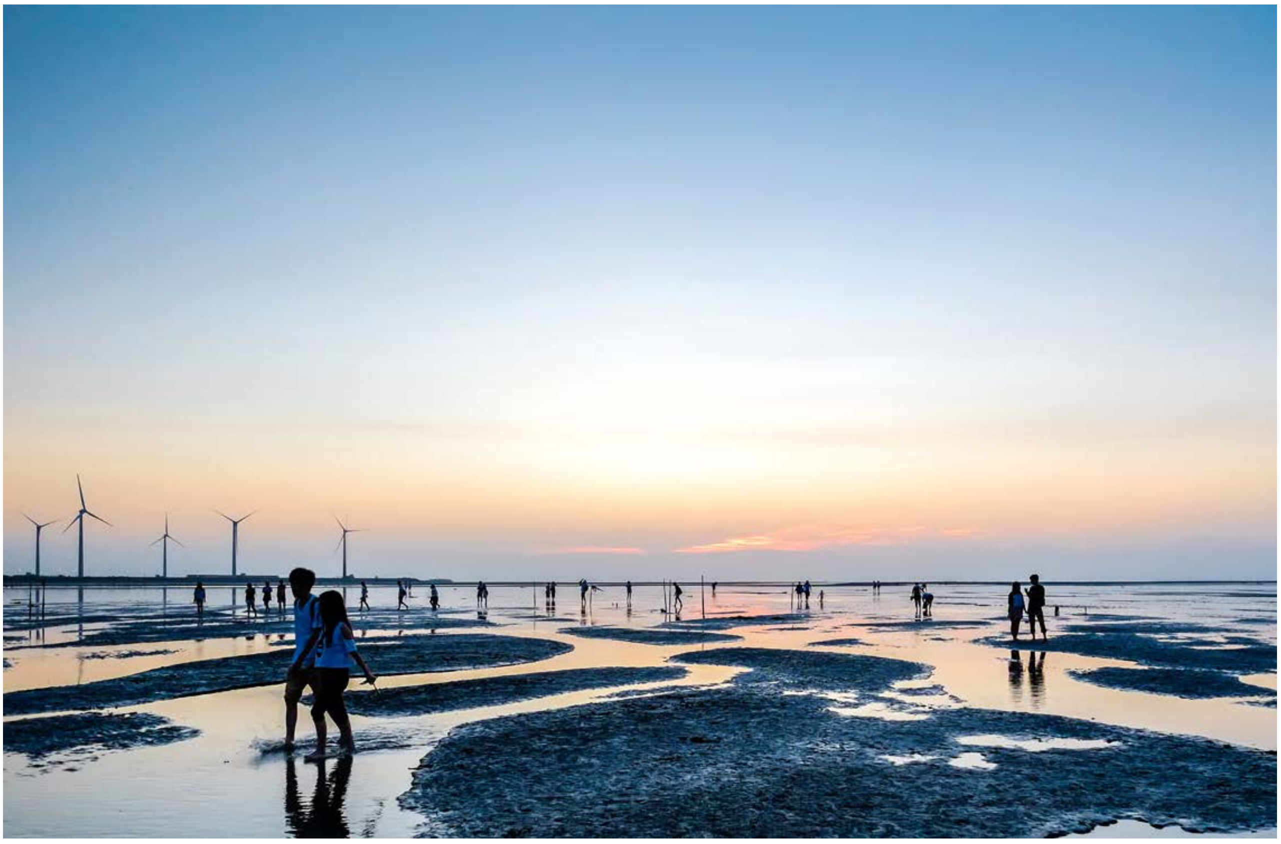
THE RESILIENCE SHIFT

Towards an Operational Paradigm for Engineering Resilience of Interdependent Infrastructure Systems

Agenda Setting Scoping Studies Summary Report



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Summary

The field of resilience engineering tends to propose resilience-enhancing principles which remain theoretical, abstract, and very broad. Furthermore, the need for an operational framework of resilience engineering need to stretch across the coupled domains of ecological resilience, social resilience, and resilience engineering with concrete and specific components. In this research, we carry out a desk review of resilience-enhancing principles for critical infrastructure systems and make recommendations for an operational paradigm for resilience engineering. Specifically, we explore institutional dimension of resilience engineering through multiple case studies. These cases expose the need for an operational paradigm of resilience engineering based on institutional arrangements in the context of interdependent infrastructure systems. We explore three distinct notions related to resilience engineering as follows: (i) definition of resilience and the difference between risk and resilience approaches to clearly differentiate them in practice, (ii) metrics for resilience engineering and common quantification methods, (iii) systematic approach to resilience engineering including modelling and simulation. We argue that the proposed approach to enhance resilience engineering should use a conceptual institutional theory framework involving regulative, normative, and cultural-cognitive elements. Main features of resilience include the necessity to establish critical functionality through stakeholder engagement, ability of the system to integrate temporal evolution in recovering from threats, as well as integrate memory of past experience through adaptation. Resilience is connected to risk in the phase of absorbing threats where thresholds and comparative benchmarks should be established. Our review can serve as a basis to develop an operational paradigm which sets the stage for future initiatives for resilience engineering in practice that act as a framework for development of governance strategies.

Introduction

Societies and firms face large numbers of risks and threats, including unexpected man-made events such as terrorism and increasingly problematic extreme weather events driven by climate change. Data on extreme weather events and disasters indicate that the number of events and their impact on the lives and financial conditions of residents continue to increase. Given that it is impossible to defend against all possible risks, resilience—the ability to recover from a shock and adapt to change—remains a critical goal for organizations and government alike. To date, many resilience engineering studies have focused on identifying heuristics or principles for enhancing resilience. But the knowledge generated in these studies tends to be theoretical and abstract (Chang et al. 2014) and how these principles should be encouraged or implemented in practice remains poorly understood. Our review of the current literature confirms this finding. Resilience scholars based in engineering, ecological, and social resilience domains have made substantial progress on what broadly constitutes the principles for enhancing resilience (Hollnagel et al., 2006, Walker and Salt 2006, MCEER 2010, Aldrich 2012, Biggs et al., 2012, Park et al. 2013, Ayyub 2014, Aldrich and Meyer 2015). For example, Hollnagel et al. (2006) suggest that four system-level abilities or principles are essential for the resilience of socio-technical systems: the ability to monitor, respond, learn and adapt, and anticipate. Similarly, several studies based in the Resilience Alliance highlight the importance of seven principles: diversity and redundancy, connectivity, slow variables and feedbacks, learning, participation, understanding SES as a complex adaptive system, and polycentricity (Biggs et al. 2012). To push the field of resilience engineering to a next level, there is a critical need to understand an operational paradigm of building resilience, i.e., which configurations of these resilience-enhancing principles and their underlying conditions contribute to resilience the most. In the absence of such knowledge, opportunities for effective, actionable strategies for improving system resilience in different sectors and areas will be lost.

Furthermore, one crucial aspect is missing in most of these studies—the role of institutions or institutional arrangements. Institutions are the rules of the game in society or humanly-devised constraints (e.g., formal rules or informal norms of conduct) that regulate human interactions with one another and their physical environment in repetitive and structured situations (North 1990, Scott 2001, Ostrom 2008). Formal and informal institutions are critical to resilience, as they strongly influence patterns of interaction between and among individuals and their social organizations. Without appropriate institutional arrangements, more uncertainty would exist and the level of trust would decline in the exchanges among individuals. Institutions are also crucial to how humans control and manage critical infrastructure systems or how they respond to or prepare for natural disasters (Cifdaloz et al. 2010). Protocols for managing interdependent infrastructure and disaster response plans to cope with contingencies are all examples of institutional arrangements. Yet, despite their importance and pervasive presence, the role of institutions is not explicitly captured in most of the heuristics proposed by resilience studies, especially in resilience engineering. For example, it is argued that the technical resilience enhancement strategies often do not give enough consideration to the importance of the integration of social norms and infrastructure systems (Opdyke et al. 2017).

These strategies exist in a vacuum which ignore the legal, cognitive, and formal institutions which impact project and resilience outcomes.

Table 1.1. Resilience enhancing principles

Domains	Scholars and their core contributions to the resilience space		
Resilience engineering	Hollnagel et al. (2006) Monitoring, Learning, Response, Anticipation Park et al (2013) Sense, Anticipate, Adapt, Learn	National Infrastructure Advisory Council (2010), and National Academy of Science (2012) Plan/Prepare, Absorb, Recover, Adapt	Bruneau et al. (2003), Multidisciplinary Center for Earthquake Engineering Research (MCEER) (2010) Robustness, Redundancy, Resourcefulness, and Rapidity
Ecological or social-ecological resilience	Biggs et al. (2012) Diversity and redundancy, Connectivity, Slow variables and feedbacks, Learning, Participation, Understand SES as complex adaptive system, Polycentricity	Walker and Salt (2006) Diversity, Openness, Reserves, Tightness in feedbacks, Modularity	Carpenter et al. (2012) Diversity, Modularity, Openness, Reserves, Feedbacks, Nestedness, Monitoring, Leadership, Trust
Social resilience	Aldrich (2012) and Aldrich and Meyer (2015) Bonding, bridging, and linking social capital	Chamlee-Wright (2010) Narratives and cultural norms about autonomy	Klinenberg (2003) Neighbourhood cohesion and social ties

Background

Resilience in Interdependent Infrastructure Systems

Even in physical domain, resilience enhancement principles are overlooked in codes and standards, or suffer from a lack of unified governance structure. For example, firms and developers may include resilience enhancement in the routine infrastructure development process. Alternatively, philanthropic and international NGOs may push new resilience enhancement initiatives such as the 100 Resilient Cities initiative under the leadership of the Rockefeller Foundation, or the United Nations project Habitat the City Resilience Profiling Programs. The RC100 initiative has engaged a number of stakeholders in multiple nations, but the program itself remains at the discretion of the local Chief Resilience Officer. Hence Boston’s plan for resilience may be radically different than that of Mumbai, and neither is required to engage the resilience engineering literature or framework. Other fragmented international frameworks for resilience include global policy frameworks such as: Sendai Framework for Disaster Risk Reduction (2015) by United Nations Office of Disaster Risk Reduction (UNISDR), the Sustainable Development Goals (2015) by United Nations, and the Paris Climate Accord (2015) by United Nations Framework Convention on Climate Change (UNFCCC).

Routine infrastructure development comprises of the following steps (Goodman and Hastak 2015): (1) Establishment of goals and objectives, (2) problem identification and analysis, (3) solution identification and impact assessment, (4) formulation of alternatives and analysis, (5) recommendations, (6) decisions, (7) implementation, and (8) operation and management. Resilience enhancement is yet to be part of the routine procedure in any of these steps, except occasional consideration in formal operation and management. Even at this stage, resilience enhancement approaches are often ad-hoc and not included in routine maintenance, rehabilitation and repair (MR&R) strategies (Izaddoost et al. 2017). For example, Infrastructure Australia focuses on cost-benefit analysis and social welfare for the prioritization and selection of the projects (REF.) and there is no consideration for resilience. This is an example of lack of regulative elements of institutions in the infrastructure process. Another example is the neglect of formalized risk assessment methods neglected overconfidence of designers in nuclear construction as a cultural-cognitive element of institutions. (Hollnagel and Fujita 2013). In the later case, resilience suffers from lack of institutional arrangements, established governance framework including regulative, normative and cognitive elements, and lack of enforcement strategies to achieve goals. It should be noted that by in this research we use the term “fragmented resilience engineering initiatives” for efforts by actors such as funds or international agencies to support, formalize and establish resilience for cities, infrastructure systems, or rural areas.

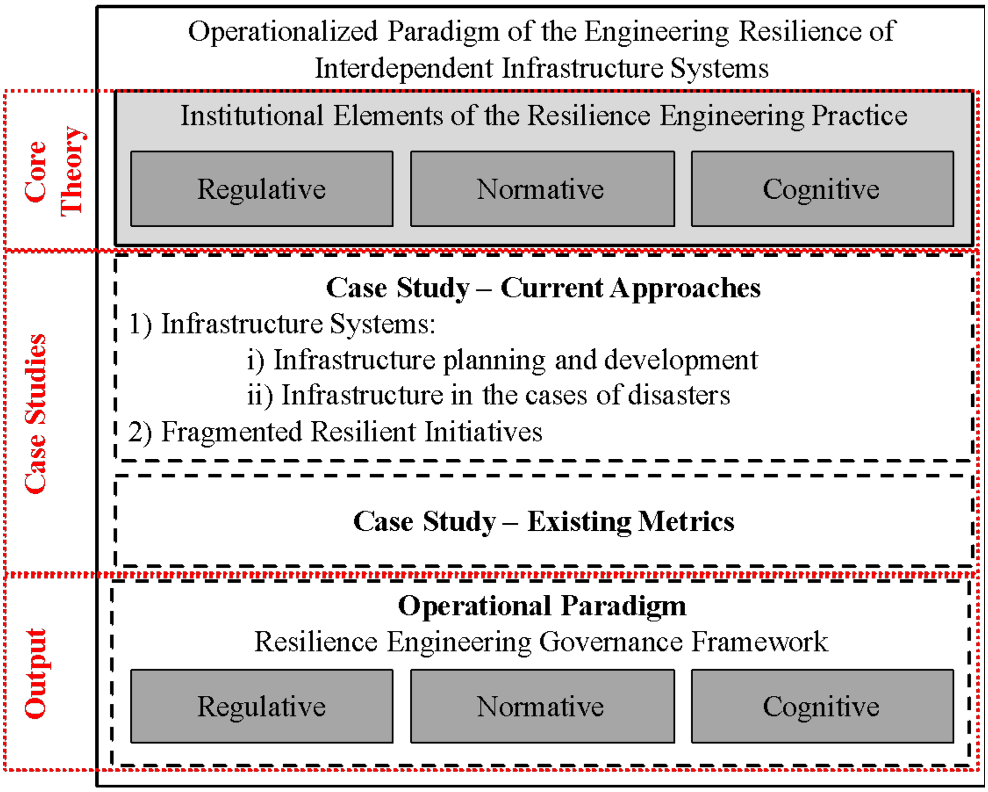

Fig. 1.1. Proposed Framework for Operational Framework

Objectives

By "operational paradigm," we mean establishing detailed and practical knowledge on how to implement resilience-enhancing principles in practice and how to refine the principles themselves. This proposal, therefore, contributes to the theme of use of integrated systems approaches as the context for major engineering projects. We identified key research gaps by (i) reviewing the definition of resilience across multiple domains and its practical implications, (ii) reviewing a range of quantification approaches to resilience engineering, (iii) reviewing the systematic approach to resilience engineering of interdependent systems. With the focus on integration of institutional arrangement we then draw on multiple case studies based in diverse sectors and geographic areas, including the cases of tsunami resilience in northeastern Japan, and flood resilience in southwest Bangladesh. As shown in Fig. 1.1, the operational paradigm can be developed based on the suggestions of this review, and should be initially framed based on regulative, normative and cognitive elements of institutions. We explore the need for an operational framework across these case studies. This exploration will provide the foundation for framing the future studies to develop operational paradigm for engineering resilience of interdependent infrastructure systems.

Definitions

A wide range of definitions have been proposed for resilience as a result of a varied application of the term across different disciplines and lack of a unified approach (Opdyke et al. 2017). Most of the definitions of resilience come from ecological resilience (Holling 1973) and engineering resilience (Pimm 1984) as an approach to conceptualize response to disturbances (Vale 2014). In this sense, resilience is defined as the capacity of the system to return to its original state after shocks (Holling 1973 and Folke 2006). This definition covers four different perspectives of resilience engineering, including: rebound indicating how the system returns, robustness indicating how the system responds to disturbances, graceful extensibility indicating how the system extends its adaptive capacity, and sustained adaptability indicating how the architecture of the system can ensure sustained functioning in a changing environment (Woods 2015). While originally the focus was to return to the original state of the system, the definition of resilience was then shifted towards multiple equilibria and the possibility of reaching a new stable state, different from the original equilibrium. Furthermore, the definition has evolved to reduce the emphasis on the risks and focus on sustaining the function of the system in all of its states.

Fig. 2.1. Risk versus Resilience
From Linkov et al, Nature Climate Change 2014

As a result, the current definition of resilience may refer to a system that can sustain its function by constantly adjusting itself prior, during, and after the shocks (Hollnagel 2016). Implications of this definition in resilience engineering is multifaceted. First, various applications evolve to incorporate the human-dimension of resilience, that is, adaptability and transformability of the system. The evolved applications imply the importance of the governance structure of resilience engineering of the systems to ensure a systematic approach to their adaptability and transformability. Second, while resilience engineering classically emphasizes the aspects of robustness and recovery, this definition broadens the application to prior and during the shock and includes preventing a damage before the disturbance, mitigating losses during the events, and improving the recovery capability after the events. In summary, the operational paradigm for resilience engineering in view of the current definition should focus on maintaining the operation of the system in different scenarios before, during, and after the disturbance, and as stated by Hollnagel (2016), should focus on the function of the system rather than what can go wrong.

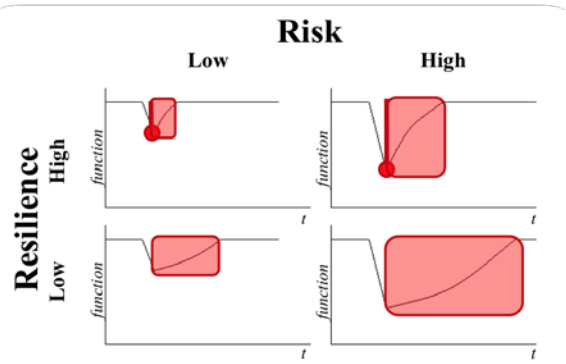

Fig. 2.2. Risk versus Resilience
From Linkov et al, Nature Climate Change, 2014

Risk versus resilience

While in the conventional safety approach there is a focus on failures, as stated by Hollnagel (2016), the resilience approach based on the current definition focuses on how the system can function under different scenarios. As a result, resilience is a dynamic concept that covers a continuous state of the system in contrast to static focus at the time of failure (Park et al. 2013, Linkov et al. 2014). Despite this difference, resilience is not a replacement for conventional risk approach and both concepts should be used as complementary in infrastructure systems (Park et al. 2013, Linkov et al. 2014, Hollnagel 2016). As seen in Fig. 2.1 from Linkov et al. (2014), while risk analysis can provide the policy makers and operational managers with the detail analysis of the time of failure, the resilience approach can provide an analysis of trends and dynamics before, during, and after the failure in the form of shock or disturbance. In operational paradigm this distinction implies the application of incremental adaptations of risk analysis in quantitative analysis of resilience engineering (Park et al. 2013). For instance, as shown in Fig. 2.2 from Linkov et al. (2014), a quantitative interplay between risk and resilience can be depicted showing the function of a system in different scenarios of shocks with higher impacts or more loss of functions (associated with higher levels of risk) versus lower impacts or less loss of performance (associated with lower levels of risk) in contrast with longer recovery (associated with lower degrees of resilience) versus lower recovery time (associated with higher degrees of resilience). As shown in Fig, 2.3, while risk management is a bottom-up approach that starts from data collection to development of management strategies, resilience enhancement starts from the values of the stakeholders and then applies models and metrics to inform risk assessment (Linkov et al. 2016). As it will be discussed in the next section, the combination of recovery time and performance of the system is a common quantification approach to analyze the dynamics of the system before, during and after the shock, reflecting the concept of resilience. Therefore, it is necessary to differentiate the concepts of risk and resilience while they should be used in conjunction for more comprehensive analysis of the infrastructure system behavior.

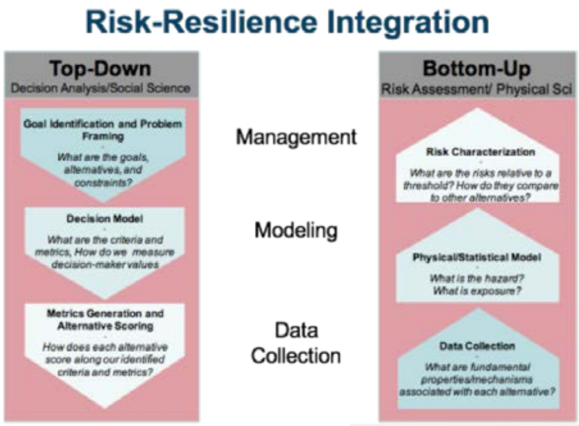

Fig. 2.3. Risk-Resilience Integ[illegible] Linkov et al., 2014

Quantification methods (metrics)

Linkov and Fox-Lent (2016) proposed a three tiered approach to resilience management that ranges from simple screening and ranking (tier 1), to quantification metrics (tier 2), and finally, complex models of interactional dynamics (tier 3). Depending on the resources and the required precision of the analysis, decision makers can take the appropriate tiered approach. However, analysis of engineering resilience requires both quantitative data from engineering models, historical records, and qualitative data from experts and diverse stakeholders (Linkov et al. 2015). For example, there is a need for qualitative studies to validate the quantitative analysis of simulation models as well as quantitative studies to model new phenomena observed in qualitative studies (Opdyke et al. 2017). The data collection often faces challenges such as lack of quantitative data on extreme case, reliability of qualitative data, as well as limitations due to ethics and resources for data collection (Linkov et al. 2016). Other issues related with the metrics-based approach includes difficulty of quantifying emergent dynamics as well as difficulties in translating the data and analysis into decisions, policies, and behavioral changes.

Baseline Resilience Indicators for Communities (BRICS)

An example of a tier 1 approach is proposed by Cutter et al. (2010), as a composite indicator based on the combination of qualitative and quantitative indicators in five categories of: social resilience, economic resilience, institutional resilience, infrastructure resilience, and community capacity. The assessment is regional, with the county level resolution, and spatial presentation of results. Composite indicators are tools to facilitate public communication, raising awareness for data driven decision making, and trend analysis associated with policy making based on a range of issues (Saisana and Cartwright 2007, Nardo et al. 2008, Naderpajouh et al. 2016).

It should be noted that the focus of composite indicators to cover a broad range of issues often discounts meaningful interpretation of the combined trends (McGillibray and Noorbakhsh 2004). Often the composite indicator can help as an initial tool to assess overall status of a wide region for further detailed analysis. To increase the effectiveness of the composite indices for quantitative assessment of resilience enhancement of interdependent infrastructure systems and ensure data driven policy making, there is a need to perform complementary quantitative or qualitative analysis in conjunction with the application of the composite indices.

NOAA Community Resilience Index

The NOAA provided coastal communities and their leaders with a set of indices to help them predict their level of resilience to storms and extreme weather events (Alessa et al. 2008, Bakkensen et al. 2017). The index helps decision makers identify past and expected storm strength for benchmark scenarios. A checklist is provided for the likely losses to critical infrastructure and facilities under each scenario. The index sets up a focus on six main areas: critical facilities and infrastructure, transportation issues, community plans and agreements, mitigation measures, business plans and social systems. The goal is to understand the length of time it will take the town, city, or hamlet to recover in these areas after the disaster. In each category, the leaders are asked to rank resilience as high, medium, or low, and does not use relative weights. The NOAA CRI has been pilot tested in 17 communities in five states, that is, Alabama, Florida, Louisiana, Mississippi, and 416 (Bakkensen et al. 2017).

Resilience as the function of recovery time and performance of the system

The most common metric for the analysis of the second tier is to quantify resilience considering both the recovery time and the

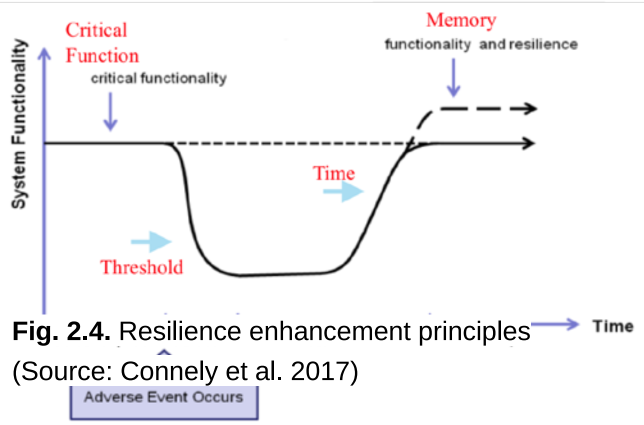

Fig. 2.4. Resilience enhancement principles (Source: Connely et al. 2017)

performance of the system (Bruneau et al. 2003, Miles and Chang 2006, Chang and Shinozuka 2004, Cimellaro et al. 2010, Rodriguez-Nikl 2015, Bonstrom and Corotis 2014, McAllister 2015, Hosseini et al. 2016). As depicted in Figs. 2.1., 2.2, and 2.4, the functionality (or performance level) of the infrastructure system will drop because of the shock or disturbances and depending on the resilience of the system, and its interdependencies across different domains, there is a need for time to recover from the shock (Bruneau et al. 2003). It should be noted that this metric can be related to the resilience enhancing principles proposed by Bruneau et al. (2003) and Multidisciplinary Center for Earthquake Engineering Research (MCEER) (2010), including: robustness, redundancy, resourcefulness, and rapidity. While resourcefulness and redundancy contribute to robustness and rapidity, resilience of the system is measured by its robustness and rapidity (Bonstrom and Corotis 2014). The drop in the performance of the system is an indicator for the robustness of the system, while the recovery time is an indicators of the rapidity. Variations of this approach to quantify resilience is used in different aspects of interdependent infrastructure systems (Tierney and Bruneau 2007, Cimellaro et al 2010, Ouyang and Due˜nas-Osorio 2012, Bonstrom and Corotis 2014).

Social Network Analysis Metrics

Furthermore, resilience can be quantified through a network science approach by considering different domains and considering interdependency within the networks as an example of tier 3 approach. The network analysis may consider physical, information and social domains. In this sense, network topology is defined by its nodes (N) and links (L). Network adaptive algorithms (C) are then used to define how the properties of nodes and links and their associated parameters evolve through time against adverse events (E) (Ganin et al. 2016). Therefore, resilience will be defined as the evolution of these properties before, during, and after the shock:

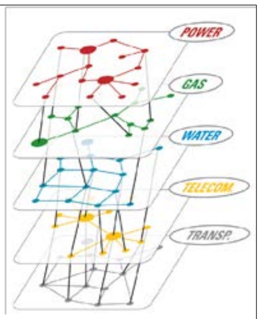

Fig. 2.5. Network approach to resilience

R = f(N,L,C,E)

The major variable in this definition is critical function of the network (system) defined by network properties (Ganin et al. 2016). As a result, resilience is measured not based on the probability of the adverse event but based on its impact on functionality over the time interval of interest (Ganin et al. 2016)

As seen, these frameworks are still fragmented and does not provide a generic framework that can be tailored based on the institutional elements. Therefore, the major quest can be set to answer the following question: *How can we propose and operational framework for resilience engineering using institutional framework?* This question specifically aims to respond to the challenge of fragmented approach to resilience engineering and integrate the operational framework for each context, defined by their institutional nuances.

Case Study: Resilience Matrix Approach for Rockaway Peninsula, New York

Resilience Matrix (RM) framework utilizes local stakeholder-informed metrics aligned with the temporal stages of the National Academy of Science definition of disaster resilience. Lent et al (2015) demonstrated the application of the RM to coastal community resilience at Rockaway Peninsula, New York, using both qualitative and quantitative metrics drawn from post-Hurricane Sandy reports. The Rockaway Peninsula is a seven square-mile strip of land in Queens, NY, that lies between the Atlantic Ocean and Jamaica Bay. Resilience Matrix (Linkov et al., 2013) includes populating sixteen cells that provide a general description of the functionality of the system through an adverse event. Resilience is assessed by assigning a score to each cell that reports the capacity of the system to perform in that domain and time. For example, the Information-Recover cell is assigned a rating according to the ability of the system to collect (monitor) and share (analyze and disseminate) data that will aid in recovery. The Social- Adapt cell is assigned a rating according to the capacity of the system users to modify behavior and sustain changes beyond the immediate incident response. The matrix of scores can be aggregated to represent a snapshot of overall system resilience, which can be monitored over time, used for comparison with similar systems, or examined more closely to illuminate gaps in system capacity (Eisenberg et al. 2014).

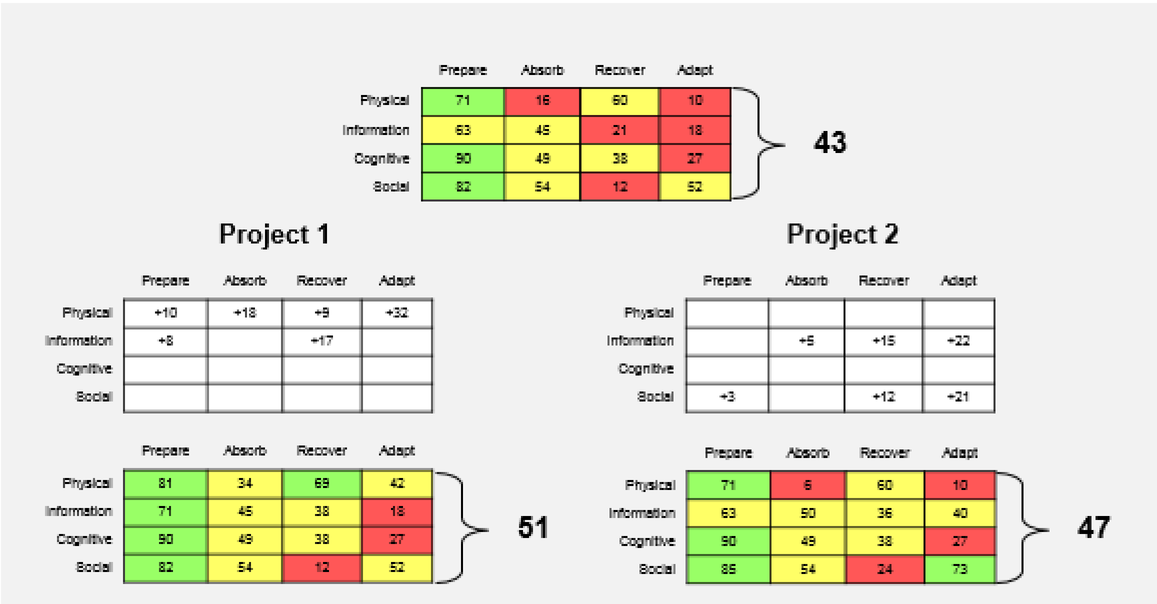

Fig. 2.6. Performance scores for the critical function (illustrative case). Project 1 increases resilience from 43 to 51 by investing in physical infrastructure. Project 2 increases resilience from 43 to 47 by enhancing social and information infrastructure. Overall, project 1 is more beneficial. (Source: Fox-Lent et al. 2015)

Fox-Lent et al., (2015) found that housing/shelter in the community has greater capacity to prepare for and absorb coastal storm events than to recover from them and adapt accordingly. Similarly, it has somewhat greater capacity across the social and physical domains compared to the information and cognitive domains (Figure 2.6). Low scores are largely due to the inadequately long time period to perform tasks, rather than an outright lack of resources. Although not demonstrated here, the matrix approach can be effectively used to this end via a qualitative approach. Proposed projects can be assessed by determining which indicators of which critical functions would be affected by implementing the project and recalculating the resilience scores to compare against the baseline.

Systematic approach to resilience

Interdependent infrastructure systems can be defined based on the lexicon and taxonomy of system of systems (SoS) proposed by Jamishidi (2008). In order to define the interdependent infrastructure systems as SoS, five characteristics described by Maier (1998) need to be satisfied: as the component of the SoS need to be operationally and managerially independent, geographically dispersed, exhibit evolutionary behavior, and emergence at different levels. These characteristics can be observed in the interdependent infrastructure system of a community with the interactions across social and ecological domains. Defining the interdependent infrastructure systems through the framework of SoS may facilitate modeling, quantification, and communication of the models across different boundaries. For example, a network of interdependent infrastructure systems can be defined based on the framework of SoS and modeled based on the approach proposed by Ganin et al. (2016), as discussed above, to facilitate framing the problem. A major contribution of this framework is to integrate dynamics of social systems (i.e., communities) with the technical systems (i.e., infrastructure systems). This framework can be then used based on different modeling and quantification methods. Examples include modeling and simulation of infrastructure and social systems for the case of extreme events in Southeast Asia by Bristow et al. (2012), as well as UK by Thacker et al. (2017).

Systematic approach to resilience engineering should be complemented by further analysis through modeling and simulation as well as qualitative studies. The resilience-enhancing principles proposed by Hollnagel et al. (2006) and Biggs et al. (2012) are mainly based on qualitative methods (case studies and conceptual analysis). A research gap for future studies is observed in application of quantitative methods (e.g., modeling and simulation) or micro-level empirical methods (e.g., human-subject behavioral experiments) for fine-tuning the principles. Existing quantitative approaches to resilience include metrics based on performance level and recovery time (Linkov et al. 2014, Francis and Bekera 2014, Rad and Jahromi 2014, Chan and Schofer 2015, Levenberg et al. 2016) or input-output models (Haimes et al. 2005, and Pant et al. 2014). These methods still do not sufficiently reflect the interdependency of the infrastructure systems or provide a comprehensive picture of the associated dynamics. Above all, the lack of operational applicability is reflected within the metrics, as they are not sufficiently detailed for use in practice. A systematic approach to resilience based on the framework of SoS may facilitate reflecting interdependencies within the system and across domains of social, technical and ecological resilience in the model through the lexicon and taxonomy of SoS, while providing a real picture of the dynamics and interactions of multiple systems.

Institutional framework for operational resilience engineering

Institutions are the rules of the game that shape human interactions with one another and the surrounding environment in a repetitive, structured situation (North 1990). Institutions thus reduce uncertainties in the exchanges among parties, promote trust among people, and alleviate the cost of exchange in such interactions. Although less visible than physical infrastructure, institutions are in fact a form of “soft” human-made infrastructure that gives structure to recurring situations that people face. More importantly, institutions also matter for community resilience. Interdependencies between institutions and physical infrastructure, or the “fit” between institutions and the biophysical context within which they operate, can heavily influence how well people cope with the challenges that face, be they natural hazards, social problems, or a combination of both. This beneficial role of institutions is particularly relevant for promoting four system-level abilities linked to infrastructure resilience (the ability to monitor, respond, learn and adapt, and anticipate). These four system-level abilities cannot function effectively without governing institutions. Normal and emergency manuals used by managers and engineers, hazard mitigation plans used by communities, and norms of conduct among people as they organize community-level actions to deal with and recover from natural disasters are all instances of rules or institutional arrangements that contribute to these four abilities. The three cases presented here illustrate the institutional dimensions and governing strategies related to operationalizing the four abilities.

Institutions can also operate at multiple levels of social organization: operational, collective-choice, and constitutional rules (Ostrom 1990). Rules operating at the operational-level concern the rules that people, engineers, or managers use in their field settings, e.g., rules that specify people’s interaction with one another and their use of infrastructure. Collective-choice and constitutional rules concern a broader direction in rules (i.e., a policy) and rules about the rulemaking, respectively. The working manuals used by engineers, managers, and people (e.g., disaster plans, emergency manuals, etc.) are instances of the operational-level rules.

Further, as stated in Chapter 1, two common venues to enhance resilience of infrastructure systems are through integration of resilience concepts in infrastructure development as well as fragmented resilience enhancement initiatives. However, current policy landscape for infrastructure resilience face managerial barriers that can be framed by awareness, judgment, motivation, and action (Hannah et al. 2011, Seager et al. 2017). As a result, resilience in infrastructure systems faces practical challenges due to lack of awareness on the scope of resilience in infrastructure systems, lack of judgment on the direction of resilience in infrastructure systems, lack of motivation, as well as obstacles to transform the governance structures to action (Seager et al. 2017). A successful. institutional framework for resilience engineering needs shared norms to increase the awareness, cognitive elements to provide a shared judgment, and regulations to both providing incentives for different parties to motivate them as well as facilitating translation of policies to action.

We have already outlined the weaknesses of the existing methods which have sought to build resilience engineering. Typically, assessments of resilience are built in ad-hoc manner; as such, they are not included in standard infrastructure development steps. Too often these approaches involved top-down decision making without institutional arrangements. They lack holistic perspectives and fail to consider interdependencies with other systems, including governance and normative. Standard approaches focus on physical facility and neglect institutional elements. Finally, they assess vulnerability by risk metrics rather than assess resilience through capabilities to absorb, recover, and adapt. In the full report (Naderpajouh et al. 2017), we elaborated on three case studies from various engineered-social systems around the world to underscore how standard approaches fall short of the ideal that we propose as well as to highlight why and how institutions matter to resilience.

Lessons from the case studies

We have brought these case studies to illustrate the challenges in adopting standard engineering frameworks rather than broader, more holistic ones that explicitly incorporate the role of institutions (i.e., the rules of the game that shape human interactions in repetitive, structured situations). In the Fukushima nuclear disaster, we noticed a number of challenges, including the neglect of social networks in recovery and adaptation, a lack of fit between institutions and local context, and a lack of recognition of potential cascading failures and interdependencies. In the case of southwest Bangladesh, we recognize the importance of collective action for enabling community resilience and the role of institutions in regulating people’s behavior during collective action. Without a proper set of institutions including regulative elements to enforce resilience engineering in plans, designs, and operation guidelines, the presence of social norms that enforces them, and shared belief and mindsets to facilitate their communication, many communities in the vulnerable parts of the world may not be able to effectively cope with and recover from natural hazards. The Pumpa irrigation system and the adaptive irrigation rules used by the community managing the system also demonstrate the importance of institutions for enhancing community resilience. By dynamically switching among different water distribution rules (e.g., open-flow, sequential, 12-hour rotation, 24-hour rotation) depending upon changing system condition, the community can reduce the sensitivity of its crop output in the face of climate-related disturbances.

Across these cases over space and time, we have seen how engineers and managers have not have sufficiently considered the elements we propose, namely regulative, normative, and cognitive elements. Where planners have failed to include regulative elements, we saw a lack of institutional arrangements for resilience enhancement principles to plan, absorb, recover, and adapt. Just like how physical infrastructure can provide improved resistance to an external shock, use of institutional arrangements can less the impact of such shocks on a community exercising them. Where they have missed normative elements, they have neglecting the norms in resilience enhancement policies and strategies. Norms of conduct reinforce institutions by attaching social cost to disregarding them, which helps to increase people's conformance to institutions and thus leading to enhanced community resilience. Finally, we have seen how cognitive elements have been neglected, leading to fragmented and multi-directional approach to definitions (e.g., interchangeable use of psychological and engineering definition of resilience in the 100 resilient cities framework), as well as lack of shared belief on safety practices between engineers of nuclear power plants.

Conclusions

In general, scientific research in the field of resilience is in its infancy. It is clear that adoption of resilience approaches by government agencies will lag until steps are taken to formalize resilience methods, similar to risk analysis in the 1980s. Operational framework for resilience enhancement has to consider institutions and their regulative, normative, and cognitive elements. In that sense, science of resilience must evolve towards embracing systems-level methods and tools for dealing with "unknown unknowns" in cost efficient ways.

Tools for resilience do not necessarily need to be complex; some needs can be met with simple scorecard or metric approaches, while others will need more advanced system configuration modeling and scenario analysis. Despite differing levels of mathematical complexity, the scientific challenges are in addressing system-level processes and tailoring methodologies to specific needs. The major criteria to define the level of complexity, however, is integration of institutional elements. These elements include regulations in infrastructure development, norms of the associated community as well as norm of practice among the planners, designer, and operators, as well as their cognitive elements such as mindsets and sense-making processes. Methodologies developed considering these institutional elements crosses boundaries of organizations and can facilitate operation of resilience enhancement practices and their analysis. A number of efforts have focused on developing metrics that are applicable to a variety of systems, including social, ecological and technical. Using these metrics, agencies will be able to offer a quantification of various resilience-enhancing investments to demonstrate improvements that are otherwise neglected in traditional cost-benefit accounting. The current lack of universally applicable resilience metrics as well as inability to formalize value systems relevant to the problems at hand have been barriers to wide implementation of resilience-based methodologies. These barriers root in neglect of institutional frameworks to back the governance structures. A systemic approach to resilience based on frameworks such as the lexicon and taxonomy of system of systems can be used to infuse institutional elements into the practices. Furthermore, advanced decision analytic methods (e.g., MCDA) offers a venue to address these challenges, with methods to objectively assess the impact of trading off resilience attributes (e.g., flexibility, redundancy) with values currently considered in the decision-making process (e.g., cost, environmental impact, risk reduction) for diverse investment alternatives. Further research on this topic can greatly benefit both management and investment decisions for system resilience.

While probabilistic risk assessment has been used as a mathematical framing of risk analysis, network science is emerging as a methodological framing for the future of resilience as a scientific discipline. In network science, the system is represented as an interconnected network of links and nodes that exhibit behavior in space and time. These methods have been demonstrated; though only for limited case studies where network recovery was explicitly modeled. The challenge is to frame resilience as characteristic of several major network properties that would provide a universal foundation to the field with cross-domain applications, similar to how the threat-vulnerability-consequence framework is used in the field of risk analysis. This shift in thinking and assessment tools can be materialized through systematic approaches, such as the framework of system of systems, and is needed to encourage adaptability and flexibility in addition to adequately assessing the tradeoffs between redundancy and efficiency.

All resilience assessment tools require consideration of uncertain futures. Scenario-based preferences analysis is an extended methodology to explore the impact of multiple possible paths of system evolution and decisions over the lifecycle of the investments. This method can be used to identify investments that are resilient to a variety of potential natural disasters, as well as explore how management decisions are affected by the evolution of preferences during the lifecycle of such investments. In past work, risked-based criteria have been used within MCDA, and, with the development of adequate resilience metrics, a similar method can be used to incorporate considerations of resilience, as was demonstrated in the Mobile Bay study. Resilience policies and investments can be developed through scenario-based preferences analysis, helping decision-makers understand tradeoffs and priorities under a variety of uncertain futures.

Finally, there is a need for provision of a governance rubric to operationalize resilience enhancement principles that includes: (i) blueprints of regulative needs to expand the impact of resilience enhancement principles, (ii) theories on the patterns of neglecting norms in resilience enhancement principles and propose strategies that reflect normative elements, as well as (iii) unified resilience engineering mind-set among different stakeholders. Further case studies may explore barriers and motivators to operationalize resilience engineering for three dimensions of regulative, normative, and cultural-cognitive in infrastructure planning as well as within the resilience enhancement initiatives.

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