1 Introduction to resilience of socio-technical systems

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In recent years the resilience concept has received considerable attention in a wide range of disciplines, from engineering and biology to the health and social sciences, business and policy, and beyond. With the different interests of these disciplines come important nuances in the way resilience is interpreted. Some of these nuances find their expressions in the various chapters of this *Handbook* and are illustrated through corresponding case examples and applications. Common to all is the notion that resilience – the ability to withstand or bounce back from some shock – is inherently a systems feature. What relevant system elements interact with each other, how these interactions manifest themselves through space and time and how they can be shaped through active intervention are all key issues in resilience research.

However, resilience has become more than a systems feature to be observed and shaped. It is increasingly taking on normative values. Overall system resilience is typically perceived as desirable; ecosystems that quickly return to their structure and function and display high species diversity and richness after a drought or fire for example, infrastructures that continue to provide services during some seismic event, or societies that bounce back from an economic shock, all are preferred to those that do not retain or make it back to their original performance levels. However, depending on long-term goals, resilience may also hinder development. For example, many economies exhibit persistent power imbalances that present considerable inertia to change. The situation may manifest itself in the form of inequities in standards of living and seriously curtailed opportunities for a wide segment of the population – women and minorities underpaid for their labor, children exploited, rights of owners of land and other resources being disrespected. To the extent that the associated injustices further entrench and reinforce the mechanisms for unjust treatment, the system remains, undesirably, resilient to change.

To ensure resilience sometimes requires that the performance of some part of the system is sacrificed. Typical engineering examples include fuses and circuit breakers, which are designed to absorb and shield the remainder of the system from excessive shock. On a larger scale, the shedding of parts of an electricity grid in order to stabilize operations for the rest of the grid is such an example. In the business and policy world, individuals are removed from their posts and entire units are abolished or reorganized to protect firms or governments from widespread collapse. Which subsystems to sacrifice, and when to do so, may not always be clear a priori, especially if the magnitude and duration of a shock to the system are not well known. Similarly, which system components and interconnections to strengthen, and how to do so, in anticipation of possible shocks is a challenge common to the management of natural, engineered and social systems alike.

Of particular interest to this volume is not so much the resilience of technical or social systems on their own, but how the two interact with each other to promote or undermine

resilience for one or both. Attention is given here, in equal measure, to the foundational elements of resilience research in the socio-technical realm (Part I) and to specific forms of analysis and applications to particular system issues (Part II).

While it may be relatively straightforward to identify for technical systems a reference state that should be maintained or to which it should be able to bounce back in light of a shock, the identification of a constant benchmark for social systems is less meaningful. Societies change in many subtle as well as not so subtle ways irrespective of outside shocks. As they do so, they develop and deploy new technologies, which in turn shape their future change. The ability to learn, anticipate and plan is integral to the resilience of the combined socio-technical system. Where barriers to system improvement must be removed and new behaviors, institutions and technologies need to be put in place, a host of ethical issues arise, as Axel Schaffer and Martin Schneider outline in Chapter 2 of this volume.

The history of the resilience concept is one of permanent transfer between disciplines and reinterpretation as Hans Dieter Hellige explains (Chapter 3). He describes, from a historic perspective, how resilience has become a ‘borderline concept’ with manifold layers of meaning and a diverse range of applications. Societal expectations, he argues, provide a defining context for the transformation of the resilience concept and its meaning. This type of scientific development, introduced here as ‘analogical thinking’, has its limits and needs to be done carefully in order to bear fruit. The source and target system of such conceptual transfers need to be similar enough to not lead into ‘blind alleys’. Hellige describes his observations in more detail using the example of C.S. Hollings’s resilience concept for ecosystems and its potential transfer to energy systems and socio-economic theory. Later in this book (Chapter 16) the genesis and the meaning of the resilience concept in the design of energy systems is analyzed in more depth by Hellige.

What are the preconditions for targeted changes that support increased resilience? What are the barriers that need to be overcome? Chapters 4 and 5 address each of these questions in turn. David Woods (Chapter 4) extends earlier conceptualizations of the ‘essentials’ of resilience, emphasizing that organizations that intend to bring about change must be poised to do so, possess and retain a readiness to respond to meet new challenges, be able to properly assess trade-offs, especially between short-term and long-term performance criteria, and take initiative accordingly. All this, in turn, means that individuals and institutions must have some kind of intellectual bandwidth to comprehend how the systems of interest to them function, that is, what the relevant system components are and how they interrelate under a wide range of conditions. That bandwidth sometimes is expanded (or reduced) through experience from past failures, but it can also be enhanced through targeted interventions, such as through education, simulation games and the use of scenarios. However, that bandwidth may also degrade on its own, and existing knowledge may become obsolete. Complacency – proceeding as usual, perhaps because there are no challenges to be dealt with in the interim – also can undermine the capacity for change, as can a lack of diversity in thinking, which in turn may be the product of limited diversity among those assessing a situation and engaged in making decisions.

Despite all the best intentions and decades of research into conditions that affect system resilience, critical infrastructure systems – most notably the lifeline networks that provide water, energy and transportation, for example, and the institutions that govern their performance – remain fragile, resulting in sub-par social and economic development.

Drawing on experiences from the USA, David Alderson (Chapter 5) identifies systematic barriers to greater scientific understanding of critical infrastructure that must be overcome in order to promote progress. Recent terrorist activities (most notably the attacks of 11 September 2001 in the USA), but also particular climate events (such as wildfires in California, flooding in Virginia and hurricanes in Texas and Puerto Rico), have led to an ‘overemphasis on predefined threat scenarios’. Yet critical infrastructure system resilience must be enhanced in light of multiple possible hazards, and must recognize the interdependencies of these systems, for example, when transportation requires electricity to operate signals, fuel-pumping stations and communications technology, and conversely, when transportation is central to adequate fuel supply to power plants. Alderson provides recommendations to overcome barriers to improved understanding of critical infrastructure resilience, including the expansion of case studies, the creation of repositories of infrastructure system data and an evolution in the mission of actors charged with critical infrastructure protection and resilience.

Arnim von Gleich and Bernd Giese (Chapter 6) take what may be called a top-down approach to understanding the mechanisms that help prepare systems for complete surprises. Rather than focus on the specifics that shape how socio-technical systems are composed and work, they draw on insights from evolution, where the interplay of random mutations and natural selection over long periods of time calibrate the performance of system elements, such as individual species, and large assemblages of these elements in an ever-changing physical and biological environment. Their ‘biomimetic approach’ points towards the need for low-risk construction where learning is from the results of evolution, the network, material and energetic characteristics of resilient systems, and the associated processes of competition and synergism.

Mary Warner, Udit Bhatia and Auroop Ganguly in their contribution on risk analysis, resilience and network science (Chapter 7), pick up, in a particular way, on the relevance of network characteristics and connect to several other themes identified in prior chapters, most notably the need to consider multiple hazards and to develop and draw on a suite of tools for the assessment of resilience in the context of concrete cases. The examples they present include one for the Indian Railway System, and one for the US National Airspace. For both cases, Warner et al. identify shortcomings of traditional probabilistic risk assessments and showcase how those assessments can be enriched with insights from network analysis. All of this lends further support to Alderson’s earlier call (Chapter 5) for institutional evolution that integrates resilience in system design and regulatory structures.

Stefan Goessling-Reisemann and Pablo Thier (Chapter 8) further explore the differences between risk management and resilience management for critical infrastructures. They differentiate the two approaches along three aspects: the type and uncertainty of the stressor acting on the system in question, the uncertainty of the impact on the system and the uncertainty of the state of the system itself. They argue, that with more uncertainty, and especially ‘deep’ uncertainty, which cannot be reduced by more analysis, comes the necessity to design systems for the unexpected. The type and magnitude of uncertainty is thus, according to these authors, the major distinction between risk and resilience management. While risk management is well established and very successful in managing known threats with known impacts, resilience management tries to prepare for the unknown, the ‘black swan’ events. They further discuss several attempts to operationalize

resilience management and resilient design for critical infrastructures, and present their own strategy to improve the resilience of infrastructures as socio-technical systems. In conclusion, they point towards some critical issues for resilience research and practice that need to be tackled in order to progress towards resilient critical infrastructures.

Following on the recognition that resilience analysis is more than risk assessment, Benjamin Trump, Kelsey Poinsett-Jones, Timothy Malloy and Igor Linkov in their contribution on resilience and risk governance (Chapter 9) argue that risk governance strategies must incorporate aspects of hard and soft law that enable government and industry organizations to predict, mitigate and recover from systemic risks. They then propose that risk governance strategies adapt to improve system predictive capacity and recovery from system shocks, such that best practices and risk management requirements shift in order to help organizations better adapt to future threats. Trump et al. illustrate for various government agencies and industry practitioners within the United States how resilience has been embedded in their guidelines and practices, and expand their discussion to efforts in the Organisation for Economic Co-operation and Development (OECD), the United Kingdom and elsewhere. They argue for new methodologies to facilitate decision making under high uncertainty and the need to integrate available information across a multitude of stakeholders who may pursue different objectives and assess them with a variety of criteria, much as is described in more detail in Chapter 19 by Sahar Mirzaee and her collaborators. Trump et al. also advocate for requiring regulatory agencies and environmental law to be adaptable and flexible in the face of uncertainty, where institutional and legal rigidity may make such systems incapable of recovering quickly from adverse events. That proposal is reminiscent of the need for learning and institutional evolution identified in prior chapters.

Technical and infrastructure systems are highly complex, in that they consist of a multitude of interrelated systems and processes, and not all that needs to be known to apply risk analysis is known about their behaviors and the potential stressors. Interrelations can serve as conduits of shocks on one part of the system that then ripple through to other parts. Since the social systems responding to, and shaping, technologies and infrastructures, operate with incomplete information, and since institutions in charge of one technology or one infrastructure may not possess the requisite knowledge or administrative reach to manage cascading events, additional challenges arise for the management of the combined socio-technical system. As Stefan Hiermaier, Benjamin Scharte and Kai Fischer (Chapter 10) emphasize, an additional challenge comes from unpredictable large-scale, large-impact events of extremely low probability of occurrence, such as the Tōhoku earthquake, tsunami and the subsequent Fukushima Daiichi nuclear disaster, as well as the global disruption of supply chains that ensued for many manufacturing products. Drawing on the work of David Woods (see Chapter 4), they advocate for an analysis of the conditions that need to be met for engineering systems to function within desired bounds. Such an analysis, in turn, would point to interventions that promote resilience even in light of very low-probability, high-extreme events. They then lay out, for the case of urban environmental change, a framework for the quantification of resilience.

The kind of benchmark performance that could be used to assess whether and how an engineering system resists or bounces back from some external shock, however, is of limited applicability for social systems because social systems are replete with transitions. A shock may be used to fundamentally restructure a system so that it exhibits enhanced

performance, rather than just return to its prior performance levels. The Tōhoku earthquake in Japan again provides a recent example as it spurred an aggressive transition of Germany's energy sector from nuclear power to renewable fuels, rather than leading to measures that would help ensure nuclear safety under some newly experienced, extreme event. The result has been not only a considerable transformation of power supply, but it also stimulated major economic changes by creating employment in small and large businesses alike – multinational corporations producing the control equipment and other technical components for the development of a new kind of electricity generation, distribution and storage system, as well as small and medium-sized local businesses that help deploy at the household and community level biogas generators, solar collectors and more.

Given the ubiquity of both socio-economic and technological transitions, how may the concepts of resilience and transition be reconciled and made fruitful in their combination? This is the key question addressed by Claudia Binder, Susan Mühlemeier and Romano Wyss (Chapter 11), who present an indicator set to operationalize key attributes of resilient social and technical subsystems in transition using (1) three fundamental diversity properties – variety, balance and disparity – and (2) three basic connectivity properties from the field of social network analysis – path length, centrality and modularity. In doing so, their chapter not only connects back to the plea for an infusion of network analysis into resilience assessments provided by Warner et al. (Chapter 7) but also lays the groundwork for empirical application and measurement to specific system transitions, such as those occurring in a national or regional energy sector, and broader sustainable development trends.

Russell Bowman (Chapter 12) explores in more detail the lessons learned from a wide range of resilience assessments that have been carried out under the auspices of the United States federal government. These assessments took place over years (and continue to be part of the portfolio of Department of Homeland Security activities) and included close collaboration with local and sectoral representation. Bowman conducts a qualitative analysis of the reports generated by these assessments, to identify how the information these reports contain can be leveraged across sectors, regions and infrastructure systems to support the resilience of a wide range of sectors, regions and infrastructures.

While Bowman focuses on the processes of information gathering, sharing and knowledge generation, Noah Dormady, Adam Rose, Heather Rosoff and Alfredo Roa-Henriquez (Chapter 13) focus on firm-level activities carried out to improve resilience. Drawing on microeconomics and using a survey-based approach, they develop a method by which the cost-effectiveness of resilience actions can be quantified. Dormady et al. demonstrate their approach with a sample application to the impacts of Superstorm Sandy that hit in 2012, among others, the New York and New Jersey coastal areas of the United States.

Historically, the kind of resilience projects carried out at the regional scale and for individual infrastructure sectors, such as those discussed by Bowman (Chapter 12), and the kind of firm-level resilience projects that are the subject of analysis by Dormady et al. (Chapter 13), have largely been in the forms of engineering and management interventions. In contrast, Ashley Cryan, Brian Helmuth and Steven Scyphers (Chapter 14) turn to the role of natural systems – green infrastructure – to provide essential services to society, such as flood control for coastal communities. In many cases, green infrastructure

has served the same, if not better, roles than the engineering systems with which they were replaced, such as seawalls, bulkheads and revetments. Given the existing tendency to seek engineering solutions, and the limited knowledge of how green infrastructures may be re-established in ways that avoid investment in grey infrastructures or perhaps enhance their performance, challenges persist to finding ways that promote resilience to climate and other environmental changes, especially in urban coastal environments.

Returning to the notion that socio-technical systems constantly change (Chapter 11), and connecting to the notion that ecosystems provide essential services to society, Kristi Maciejewski, Reinette Biggs and Juan Rocha (Chapter 15) focus on regime shifts in socio-ecological systems, drawing on a rich literature on systems ecology and complex adaptive systems. Their contribution lays out a set of methods that can be used to analyze regime shifts and draws conclusions for managing socio-ecological systems to enhance their resilience and sustainability.

Energy plays a central role in helping maintain lives, livelihoods and standards of living. The lifeline infrastructures that were developed to facilitate large-scale generation and distribution of electricity are prone to disruptions – whether caused by natural events such as storms or by human action such management failures or deliberate attacks. Energy systems have therefore long received considerable attention in resilience research. The growing role of information technology (IT) in managing these systems has to some extent helped enhance their performance but also introduced new challenges. Recent expansions of power generation from renewables, such as wind and solar, is further shifting the landscape of power generation, distribution and use, and how to manage them all in ways that minimize disruptions.

A series of three chapters explore these issues. Continuing the historical analysis of the resilience concept, Hans Dieter Hellige (Chapter 16) explores the genesis of resilient energy systems as a design concept from the early 1970s to the early 1980s. He shows how metaphorical thinking led to a concept transfer from ecosystem research to engineering and system design which was believed to make energy systems less vulnerable and better adapted to the limited carrying capacity of Earth in terms of climate change and fossil resources. Hellige demonstrates the long history of metaphorical thinking in the design of socio-technical systems, especially infrastructures such as electricity, gas or telecommunication networks, that was driven by Lovins and Lovins in their discussion of ‘brittle’ energy systems. A persistent motive is the belief that decentralized, redundant and non-hierarchical designs yield systems of higher resilience. Spurred by discussions in the 1970s this has led to the development of our modern internet structure and is currently debated (again) as a guiding principle also for energy systems. Hellige also shows that some ecosystem metaphors for designing energy systems were probably too early to be successful. For example, the homeostasis principle introduced by Schwegge in the 1970s was basically a forerunner of our modern idea of a smart grid but was too advanced and definitely not adequate in the fossil-dominated and centrally organized electricity supply systems of the late twentieth century.

Nowadays, smart grids have become reality, however, and IT-security becomes an integral part of energy security. Lars Fischer and Sebastian Lehnhoff (Chapter 17) explore the role of IT security in providing functional resilience in energy systems. Their contribution to this volume focuses on cyber-attacks on energy infrastructures – the intentional, malicious disruption of the energy generation and supply networks on which much of

modern life depends. They introduce the concept of event-centric IT security, which not only attempts to avert system disruptions but deals with an attack in a responsible manner. For the latter, operational technology and security objectives must be developed in synch with information technology, as well as the broader institutional learning processes identified by Woods in Chapter 4.

A growing share of renewable energy sources in the overall energy portfolio will help communities, regions and countries to diversify their energy sources and thus may increase their resilience to shocks that affect one or a small subset of them. However, a renewable energy transition may also undermine resilience. Large-scale biomass-based power generation, for example, relies on the availability of organic matter as feedstock. During droughts and heat waves, biomass production may be seriously curtailed – just at times when power demand for cooling or irrigation, for example, may be highest. As Jennie Stephens argues in Chapter 18, depending on how resilience is framed in terms of scale and time frame, different types of energy system changes with variable societal impact could be prioritized and justified by the resilience imperative. By connecting energy policy to social and political outcomes, she explores the potential for enhancing societal resilience during the renewable energy transition.

The remaining two chapters of the book return to the issue of how, specifically, human decision making may be enhanced to help promote resilience. Sahar Mirzaee, Matthias Ruth and David Fannon begin that discussion with an introduction to multi-criteria decision making – an approach that recognizes that the complexity of interactions between social and technological systems is met by decision makers who may have very different backgrounds, information, interests and goals when identifying ways in which to promote resilience. Mirzaee et al. introduce several methods to elicit the perspectives of individuals and to reconcile them in consistent ways with each other for the identification of preferred actions. Eric Gordon (Chapter 20) draws on design thinking as a means to help articulate people's understanding of complex socio-technical systems, and to structure that understanding by developing games for problem solving. While considerable attention has been paid in the literature and by practitioner communities to the role of games, this 'pre-gaming' approach reveals the understanding of the problems to be solved in the first place. By breaking complex issues into 'playable problems' creative, if not novel, solutions may be found.

As indicated at the outset of this introduction to the *Handbook on Resilience of Socio-Technical Systems*, both social and technological systems are complex, and their interactions require considerable attention not just to the workings of each in isolation, but on the way in which they are connected and shape each other over time. Creating resilient socio-technical systems is an iterative process by which not only technologies, and interventions, evolve, but also learning takes place by individuals and institutions – all in the light of fundamental uncertainties and surprises. This *Handbook*, therefore, not only lays out the many conceptual, methodological and empirical challenges to advance the resilience agenda in these areas, but also identifies avenues for further research and analysis for decades to come.