014).

Resilience analysis focuses on both everyday dangers and hazards to organizational and infrastructural condition along with longer term or lower probability threats that have significantly negative outcomes. The purpose of such focus is to improve the target's ability to 'bounce back' from an adverse event, or reduce the time and resources necessary to return the impacted infrastructure back to normal operating procedures. In this way, resilience analysts are by default required to consider risk over the extended or long term and review those events which could prevent a system or infrastructure from returning to full functionality for an extended period. Though not universally true, resilience management *may* afford policymakers and stakeholders a greater upfront defense against system endangering hazards such as those that occurred in the case of Hurricane Katrina or Superstorm Sandy.

A conventional way to determine how risk and resilience are complementary is to consider that risk assessment as the preliminary phase to resilience analysis. It provides the first elements needed to trigger, or not, the need for resilience assessment. This is particularly true in the case of low-probability, high consequence risks of the distance future, such as those associated with climate change, large-scale cybersecurity threats, or severe weather events on the coasts. In this way, resilience analysis adds a different perspective that traditional risk analysts may otherwise miss – the ability to understand the capacity of an organization or infrastructural system to rebound from a massive external shock. While it is impossible to fully predict a highly uncertain and infinitely diverse future, a robust resilience analysis can offer system level preparation across physical, information and social domains thus improving the functionality of the system in the midst of a crisis. While low-probability high-severity events are rare, several have been experienced in recent memory (ranging from the September 11th terrorist attacks to the Fukushima Daiichi nuclear disaster), making resilience assessment both a realistic and highly useful tool to minimize unnecessary losses to infrastructure, capital, and most importantly, human wellbeing.

These benefits of resilience analysis do not immediately mean that resilience analysis is an all-around improvement over conventional risk analytic methods. For traditional risk analysis, risk planning is a multistage effort that requires advanced threat identification for hazardous events prior to their occurrence with follow-up risk mitigation focused on hardening vulnerable system components. Resilience analysis starts with identifying critical functions of the system and stakeholder values with subsequent assessment of system improvement alternatives. Resilience analysis centers on the integration of risk perception (the active identification of risk and hazard in the midst of uncertainty), risk mitigation (steps taken to reduce harms before they occur), risk communication (the need for a clear and meaningful discourse on the seriousness of risk to the general population), and risk management (post hoc measures to address a realized hazard) collectively guide any risk or resilience effort. In this way, resilience analysis *is* far more than a focus on rebounding from a serious risk event, but rather a series of similar steps as with conventional risk analysis that has its own angle on how to best prepare for such hazards.

Resilience analysis cannot, however, replace risk assessment. Its systems approach is characterized by a higher complexity of conceptualization and disconnect from specific system components that needs to be engineered individually. Moreover, less severe and better characterized hazards are better served by existing conventional methods that adequately assess perceived cost and benefits for a given action.

Resilience as Understood by Various Experts

This paper serves as a general introduction to the concept and application of resilience, specifically as it relates to traditional risk management, and in particular about suggestions for metrics or indicators that can be developed to assess resilience in a system, and the performance of resilience strategies. IRGC has invited experts, scholars, and practitioners of resilience from across the globe who were asked to provide (i) their view of an operating definition of resilience, (ii) discussion of the purpose and utilization of resilience, (iii) instruments to deploy resilience, and (iv) potential metrics and criteria for resilience management. As such, each entry offers a unique view of how resilience is understood and utilized in general or for specific applications – all within a comparable framework by which the reader may assess the similarities and differences across the body of included experts.

References

Aven, T. (2011). On some recent definitions and analysis frameworks for risk, vulnerability, and resilience. *Risk Analysis 31*(4), 515-522.

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

Allen, C. R., et al. (2016). Quantifying spatial resilience. *Appl. Ecol.*

Angeler, D. G., Allen, C. R. (2016). Quantifying resilience. *Appl. Ecol.*

Aven, T., and Krohn, B. S. (2014). A new perspective on how to understand, assess and manage risk and the unforeseen. *Reliability Engineering & System Safety 121*, 1-10.

Barthel, S., Sörlin, S., Ljungkvist, J. (2010). In The Urban Mind, P. J. J. Sinclair, G. Nordquist, F. Herschend, C. Isendahl, Eds. (Uppsala Universitet, Uppsala, Sweden, http://www.diva-portal.org/smash/record.jsf?pid=diva2:395721), pp. 391–405.

Baruth, K. E., and Caroll, J. J. (2002). A formal assessment of resilience: The Baruth Protective Factors Inventory. *Individ. Psychol. 58*, 235–244.

Crichton, M. T., Ramsay, C. G., Kelly, T. (2009). Enhancing organizational resilience through emergency planning: Learnings from cross-sectoral lessons. *Contingencies Cris. Manag. 17*, 24–37.

Connelly, E., Allen, C., Hatfield, K., Palma-Oliveira, J., Woods, D., and Linkov, I. (2016). Resilience as the Feature, or Features of Resilience? Forthcoming.

Cumming, G. S., Cumming, D. H. M., Redman, C. L. (2006). Scale mismatches in social-ecological systems: Causes, consequences, and solutions. *Ecol. Soc. 11*(20).

Dakos, V., Scheffer, M., van Nes, E. H., Brovkin, V., Petoukhov, V., & Held, H. (2008). Slowing down as an early warning signal for abrupt climate change. *Proceedings of the National Academy of Sciences*, *105*(38), 14308-14312.

Fath, B. D., Dean, C. A., Katzmair, H. (2015). Navigating the adaptive cycle: an approach to managing the resilience of social systems. *Ecol. Soc. 20*, doi:10.5751/ES-07467-200224.

Fekete, A., Hufschmidt, G., and Kruse, S. (2014). Benefits and challenges of resilience and vulnerability for disaster risk management. *International Journal of Disaster Risk Science 5*(1), 3-20.

Gao, J., Barzel, B., & Barabási, A. L. (2016). Universal resilience patterns in complex networks. *Nature*, *530*(7590), 307-312.

Hughes, T. P., Bellwood, D. R., Folke, C., Steneck, R. S., and Wilson, J. (2005). New paradigms for supporting the resilience of marine ecosystems. *Trends in Ecology & Evolution 20*(7), 380-386.

Hulett, D. T., Preston, J. Y., and CPA PMP. (2000). Garbage in, garbage out? Collect better data for your risk assessment. In *Proceedings of the Project Management Institute Annual Seminars & Symposium*, pp. 983-989.

Kinzig, A. P., Ryan, P. A., Etienne, M., Allison, H. E., Elmqvist, T., & Walker, B. H. (2006). Resilience and regime shifts: assessing cascading effects. Ecology and society, 11(1).

Merz, B., Elmer, F., and Thieken, A. H. (2009). Significance of high probability/low damage versus low probability/high damage flood events. *Natural Hazards and Earth System Science 9*(3), 1033-1046.

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 Anal. 33*, 356–367.

Park, J., T., Seager, P., Rao, P. S. C., Convertino, M., and Linkov, I. (2013). Integrating risk and resilience approaches to catastrophe management in engineering systems. *Risk Analysis 33*(3), 356-367.

Resilience Alliance. (2010). Assessing resilience in social-ecological systems: A practitioner's workbook. Version 2.0 (available at http://www.resalliance.org/3871.php).

Scholz, R. W., Blumer, Y. B., and Brand, F. S. (2012). Risk, vulnerability, robustness, and resilience from a decision-theoretic perspective. *Journal of Risk Research 15*(3), 313-330.

Walker, B., Holling, C. S., Carpenter, S. R., Kinzig, A. (2004). Resilience, adaptability and transformability in social – ecological systems. *Ecol. Soc. 9*(5).

Woods, D. (2003). Creating foresight: How resilience engineering can transform NASA's approach to risky decision making.