State of the research in community resilience: progress and challenges

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Abstract

Community resilience has been addressed across multiple disciplines including environmental sciences, engineering, sociology, psychology, and economics. Interest in community resilience gained momentum following several key natural and human-caused hazards in the United States and worldwide. To date, a comprehensive community resilience model that encompasses the performance of all the physical and socio-economic components from immediate impact through the recovery phase of a natural disaster has not been available. This paper summarizes a literature review of previous community resilience studies with a focus on *natural* hazards, which includes primarily models of individual infrastructure systems, their interdependencies, and community economic and social systems. A series of national and international initiatives aimed at community resilience are also summarized in this study. This paper suggests extensions of existing modeling methodologies aimed at developing an improved, integrated understanding of resilience that can be used by policy-makers in preparation for future events.

Keywords

Community resilience; critical infrastructure; computable general equilibrium economic models; disaster recovery; social systems

Introduction

Natural and human-caused hazards can result in significant damage and disruption to communities, including their buildings, distributed infrastructure systems, the economy, and

the availability of social services. The concept of community resilience, which includes planning for, resisting, absorbing, and rapidly recovering from disruptive events (PPD-21, 2013), has gained traction over the last decade around the world. In the United States, national and local programs and research on community resilience has been influenced by the local and national impacts of Hurricane Andrew in 1992, the 1994 Northridge Earthquake, the 2001 World Trade Center and Pentagon terrorist attacks, 2005 Hurricane Katrina, the 2011 Joplin, MO tornado, 2012 Superstorm Sandy (McAllister, 2016), 2017 Hurricanes Harvey, Irma and Maria, as well as worldwide the 2009 L'Aquila, Italy Earthquake, 2011 Christchurch, New Zealand Earthquake, 2011 Great East Japan Earthquake, 2016 Central Italy Earthquake have motivated resilience research. Community resilience concepts evolved after each of these natural disasters, as resilience programs increasingly addressed emergency response, preparedness and security, mitigation, risk communication, and recovery of communities from physical, economic and social disruptions. Over time, community resilience began to address the long-term impacts on communities following events, rather than solely focusing on individual facilities or organizations. A community perspective gives the necessary context for developing the desired performance and recovery of individual facilities and organizations, and their role in community recovery.

Concurrently, research addressed resilience gaps identified after each hazard event, though the research goals or focus often varied widely with regards to resilience concepts. Until recently, despite the broad interest engendered by recent hazard events and research funding initiatives, there has been little coordinated effort to address the complex interactions between physical, social, and economic infrastructure that enable community resilience. Instead, most studies have focused on a single hazard (often earthquakes) or specific infrastructure (e.g. health care facilities).

A number of federal agencies have programs that contribute to community resilience that address emergency response, preparedness and security, mitigation, risk communication, and recovery of communities from physical, economic, and social disruptions. For example, in the US, recent programs by the National Institute of Standards and Technology (NIST) are developing science-based methods, tools, and guidance for community resilience. The US Department of Homeland Security (DHS) is also addressing critical infrastructure and community resilience through programs in the Office of Infrastructure Protection and FEMA's National Preparedness Goal and Framework. In Europe, the Joint Research Center (JRC) has developed the Geospatial Risk and Resilience Assessment Platform (GRRASP), which focuses on geospatial technologies and computational tools for the analysis and simulation of critical infrastructure resilience assessment.

In this paper, a multidisciplinary perspective on community resilience to natural hazards is presented through a review of current resilience initiatives and a representative body of literature, with a focus on the built environment, social, and economic institutions and functions that depend on the built environment. First, definitions of resilience by multiple disciplines (engineering, sociology, and economics) are presented for comparison. Next, research supporting resilience models, tools, and metrics at various scales (national, regional, and local) are reviewed. Finally, research on resilience of physical, social, and

economic systems is presented, followed by a discussion of critical gaps and research needs to enable and improve community-level resilience assessment and assurance. The focus of this paper is on publically available documents; therefore, some government related studies may not be included such as documents from Europe and Asia.

Definitions of resilience

The concepts of resilience in general and resilience to hazard events in particular have found wide application in a host of disciplines, including psychology and psychiatry, public health-related sciences, and environmental sciences, engineering, and the broader economic, social, and behavioral sciences (Haimes, 2009; Hicks-Masterson et al., 2014; Klein, Nicholls, & Thomalla, 2003; Manyena, 2006; Norris et al., 2008). These concepts have been applied to phenomena of varying scales and complexity, from components of engineered public infrastructure systems, or social groups to systems and networks of systems such as communities, socio-ecological systems, regional economies, and networks of infrastructure systems. Table 1 offers a number of alternative definitions, chronologically ordered, drawn from the broad social, engineering, and disaster sciences literature including recent examples addressing the resilience of specific infrastructure systems.

The first definition in Table 1 is from Holling (1973), who is often credited with being one of the first researchers to define resilience as the ability of ecological systems to absorb and bounce back from external shocks. This notion of bouncing back has been often criticized as being too narrow, and only reproducing vulnerabilities (Barnett, 2001; Doorn, 2017; Jordan & Javernick-Will, 2013). Gordon (1978) offers a similar approach when addressing the resilience of physical structures, whether engineered or natural, and their ability to resist, absorb, or deflect energy loadings while they maintain their form and structure. Timmerman (1981) also drew directly from Holling (1973), and was one of the first to think of resilience to disasters and hazards, again focusing on the abilities of systems to recover from a hazardous event. The focus on resistance to impact and rapid recovery remains central to most definitions of resilience, including both Mileti (1999) and Paton and Johnston (2001), who observed that when dealing with social systems, the ability to effectively utilize physical and economic resources with limited dependence on external (extra-local) resources promotes rapid recovery.

The first decade of the new century was marked by the addition of critical dimensions – human and social factors – to the concept of resilience, particularly when addressing resilience to hazard events. For example, Folke et al. (2002) suggested that the inclusion of human and social factors as part of socio-ecological systems required the acknowledgment of learning and adaptation as critical components of resilience. From this perspective, resilience is not simply the ability to resist or absorb systemic shocks and to rapidly recover from impacts, but also learn to adapt to future shocks and vulnerabilities. Rose and Liao (2005) extended the work of Folke et al. (2002) by decomposing resilience into two components. The first component is inherent resilience where the economy naturally substitutes out of damaged infrastructure such as building into more flexible factors, such as labor, which minimizes the economic impact of the hazard. The second component is referred to as adaptive resilience where economic policies can be implemented quickly such

as providing information to the market to coordinate suppliers and demanders of critical goods and services. Bruneau et al. (2003) offered a comprehensive focus on social system resilience with a strong emphasis on the built environment, and suggested that resilient systems are robust or resistant to hazards, rapidly recover when impacted, and reduce future impact through learning and adaptation as part of the recovery process. This work draws on engineering and social research findings regarding pre-existing physical vulnerabilities such as weak building codes/standards and social vulnerabilities such as disparate access to resources necessary to anticipate, cope, and respond to disasters. According to Bruneau et al. (2003), rapid recovery or restoration to pre-impact conditions is problematic if pre-existing vulnerabilities are not remedied; rather, resilient recovery includes adaptation or mitigation to reduce future disaster vulnerabilities.

This tripartite view of resilience – reducing impacts or consequences, reducing recovery time, and reducing future vulnerabilities – has been prevalent over the last decade, although there are certainly variations in emphasis. The tendency in many recent definitions is to address all three dimensions of resilience when considering broader social systems, such as communities (Adger, Hughes, Folke, Carpenter, & Rockström, 2005; Cutter et al., 2008; Maguire and Hagen 2007; Resiliency Alliance 2007; UN/ISDR, 2005; Walter, 2004). The exceptions appear to be when addressing particular components of a community's infrastructure system, such as healthcare (e.g. Cimellaro, Reinhorn, & Bruneau, 2010 and Kirsch et al., 2010), transportation (Adams, Bekkem, & Toledo-Durán, 2012), or power/ energy transmission (Ouyang and Dueñas-Osorio, 2012). In these cases, there is a tendency to focus on the narrower dimensions of resistance to impacts and restoration to pre-existing conditions. These contrasts in emphasis will become evident in subsequent discussions of research below. Nevertheless, it is clear that the general focus of the broader research community, particularly as it relates to resilience to hazard events is on the three key dimensions of resilience. Indeed, this broader perspective is clearly seen worldwide efforts to promote resilience to hazard events. The IPCC (2007, 2014) defined resilience as 'the ability of a social or ecological system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity of self-organization, and the capacity to adapt to stress and change.' In the US, the term resilience was defined in Presidential Policy Directives (PPD)-8 (2011) as 'the ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies.' PPD-21 (2013) expanded the definition to 'the ability to prepare for and adapt to changing conditions and to withstand and recover rapidly from disruptions.' These PPDs established common definitions for use by federal agencies and federally sponsored research for resilience guidance, tools, and metrics. Finally, the US National Academies (2012) also defined resilience as 'the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events.'

Community resilience initiatives on international, national, regional, and local levels

The concept of resilience has also had an impact on how Federal, State, and local government agencies have responded to natural disasters. Resilience can be addressed at a range of scales, depending on the impact and consequences related to loss of function or

service of a given facility or system within a larger 'system-of-systems,' and the presence of a governance structure for funding, decisions, and implementation. Examples of each scale of resilience planning are provided in the discussion below, but there are many programs and initiatives that are not addressed here.

International initiatives include the United Nations International Strategy for Disaster Reduction Resilience Scorecard (UNIDSR 2014) as well as the Rockefeller Foundation 100 Resilient Cities. The Rockefeller Foundation 100 Resilient Cities (100RC) initiative (Rockefeller, 2016) is dedicated to helping communities around the world become more resilient to physical, social, and economic challenges. This initiative began in 2013 by providing resources to support community resilience plans and implementation. The 100RC initiative supports the view of resilience that includes not just sudden events or shocks – earthquakes, fires, floods, etc. – but also the chronic stresses – unemployment, food, lack of affordable housing, water shortages, and lack of transportation – that weaken communities.

Critical infrastructure systems are addressed at a national scale in the United States, where goals and consequences, as well as design, mitigation, and recovery plans to minimize the impact and disruption of function, can be assessed. The DHS (DHS, 2016a) provides strategic guidance to public and private partners and coordinates the effort to promote the security and resilience of the nation's critical infrastructure. Critical infrastructure includes sixteen critical sectors identified by DHS (2016b), including power, water, transportation, and communication systems that support other critical sectors such as emergency services, critical manufacturing, food and agriculture, and public health.

The US Federal government has worked to improve the resilience of communities by developing guidance documents and tools. The Federal Emergency Management Agency (FEMA 2015a, 2015b), in response to PPD-8, developed methodologies and a National Preparedness Goal and Framework to address prevention, protection, mitigation, response, and recovery of communities, individuals, families, businesses, local governments, and the federal government. The NIST has developed two planning guides for community resilience based on a national outreach effort, the Community Resilience Planning Guide for Buildings and Infrastructure Systems (NIST, 2015a) and the Community Resilience Economic Decision Guide for Buildings and Infrastructure Systems (NIST, 2015b). These documents provide a comprehensive process for communities to plan and implement resilience measures that address the community physical, social, and economic systems based on a metric of 'recovery time to function' for all community systems. Gilbert (2010) conducted a literature survey and developed an annotated bibliography of resources of data and tools to inform development of resilience methodologies for structures and communities. A critical assessment of nine methodologies used for measuring the resilience of social and physical systems in communities was conducted by Lavelle, Ritchie, Kwasinksi, and Wolshon (2015).

One important issue found in most of the reviewed methodologies is the relatively weak integration of physical infrastructure resilience metrics with social and economic systems. To remedy this weakness, a conceptual framework for assessing community resilience that included physical, social, and economic systems was developed by Kwasinski, Trainor,

Wolshon, and Lavelle (2016). The hierarchical structure of that framework explicitly considers the integration of social systems and infrastructure systems and differentiates these systems from the services that they provide. A study of social institutions and societal needs and how they should inform the performance goals of buildings and infrastructure systems assessed (a) performance requirements between codes, standards, and guidelines for buildings and infrastructure systems (Kwasinski et al., 2016), (b) societal expectations and tolerances for service disruptions, and (c) interdependencies between infrastructure systems (Applied Technology Council, 2016). These studies and the NIST planning guides are initial products of the Community Resilience Program (McAllister, 2015) that is developing science-based methodologies, tools, and metrics to support community resilience.

Regional resilience efforts are addressing common needs or resources between several communities or counties, such as water sources, fuel supplies, or recovery plans. For example, the Pacific NorthWest Economic Region (PNWER) launched the Regional Disaster Resilience and Homeland Security Program in November 2001 with the goal of improving their ability to withstand, recover, and protect its critical infrastructure from all hazards (PNWER, 2016). Based in Seattle, Washington, PNWER is a statutory organization of international scope, which was formed in 1991 by legislatures of the northwest states of Alaska, Washington, Idaho, Montana, Oregon, and Canadian provinces including the territories of Alberta, British Columbia, Saskatchewan, Yukon, and Northwest Territories. As another example, the DHS Regional Resiliency Assessment Program (RRAP, 2016) works with communities and regions to conduct cooperative assessments of select critical infrastructure within a designated geographic area and regional analyses of surrounding infrastructure.

A number of resilience initiatives by communities and states, non-profit organizations, and researchers have focused on improving community resilience with guidance or assessment methodologies. Some examples of guidance documents include the SPUR Framework (2009), NOAA's Coastal Resilience Index (Sempier, Swann, Emmer, Sempier, & Schneider, 2010), the Community and Regional Resilience Institute (CARRI) Community Resilience System (2013), the Oregon Resilience Plan (Oregon Seismic Safety Policy Advisory Commission, 2013), the Communities Advancing Resilience Toolkit (CART) (Pfefferbaum et al., 2013), and the Baseline Resilience Indicators for Communities (BRIC) (Cutter, Burton, & Emrich, 2010).

Facility and system resilience

This section reviews studies on community resilience with the main focus on: (i) resilience frameworks, (ii) physical infrastructure systems (buildings, water, power, and transportation), (iii) social systems, and (iv) economic systems.

Resilience frameworks

In the context of seismic hazard, Bruneau et al. (2003) proposed a general framework for quantifying the seismic resilience of communities, which identified the key resilience components as 'reduced failure probabilities,' 'reduced consequences from failures,' and 'reduced time to recovery.' This framework included quantitative measures of robustness,

rapidity, resourcefulness and redundancy (R^4). The framework also proposed the integration of technical, organization, social, and economic dimensions for infrastructure systems, such as power and water, and critical facilities such as hospitals. Resilience (R) was defined mathematically by Bruneau et al. (2003) as:

$$R = \int_{t_0}^{t_0 + t_1} Q(t)/t_1 dt \quad (1)$$

where $Q(t)$ is the functionality which is measured as a dimensionless function of time, t_1 is the control time of the system, and t_o is the time of occurrence of event, E.

A comprehensive conceptual model of recovery that establishes relationships among community households, neighborhoods, businesses, and infrastructure systems (including electric power, transportation, and water) was proposed by Miles and Chang (2006). The main goal of their study was to investigate community recovery and associated operational levels, such as business and household income, the year of building construction, and building retrofit.

The PEOPLES resilience framework (Renschler et al., 2010) was based on the work of Bruneau et al. (2003) and included seven dimensions for assessing community resilience. These dimensions are: population and demographics, environment/ecosystem, organized governmental services, physical infrastructure, lifestyle and community competence, economic development, and social-cultural capital. Arcidiacono, Cimellaro, and Reinhorn (2011) introduced a software platform to evaluate community resilience to hazard events using the PEOPLES framework, which was used in a case study of the 2009 L'Aquila earthquake in Italy, making comparisons between four different recovery scenarios.

In an extension of the study of Miles and Chang (2006), Miles (2011) proposed a conceptual model that used a database of infrastructure loss and restoration data that varied in time and space to support evaluation of community resilience metrics. Concurrently, Miles and Chang (2011) developed the ResilUS model, which uses fragility curves to model economic loss and probabilistic approaches (i.e. Markov chains) to model recovery over time. This model was calibrated with data from the 1994 Northridge earthquake.

The NIST six-step process for community resilience planning (NIST, 2015a) articulates an approach/methodology that helps communities prioritize improvements in the performance of their physical infrastructure during and after a hazard event, as well as the availability of social and economic institutions that depend on the built environment. As shown in Figure 1, resilience of physical infrastructure systems can be expressed in terms of *time to recover functionality*. This simple metric works well across disciplines, but must consider uncertainties due to the condition of existing systems and the plans and resources available for recovery. The six steps provide a rational framework for organizing research across and within disciplines, such as setting performance goals at the community level for physical, social, and economic systems, evaluating the anticipated performance of existing

infrastructure systems, establishing design and mitigation criteria for primary hazards, conducting risk assessment for community-scale impacts and consequences, and setting performance goals and metrics for recovery of functionality at the community scale.

Recently, the Centerville Virtual Community was developed by Ellingwood et al. (2016) to be used as a community resilience testbed and enable development of a fully integrated decision framework to achieve community resilience. That model accounted for interacting physical, social, and economic infrastructure systems (Cutler, Shields, Tavani, & Zahran, 2016; Guidotti et al., 2016; Lin & Wang, 2016; Unnikrishnan & van de Lindt, 2016) in a community exposed to earthquake and tornado hazards, and introduced a decision framework to determine optimal strategies for minimizing economic losses and population dislocation (Zhang & Nicholson, 2016). The Centerville Testbed demonstrated that it was feasible and practical to consider the performance of interdependent physical, social, and economic systems in an integrated community resilience assessment.

Gardoni (2017) introduced a stochastic life cycle analysis formulation to capture the impact of deterioration processes as well as repair and recovery strategies on the engineering systems in terms of performance measures like instantaneous reliability and resilience. Sharma, Tabandeh, and Gardoni (2017) proposed a mathematical formulation for performing resilience analysis through characterizing the resilience based on given system state, in the immediate aftermath of a disruption, as well as for a selected recovery strategy by proposing resilience metrics. The proposed mathematical framework was applied for the reinforced concrete bridge retrofitted with fiber-reinforced polymers.

Based on the studies available in the literature, it is suggested that work is needed with focus on three tasks: (i) to generalize existing frameworks for climate-related hazards, (ii) to correlate social and economic attributes in resilience frameworks, and (iii) to develop risk-informed decision-making tools. With the exception of the recent study on Centerville, the majority of the studies available in the literature have focused on quantifying the recovery and resilience of communities subjected to seismic loads. There is an imminent need to generalize existing frameworks to study the post-disaster recovery and resilience trajectories of communities impacted by climate-related hazards (e.g. tornado, hurricanes, flood, and tropical storms). Such a need was further highlighted by the recent Hurricanes Harvey, Irma, and Maria. Furthermore, the existing resilience frameworks have been focused on recovery associated with economic attributes including economic losses, restoration costs, and business status; however, there is a need to correlate the social impact of post-disaster recovery (population dislocation, school absence etc.) with economic attributes for predicting post-disaster recovery trajectory of communities. Finally, there is a need to develop risk-informed decision-making end-user tools to be considered for optimizing and prioritizing sustainable and retrofit solutions for different infrastructure systems as well as emergency response actions targeting risk and vulnerability reduction.

Physical infrastructure systems

System interdependencies—Numerous researchers have developed comprehensive models and empirical approaches to assess the physical interdependencies of infrastructure systems, including buildings, transportation systems, lifelines, and critical facilities (e.g.

Zimmerman, 2001, 2004; Zimmerman & Restrepo, 2006), based on the fundamental work by Rinaldi, Peerenboom, and Kelly (2001). Menoni, Pergalani, Boni, and Petrini (2002) introduced a model to evaluate the seismic vulnerability of infrastructure facilities exposed to earthquake hazards accounting for interconnected physical, functional, and organizational factors. Paton and Johnston (2006) introduced a numerical quantification of the infrastructure system dependencies based on an empirical approach that assumes the degree of interdependency is a function of the level of dependency. Bigger, Willingham, Krimgold, and Mili (2009) compiled a large number of complex interdependencies among electric power systems, water and wastewater utilities, natural gas and petroleum fuel systems, and communications and transportation networks dealing with services losses in the 2004 Florida hurricane season. Furthermore, Delamare, Diallo, and Chaudet (2009) proposed a model to account for the interdependencies of electrical and telecommunication networks and examined the effects on each system. Poljanšek, Bono, and Gutiérrez (2012) evaluated the gas and electricity transmission network interdependency in Europe using the strength of coupling of the interconnections with the seismic response. Dueñas-Osorio and Kwasinski (2012) proposed to form and compute an interdependency index as an empirical equation that depends on the maximum positive value of the cross correlation function (CCF) of the two data series. More recently, Guidotti et al. (2016) proposed a methodology based on a six-step probabilistic approach to model dependent and interdependent networks in order to assess their recovery process. This methodology was applied to the Centerville Virtual Community Testbed (Ellingwood et al., 2016). The main outcome of this study was the quantification of the loss of functionality and delay in the recovery trajectory of the potable water distribution network and the electric power network.

Buildings and critical infrastructure—A significant number of studies, which focused on evaluating the concept of resilience and identifying metrics for physical infrastructure, have been conducted over the last two decades. The main focus of these studies has been on the building infrastructure with an even heavier focus on healthcare facilities. Although health care facilities (i.e. hospitals) are studied as individual buildings compared to portfolio of commercial or residential buildings, they are presented together in this section representing the building infrastructure resilience research.

Based on the work of Bruneau et al. (2003), Cimellaro, Christovasilis, Reinhorn, De Stefano, and Kirova (2010) formulated a framework to quantify resilience with a recovery model that incorporated direct and indirect losses to key physical infrastructure within a community and its population. This framework was developed for evaluating the resilience of critical facilities such as hospitals, military buildings, and infrastructure systems, which can significantly affect the recovery process as well as community decisions and policies. The framework was used to conduct case studies of a typical hospital in California as well as of a network of health care facilities in the Memphis, Tennessee area. Cimellaro, Christovasilis, et al. (2010) further extended the concepts of previous studies and introduced the idea of a resilience-based design (RBD) framework, which informs the design of individual structures on the basis of community resilience considerations. Furthermore, Bruneau and Reinhorn (2007) investigated the operational and physical resilience of acute care facilities,

recognizing that the key dimension of these facilities is not just engineering parameters but broader societal attributes that were included in the study.

A damage and loss-of-function survey tool to assess the impact of the 2010 Chilean earthquake on the functions of the public hospital system was developed by Mitrani-Reiser et al. (2012). Their tool can be applied to hospitals anywhere to standardize future assessment of hospital performance following seismic events, including the impact of damage to structural and nonstructural components, utility services, and equipment, as well as loss of supplies and personnel.

Mimura, Yasuhara, Kawagoe, Yokoki, and Kazama (2011) investigated the recovery and reconstruction process focusing on adaptation plans following the Great East Japan earthquake and tsunami. An analytical, reliability-based approach to quantify the resilience of a group of buildings based on robustness and restoration rapidity following a seismic event was proposed by Bonstrom and Corotis (2014). Parameters that accounted for the reliability problem were spatially correlated seismic intensity, structural response, and duration of post-hazard recovery for certain buildings. This method was used to evaluate the resilience of a group of buildings in San Francisco following an earthquake. A mathematical model based on a multi-criteria approach was developed by Zobel and Khansa (2014) to capture the tradeoffs between the robustness of a system and the rapidity of its recovery, when multiple hazard or emergency events are occurring. An example using the proposed model compared the relative resilience of five different scenarios associated with houses affected by a multi-event disaster. A framework that incorporated probabilistic building performance limit states to assess community resilience following an earthquake was introduced by Burton, Deierlein, Lallemant, and Lin (2015). The limit states for functionality and recovery included damage triggering inspection, damage permitting continued occupancy with loss of functionality, damage not allowing continued occupancy, irreparable damage, and collapse. The framework was used to assess the likely post-earthquake recovery of shelter-in-place housing for residential buildings.

Mieler, Stojadinovic, Budnitz, Comerio, and Mahin (2015) introduced a conceptual framework, which is used to associate community-level resilience objectives with specified design targets referring to individual systems or components. This framework was applied to proof-of-concept application focusing on the seismic performance of a new residential structure. Lin, Wang, and Ellingwood (2016) introduced a methodology to relate risk-informed performance criteria of individual building structures to broader community resilience objectives and therefore relate community goals to design codes and standards requirements. The proposed methodology was applied to a set of two residential building inventories.

Based on the studies available in the literature on buildings and critical infrastructure, the following gaps are identified for future work: (i) studies focusing on resilience assessment of buildings other than hospitals or acute facilities, (ii) studies to correlate infrastructure damage with social and economic functions disruption and recovery, (iii) studies focusing on natural hazards other than earthquakes, and (iv) studies focusing on adaptation and learning. Despite the large number of studies focusing on the resilience assessment of buildings and

critical facilities, it is suggested that there is still a need for studies that evaluate the interdependencies between the physical infrastructure and community well-being (social and economic systems) following a hazard event. Furthermore, there is a need for studies that evaluate the recovery trajectory of physical infrastructure and the functions served, such as housing people and providing essential services. Such studies would focus on the recovery of building infrastructure other than hospitals or residential buildings, including commercial buildings (e.g. banks, strip malls, grocery centers), educational buildings (e.g. schools, universities, libraries), and government buildings (e.g. police stations, city halls, community centers). The recovery of such facilities affects the recovery of the community considerably accounting for social and economic attributes. Additionally, virtually all studies reported in the literature have focused on the community resilience assessment after a strong seismic event. Therefore, it is evident that there is a need to examine the resilience of a community following other natural disasters that are mainly climate-related and may have a devastating impact on the community.

Lifeline systems

Power systems: A number of studies conducted over the last decade have focused on resilience, particularly recovery processes, of power systems. The focus of these studies has been on simulating post-earthquake restoration of electric power networks by: (i) investigating methods to improve the restoration process in terms of economic losses (Davidson & Çagnan, 2004) and (ii) quantifying the resilience of water and electric systems based on loss estimation models (Chang, Pasion, Tatebe, & Ahmad, 2008; Chang & Shinozuka, 2004). Recent studies have investigated through probabilistic frameworks the resilience of power systems (Mensah & Dueñas-Osorio, 2015; Ouyang & Dueñas-Osorio, 2014; Ramachandran, Long, Shoberg, Corns, & Carlo, 2015; Unnikrishnan & van de Lindt, 2016) following wind-hazard events as well as their interdependency metrics with telecommunications services (Reed, Kapur, & Christie, 2009). Ouyang and Dueñas-Osorio (2011, 2012) and Ouyang, Dueñas-Osorio, and Min (2012) investigated the recovery of smart grid systems through a three-step resilience framework applied to the case study of the power transmission grid in Harris County, TX.

Despite these studies on the performance, interdependency, and recovery of electric power systems, further efforts are suggested (i) to identify dependencies between the power systems and social and economic systems of a community and (ii) to develop metrics for community resilience that can assess the impact of power recovery on community resilience. Societal aspects (e.g. business disruption and household functionality) impacted by power outages need to be quantified as part of the recovery trajectory of a community.

Water and wastewater systems: The recovery and resilience of water distribution networks has been investigated by first introducing the concept of a resilience index (RI) (Piratla, Ariaratnam, Arnaout, & Slavin, 2013) defined as the ratio of the surplus internal power to the maximum power that could be dissipated internally (Todini, 2000), and was further explored for more sophisticated indices including: (i) the network resilience index (NRI) that incorporates the effects of both surplus power and reliable loops (Prasad & Park, 2004); (ii) the modified resilience index (MRI) (Jayaram & Srinivasan, 2008), which accounts for the

design and rehabilitation of multiple sources of supply; and (iii) the index of network resilience (INR) which is based on the network topology (Pandit & Crittenden, 2012). More recently, an RI was introduced to account for three combined indices, the number of users temporarily without water service, the capacity of the water network, and the water quality (Cimellaro, Tinebra, Renschler, & Fragiadakis, 2015).

The resilience of the water systems in terms of performance loss, recovery time, and recovery cost of the water network, while also incorporating a hydraulic analysis of the damaged network was investigated through stochastic simulation approach (Gay, 2013; Gay & Sinha, 2012). Several key aspects of drinking water system resilience have been identified as critical to the recovery process including the water distribution system redundancy, structural stability and integrity of water systems, and backup power of water facilities (Matthews, Piratla, & Matthews, 2014), which were used to identify appropriate improvements needed to make the water systems resilient for multiple hazards (Davis, 2014). Guidotti et al. (2016) used a methodology based on a six-step probabilistic approach to evaluate the direct effects of seismic events on the functionality of a potable water distribution network, and the cascading effects of the damage of the electric power network on the potable water distribution network. Finally, studies have been conducted on risk management for capital budgeting of infrastructure assets in which waterway infrastructure projects were prioritized to maximize resilience and minimize consequential damages derived from certain economic, environmental, and social criteria (Connelly, Thorisson, James Valverde, & Lambert, 2016).

To further advance the resilience of water and wastewater systems, studies focusing on evaluation of societal expectations and the expected performance of these systems when subjected to hazards are needed. Important research aspects include assessing water quality across the community.

Natural gas systems: Resilience studies of gas distribution systems have focused on the seismic performance and vulnerability of gas pipelines when subjected to permanent ground deformations and liquefaction (Choo, Abdoun, O'Rourke, & Ha, 2007; Jeon & O'Rourke, 2005; O'Rourke & Deyoe, 2004; O'Rourke et al., 2014; Xie et al., 2013). Several studies have also addressed risk assessment methods for natural gas distribution networks, including quantitative and qualitative methods (e.g. Esposito et al., 2015; Han & Weng, 2011; Makowski & Mannan, 2009; Poljanšek et al., 2012; Yuhua & Datao, 2005). A recent study by the Applied Technology Council (2016) focused on identifying the current standard and guidelines for liquid and gas systems as well as lessons learned from recent disasters.

Further studies are needed on the recovery of natural gas systems. The interdependency of these systems with electric and water/wastewater systems needs to be identified and quantified to account for the increasing use of natural gas for electricity generation. Furthermore, the performance and recovery of the gas systems impacted by wind storms and floods requires models that can simulate the complex fuel supply network (e.g. pipelines, port facilities, fuel delivery, airport operation, train operation etc.) using reliability methods to account for all the uncertainties associated with the operational needs of the gas systems. The October 2015 gas leak in Aliso Canyon (California) demonstrated that malfunctions in

the natural gas system can constitute hazards in and of themselves. Failure of critical infrastructure may not only reduce provision of services directly, but also degrade the level of other services in an indirect fashion (e.g. housing).

A recently published NIST report (Applied Technology Council, 2016) presents a comprehensive critical assessment of infrastructure systems (electric power, gas and liquid fuel, telecommunications, water and wastewater systems) and their performance during past natural hazard events. In that report, a summary of codes, standards, and guidelines for each system is provided along with discussions on societal considerations, interdependencies, and lessons from disasters. Finally, the gaps and deficiencies for each system are identified and future research needs and considerations suggested.

Transportation systems: A number of studies have focused on the resilience of freight transportation networks during the last two decades. Murray-Tuite (2006) performed a study to examine the influence of ten transportation resilience parameters, including redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly from a hazard event. This study showed that accounting only for traffic flow does not accurately represent transportation resilience and as many as ten dimensions need to be taken into consideration since the findings were specific to the sample network and were not able to be generalized to any transportation system. Nair, Avetisyan, and Miller-Hooks (2010) investigated the intermodal (IM) freight operations of a port, while the resilience of freight transportation networks, including pre-disaster preparedness and post-disaster recovery actions, was studied by Miller-Hooks, Zhang, and Faturechi (2012), Faturechi and Miller-Hooks (2014), and Chan and Schofer (2015) for rail networks. Chen and Miller-Hooks (2012) proposed an indicator, computed through a stochastic mixed-integer program, to quantify the recovery of intermodal freight transport by accounting for the impact of the recovery activities. Zhang and Miller-Hooks (2014) proposed a stochastic, time-dependent integer approach utilizing recursive functions for assessing a rail-based freight transportation system's resilience. Vugrin, Turnquist, and Brown (2014) introduced an optimization methodology in order to identify the optimal recovery measures and maximize the resilience of disrupted transportation networks.

Bocchini, Frangopol, Ummenhofer, and Zinke (2013) and Decò, Bocchini, and Frangopol (2013) proposed a risk assessment framework that was mainly focusing on transportation networks and bridge systems. Furtado and Alipour (2014–2024) presented a methodology to prioritize important bridges and allocate additional resources for repair in order to enhance post-earthquake response and increase the resilience of the transportation network. This methodology was applied in a case study to the San Francisco Bay area highway network. The damage to the road network as well as the interdependency between a hospital and the road networks were accounted for in their study. Cavallaro, Asprone, Latora, Manfredi, and Nicosia (2014) presented a model of urban system accounting for transportation systems and networks to quantify the post-earthquake resilience and compare the ability of different reconstruction strategies in restoring the original performance of the urban system. Franchin and Cavalieri (2015) introduced a metric of network-based resilience based on the evolution of efficiency of communication between citizens during the reallocation of displaced population after the event accounting for the transportation network impact. Alipour and

Shafei (2016) proposed a comprehensive numerical framework for assessing the seismic resilience of highway bridge networks exposed to deterioration aging mechanisms. The highway network bridge system of Los Angeles and Orange County, CA, was used as a testbed for this study and resilience metrics were obtained following three different retrofit strategies.

Recently, Zhang, Wang, and Nicholson (2017) introduced a resilience-based methodology to optimize the scheduling of the post-event recovery actions of roadbridge transportation networks. This methodology accounts for network topology, redundancy, traffic flow, damage level, and available resources, while the total recovery time (TRT) and the skew of the recovery trajectory (SRT) are considered to quantify the rapidity and efficiency of the road-bridge network recovery. The applicability of the proposed methodology was demonstrated using a hypothetical bridge network of 30 nodes and 37 bridges subjected to seismic hazard.

Despite the large number of studies conducted on transportation systems' post-disaster recovery and resilience, more studies are suggested to be conducted: (i) to account for transportation system with other infrastructure systems, economic and social systems, (ii) to develop models accounting for multiple transportation networks and their interactions, and (iii) to assess urban resilience accounting for rail and light rail transit systems. The studies on transportation systems mainly focused on post-event evaluation of these systems and policies to identify an improved or optimal recovery path. Research studies focusing on the functionality of the transportation systems after a hazard event accounting for their interaction with other infrastructure systems as well as their social and economic impact and post-event adaptation are needed. Furthermore, development of multi-modal models of transportation systems and networks that include ports and harbors, airports, interfacing rail, and truck distribution systems is suggested. Finally, urban commuting populations in large cities depend heavily on rail and light rail transit to commute between their homes and places of work; the role played by commuter transit in urban resilience has yet to be considered.

Social systems

The concept of resilience has a lengthy history of being applied in a number of social science disciplines and fields within a range of topical areas including: children and families (Fothergill & Peek, 2015; Landau, 2007; Peek, 2008; Ungar & Eli, 2000), social problems (Clauss-Ehlers & Levi, 2002; Doron, 2005), class and urban studies (Sánchez-Jankowski, 2008), rural sociology (Varghese, Krogman, Beckley, & Nadeau, 2006), disaster recovery and management (Stallings, 2006), and terrorism and security (Shamai, Shaul, & Guy, 2007). Many existing applications of resilience with social science are focused on individuals or households as the unit of analysis, though work at the community level is the focus of this paper. A commonality of these social conceptions of resilience lies in the examination of the subject in relation to a stressor (e.g. divorce, job loss, economic decline) or shock (e.g. tornado, hurricane, oil spill). These diverse applications inform the use of the concept of resilience in the area of social impacts, response, and recovery to hazards.

Researchers have approached social studies of resilience in several ways, including conceptual studies aimed at informing definitions and conceptual frameworks of resilience (e.g. Cutter et al., 2008; Marshall, Fenton, Marshall, & Sutton, 2007); theoretical studies aimed at achieving a better understanding of resilience (e.g. Morrow, 2008; Obrist, Pfeiffer, & Henley, 2010); methodological studies aimed at providing a means of measuring resilience (e.g. Cutter et al., 2010; Lam, Reams, Li, Li, & Mata, 2015); and empirical studies that attempt to identify factors associated with social systems response or recovery in communities experiencing hazards (e.g. Olshansky, 2001; Olshansky, Johnson, Horne, & Nee, 2008; Thornley, Ball, Signal, Lawson-Te Aho, & Rawson, 2014; Zhang & Peacock, 2009). Across all study types, significant effort has focused on community vulnerability and disaster recovery, both concepts that are associated with the resilience of social systems.

Social scientists have attempted to theoretically and conceptually situate resilience within the broader context of disaster and natural hazards research (Colten, Kates, & Laska, 2008; Morrow, 2008; Norris, Stevens, Pfefferbaum, Wyche, & Pfefferbaum, 2008; Tierney, 2009). Considerable research efforts have tackled the development of conceptual frameworks and definitions for social resilience. Gunderson, Holling, Peterson, and Pritchard (2001) proposed a model based on a hierarchical structure where natural and human systems were linked. Berkes and Ross (2013) worked on integrating two important areas of research on community resilience – social-ecological systems and the psychology of development and mental health in order to advance the theoretical understanding of the concept. Marshall et al. (2007) proposed a conceptual model to investigate the relationship between natural resource dependency and social resilience. In this model, factors such as occupational attachment, employability, and business size were associated with higher resource dependency and lower resilience. In Magis (2010) review of the social definition of community resilience, community resilience is associated with the existence, development, and engagement of community resources by community members following a disaster.

Obrist et al. (2010), conceiving of resilience as a process, developed a multi-layered social resilience framework that emphasized the interactions between enabling factors (e.g. public attention, government support) and capacities (e.g. coping, adapting, solution generating) operating at different levels of the environment and society. Social agents, such as individuals, families, or organizations, need a combination of social, economic, and cultural capitals and capacities to be resilient. Jordan and Javernick-Will (2012) conducted an extended literature review on the definitions of community resilience and recovery in order to assess the indicators common in the measurement of each concept. This work addresses the conflation of several concepts related to resilience, including vulnerability, community capacity, and recovery. The most cited indicators of community resilience in their study were poverty, construction method, government agency commitment, attachment to place, education, recovery funds, and access to information; these indicators were organized by infrastructure, social, economic, institutional and recovery strategy categories. Similarly, Birkmann's (2006) comprehensive review of vulnerability included differing conceptual frameworks, indicators for measurement, and linkages between related concepts of resilience, risk, and sustainability. Lindell and Prater (2003) presented a conceptual model of community disaster impacts that linked physical and social impacts to the factors that reduce these impacts and thereby increase resilience.

Maguire and Cartwright (2008) introduced a methodology for communities to conduct their own resilience assessments that included vulnerabilities as well as resources and adaptive capacities. The assessment was intended to support collaboration between governmental agencies and communities and improved policies following hazard events. Cutter et al. (2008) introduced a place-based model for disaster resilience at the community level, while also evaluating the importance of various factors in recovery. Miles (2014) introduced a community resilience framework that accounts for the well-being, identity, services, capitals (WISC) of a society and aims at forecasting resilience under future events as well as assessing resilience matrices of past disasters.

The next body of social systems related research is methodological in nature and has focused on the challenge of measuring resilience. A number of research efforts, which are often tied directly to resilience, have contributed to measuring and comparing vulnerability for communities (Birkmann, 2006; Cutter, Boruff, & Shirley, 2003). Cutter et al. (2003) proposed SoVI, a social vulnerability index using principal components analysis to combine a large number of factors into a single composite score at the county level. Peacock et al. (2011) provided their own method for assessment of social vulnerability at the census block group level. In both cases, this assessment work is bolstered by community vulnerability mapping, which results in a valuable tool for resilience planning (Van Zandt et al., 2012). These methods are not based on specific hazard risks, but instead focus on the general demographic characteristics that make a community more vulnerable to any hazard.

Assessment methodologies for measuring resilience have also been developed. Cutter et al. (2010) presented a methodology known as BRIC (Baseline Resilience Indicators for Communities) for assessing baseline resilience using composite indicators of social, economic, institutional, infrastructure, and community capacities. The methodology was applied to FEMA's Region IV which includes eight southeastern US states. The research highlighted spatial variation in disaster resilience; for example, metropolitan areas exhibit higher scores on resilience metrics compared to rural areas, but it should be noted that many of these metrics focus heavily on social science. Lam et al. (2015) propose the RIM (Resilience Inference Model), which uses exposure, damage, and recovery indicators to depict the relationship between vulnerability and adaptability. Cluster and discriminant analysis are then used to derive resilience rankings. RIM has been applied in the US for the county (Lam et al., 2015) and census block group (Cai, Lam, Zou, Qiang, & Li, 2016) scales.

Empirical studies typically employ either a mostly qualitative, case study methodology or a quantitative methodology to study multiple cases with statistical analyses. Using quantitative methods, Zhang and Peacock (2009) studied single-family housing recovery, housing sales, and property abandonment after Hurricane Andrew to understand differences among neighborhoods with different socioeconomic characteristics. Recovery trajectories were found to be dependent on demographic, socioeconomic, and housing characteristics. Chang (2010) proposed a framework to evaluate empirical patterns of urban disaster recovery (including business and economic recovery) using statistical indicators and applied that framework to assess recovery following the 1995 Kobe, Japan earthquake. Bevington et al. (2011) presented a multi-disciplinary study, including economic, environmental, housing,

and social elements of the community recovery estimation, to inform an understanding of community resilience. This mixed method study included multiple study events (Hurricanes Charley and Katrina), communities, and scales in the investigation. Cox and Perry (2011) used qualitative methods in rural communities of Canada affected by a wildfire to examine the importance of context and culture on disaster recovery, including considerations of the role of social media accounts, identity, housing, and work availability. Thornley et al. (2014) presented qualitative case studies of six communities following the Canterbury earthquakes in New Zealand and identified common factors affecting their resilience through an investigation of the recovery process.

Based on the studies available in the literature, it is suggested that work is needed along three primary tracks: (i) to investigate conceptual frameworks using empirical studies, (ii) to test and validate indicators of community resilience, and (iii) to develop and advance methods for integration of physical infrastructure performance with associated social systems. With tracks (i) and (ii), the development of new frameworks and indicators may be required. Furthermore, methodological advancements should include models that account for the complexity of the social system, interdisciplinary research linking social and economic systems with physical infrastructure and the natural environment, and longitudinal studies. The utilization of multi-level models would support the measurement of variability in resilience across scales, such as individual, household, neighborhood, and community. Increased use of longitudinal studies would improve assessment of the full recovery trajectory and the long-term social impacts of both stressors and major shocks. These studies would provide insight into the dynamic process of recovery as well as the pre-event function of resilience. Innovative methodologies for empirically linking factors associated with both the recovery of the social system and physical infrastructure will support holistic studies of community resilience. Studies that examine other linkages between the social and physical systems (e.g. adaptive capacity, probability of failure) at earlier phases of the event timeline are also of value. At present, the isolation of these studies leads to conclusions and/or recommendations that are not evaluated in terms of the complex interdependencies between social and physical infrastructure systems or the full range of solutions available to a community. By filling critical gaps in studies of the resilience of social systems, the science will be positioned to support optimization of strategies for community resilience.

Economic systems

For many years, researchers used Input-Output (I-O) economic models to compute direct and indirect economic losses due to natural disasters disruption (e.g. Boisvert, 1992; Okuyama, Hewings, & Sonis, 2004; Rose, Benavides, Chang, Szczesniak, & Lim, 1997). I-O models have been combined with engineering models and available empirical data, and used successfully to connect economic impacts with: (1) transportation networks (e.g. Cho et al., 2001; Gordon et al., 2004; Sohn, Hewings, Kim, Lee, & Jang, 2004), (2) infrastructure networks (e.g. Rose et al., 1997), and (3) comprehensive disaster models (e.g. HAZUS (2003) and Okuyama (2007)). More recently, Galbusera, Azzini, Jonkeren, and Giannopoulos (2016) introduced an approach to estimate economic resilience associated with the elasticity of the sectors regarding service perturbation by using a dynamic inoperability I-O model with inventories. Galbusera et al. (2016) also presented an

optimization study for assigning the inventory levels needed to enhance the economic resilience after critical events. Rose and Liao (2005) state that 'I-O analysis is characterized by a linear and rigid response, almost devoid of behavioral content.' More specifically, I-O models hold wages and prices constant; therefore, they can adequately model demand-side shocks but have difficulty modeling impacts to supply like loss of buildings and disruptions to water and electricity.

An outgrowth of I-O models is computable general equilibrium (CGE) models which assume that firms maximize profits and households maximize welfare as a guide to making economic decisions. Whereas, I-O models assumed that resources were infinite, CGE models formally acknowledge that there are limitations to supply of resources so a natural disaster can limit the availability of resources. Rose and Liao (2005) investigated the flexibility of a CGE model to examine both short-run and long-run outcomes due to natural disasters. They decompose resilience into two components:

> (1) *Inherent*: Ability under normal circumstances (e.g. the ability of individual firms to substitute other inputs for those curtailed by an external shock, or the ability of markets to reallocate resources in response to price signals), and (2) *Adaptive*: Ability in crisis situations due to ingenuity or extra effort (e.g. increasing input substitution possibilities, or strengthening the market by providing information to match suppliers without customers to customers without suppliers).

It is identified that viewing resilience into inherent and adaptive components is a useful way to study natural disasters.

Tsuchiya, Tatano, and Okada (2007) developed a spatial CGE model to examine the impact of transportation disruptions for a hypothetical Tokai-Tonankai earthquake in Japan. Boyd and Ibarraran (2009) and Berrittella, Hoekstra, Rehdanz, Roson, and Tol (2007) use a CGE model to examine how weather events cause droughts and impact the economic activity. Hallegatte and Przyluski (2010) argued that a hybrid of a CGE model and I-O model is necessary to examine natural disasters where price stickiness is imposed in the CGE model.

A limiting factor of both I-O and CGE modeling is the quality of the data that is available to evaluate the impact of a natural disaster. Chang and Rose (2012) and Meyer et al. (2013) maintained that high-quality data has to be collected to do any meaningful analysis on resilience and recovery. Meyer et al. (2013) described an effort carried out in the European Union (EU), 'Costs of Natural Hazards' (CONHAZ). This approach looked at the impacts of floods, storms, and coastal hazards and collected data on housing, industry, transport, agriculture, the environment, and human health. CONHAZ divided the data requirements into direct costs (damage to infrastructure), business interruption costs, indirect costs where economies outside the damaged area can be affected, intangible costs that are not directly measured, and mitigation costs. Chang and Rose (2012) made similar assertions to Meyer et al. (2013), but they extended the analysis by maintaining that any serious attempt to model recovery must be linked with the recovery of households, institutions, and other aspects of the community. Both Chang and Rose (2012) and Meyer et al. (2013) maintained that CGE models are the preferred method of estimating costs and recovery patterns of natural hazards.

Cutler et al. (2016) introduced a dynamic spatial CGE (DSCGE) model that combines the use of engineering and economic models to assess the economic, demographic, and fiscal impacts of a natural disaster. Cutler et al. (2016) attempted to address the concerns of Chang and Rose (2012) and Meyer et al. (2013) by constructing an extensive data-set which includes county assessor's data. County assessor data described each parcel in terms of its size (acres), the value of the land and the value of the structure (commercial or residential building) on the parcel. This allowed the damage to infrastructure estimated by the civil engineering models to be directly fed into the CGE model.

Econometric models based on time-series data, have been suggested as statistically rigorous tools that can forecast economic losses with relatively good accuracy. Regional econometric models have been considered for estimation of losses in natural disasters including Hurricanes Hugo (Guimaraes, Hefner, & Woodward, 1993), Andrew (West & Lenze, 1994), and Katrina (Hallegatte, 2008), as well as the Northridge earthquake (Rose & Lim, 2002). The main focus of these studies was the economic losses from business interruption, which were found to increase considerably compared to direct losses. In addition to these rigorous models for estimating economic losses, there have been a significant number of simplistic surveys supporting loss estimation (e.g. Tierney, 1995, 1997). These surveys are empirical in nature, and have been characterized as being less comprehensive, inconsistent, and possibly influenced by survivor bias. These approaches offer elasticity estimates on household migration and substitution patterns between labor and capital which are used in CGE to increase performance accuracy.

There are several limitations of CGE models that still need to be addressed. CGE models are typically based on annual data, but it is important to be able to identify impacts over a shorter period of time. Rose and Liao (2005) suggested that limiting behavioral responses by reducing key elasticities may represent a shorter period of time than a year. It is also important to build spatial CGE models since a natural disaster will have uneven impacts across a community and these differences will have important impacts on the economic consequences of the disaster. A CGE model is an equilibrium-based analysis and it is common that following a disaster, such as Hurricane Katrina, causes such a large amount of damage, it may be hard to imagine that the economy can return to equilibrium in any reasonable amount of time.

Okuyama and Santos (2014) recommended using the social accounting matrix (SAM) to obviate this problem. A SAM is a method to organize the data for households, firms, and the government in a consistent way to demonstrate the interactions between all three entities. The SAM is a necessary step to use a CGE model. Okuyama and Santos (2014) suggested shocking the SAM with losses to physical capital and associated income streams due to the hazard and if the SAM is interactive enough, disequilibrium effects may be estimated.

Research needs, future directions, and closure

Despite the large number of studies reported in the literature focusing on community resilience assessment, there are still significant gaps in knowledge and an imminent need for

future research. These gaps are summarized below in four themes, as earlier organized in this document, and are associated with future research directions.

Resilience frameworks

Despite the ongoing research efforts in the engineering, sociology, and economic disciplines, much remains to be done to advance the integration of a 'system-of-systems' that includes physical, social, and economic aspects of community resilience. There are currently no general frameworks accounting for multi-disciplinary aspects of community resilience and limited metrics to quantify community resilience. When combined, current work conducted for single systems has resulted in inconsistencies of concepts, definitions, and theoretical propositions. Interdependencies between the built-environment, social, and economic aspects should be further characterized and quantified to advance models and metrics for assessing community resilience. Community resilience models should simulate interdependent physical infrastructure systems, and supported social and economic systems. While analytical methods and metrics to assess individual system performance for hazard events are reasonably well developed, much research remains to be done to develop methods and metrics that account for interdependencies and resilience at the community scale.

Resilience at the national, regional, and local scales has been investigated by academics, government agencies, and the professional community, and considerable knowledge has been gained, particularly over the last decade. Many of the studies focused on community resilience of physical infrastructure for seismic events, presumably as a result of available funding. There has not been a similar emphasis on evaluating resilience of physical infrastructure for other natural hazards including tornadoes, hurricanes and coastal storm surge, riverine floods, and tsunamis. Although community resilience goals are hazard-agnostic (i.e. specified times for education, health care, or businesses to recover their functionality (NIST, 2015a)), assessment of the anticipated performance of the physical infrastructure and supported systems require community-level models that simulate system performance for a given hazard event, as well as their spatial and temporal recovery.

Physical infrastructure systems

Buildings and critical infrastructure—The cited research for buildings and critical facilities has proposed frameworks for assessment of performance and recovery with several case studies to demonstrate or calibrate the methodologies. However, methods to evaluate community resilience need methods to adequately characterize the community building portfolio as well as approaches that account for damage, social needs and impacts, economic loss, dependencies, and recovery of function. For example, engineering models and economics simulation tools (e.g. CGE) could be integrated to estimate the spatial and temporal recovery of the building stock and its impact on social and economic systems. At this point, infrastructure, social, and economic models are developed independently. These models need to be coupled in a time-varying recovery analysis to assess the resilience of a community.

Lifeline systems—Studies have been conducted on distributed infrastructure systems, including electrical power, gas, and water networks, to address their risk, reliability, and

recovery. Despite the number of studies for each individual system, there is still a lack of knowledge about dependencies between systems and how their combined performance affects the recovery of a community. An important aspect in the recovery of infrastructure systems is that the recovery time scales of power, gas, and water systems may differ significantly. This is primarily attributed to different design criteria for each system that can then affect transportation, residential, economic, and social services. A better understanding of how recovery time scales of dependent systems affect community recovery is required.

Transportation systems research has focused on post-event activities and policies to improve the restoration of services. Opportunities for research in this area include the performance and recovery of intermodal transportation systems and the dependence of disrupted transportation networks on other infrastructure systems (i.e. electrical, water, and gas). Additionally, the effect of disrupted transportation networks on societal needs should be coupled with economic models to capture the disruption from a perspective beyond traffic flow downtime.

Social systems

Social sciences research is needed to investigate existing conceptual frameworks and indicators of community resilience using empirical studies and validation techniques, to develop new frameworks and indicators where needed, and to develop and advance methods and quantitative models for integrating physical infrastructure performance with associated social systems. Methodological advancements are needed so that statistical and, ultimately, computational models account for the complexity of the social system at multiple spatial (e.g. household, community, region) and temporal scales. To continue to advance understanding of economic systems, economics research is needed to fully couple economic models with both engineering and social science models in time-varying resilience analyses. This work would support an accurate assessment of the recovery of a community subjected to hazards.

Economic systems

Economic resilience has been extensively studied and economic models (e.g. CGE, I-O models) have been developed to quantify post-disaster economic function accounting for engineering model outputs. However, the currently considered economic models are not fully integrated with social and engineering models in a time-varying resilience analysis. Therefore, enhanced models able to couple all aspects of resilience analyses are needed in order to accurately evaluate recovery paths following a disaster.

In summary, research on integrated physical, social, and economic systems at the community scale, with the inclusion of interdependencies and recovery of functions, is needed to advance current practices and knowledge. A science basis for developing methods, tools, and metrics will substantially improve and better support resilient decision-making by communities.

The performance and interdependencies of physical, social, and economic systems are highly complex. Furthermore, the anticipated performance and recovery of community institutions is highly uncertain in most communities, as there are limited tools to support

planning and assessment at the community scale. With inherent limitations in economic and personnel resources, methods, and tools for assessing and mitigating the impact of hazard events on community systems and resilience must be risk-informed to optimize public and private investments. Models for community resilience assessment must be accompanied by improved methods that incorporate dependencies and temporal uncertainties in support of risk-informed decision-making.

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Biographies

Maria Koliou is an assistant professor at the Zachry Department of Civil Engineering at Texas A&M University, U.S.A. Her research interests span the fields of structural dynamics,

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Maria Dillard is a social scientist within the Engineering Laboratory at the National Institute of Standards and Technology. Maria's research includes community response to hazards and chronic stressors and the development of methods for measurement and modeling community resilience, well-being, and vulnerability. Her work is focused on the integration of social, economic, physical, and natural systems in research on disasters and recovery.

Harvey Cutler is a professor of Economics in the Department of Economics at Colorado State University. His research specializes in econometrics, computable general equilibrium modeling of economic systems, and understanding the impact of economic growth variables on urban and regional systems. He is also involved in using the effects of natural disasters on the built environment from civil engineering models and integrating these impacts into

economic models. The objective is to derive optimal mitigation policies in response to natural disasters.
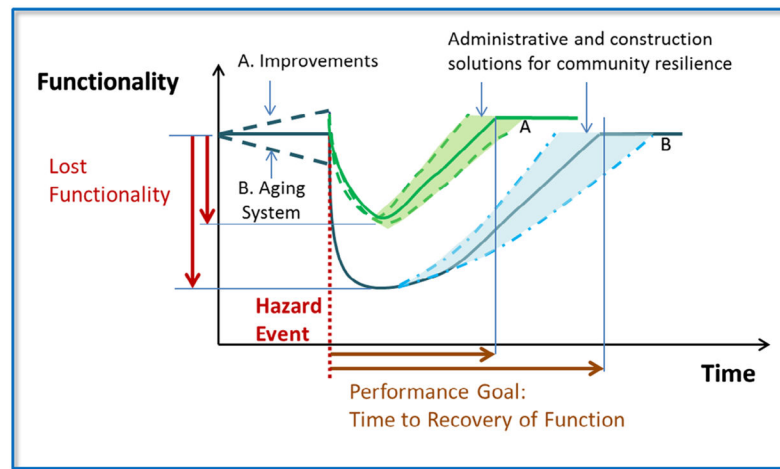
Figure 1.
Resilience measured in terms of time to recovery of functionality for physical infrastructure systems should include the existing condition of the system, the intensity of the hazard, the damage and loss of functionality, and the ability to recovery rapidly (McAllister, 2016).

Table 1

Representative definitions of resilience.

Source	Summary of resilience definition
Holling (1973)	A measure of the ability of systems to absorb changes of state, driving variables, and parameters and persist
Gordon (1978)	The ability to store strain energy and deflect elastically under a specified loading condition without breakage or deformation
Timmerman (1981)	Resilience is the measure of a system's or part of the system's capacity to absorb and recover from occurrence of a hazardous event
Mileti (1999)	Ability to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life, and without a large amount of assistance from outside the community
Adger (2000)	The capability of communities to resist external shocks to their social infrastructure.
Paton and Johnston (2001)	The ability to pick up and utilize physical and economic resources for effective recovery following hazards
Folke et al. (2002)	Resilience for social-ecological systems is related to three different characteristics: (a) the magnitude of shock that the system can absorb and remain in within a given state; (b) the degree to which the system is capable of self-organization, and (c) the degree to which the system can build capacity for learning and adaptation
Bruneau et al. (2003)	The ability of social units (organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and mitigate the effects of future earthquakes
Walter (2004)	Resilience is the capacity to survive, adapt, and recover from a natural disaster. Resilience relies on understanding the nature of possible natural disasters and taking steps to reduce risk before an event as well as providing for quick recovery when a natural disaster occurs. These activities necessitate institutionalized planning and response networks to minimize diminished productivity, devastating losses, and decreased quality of life in the event of a disaster
Rose and Liao (2005)	The adaptive response to hazards in order to enable individual and communities to avoid potential losses
Adger et al. (2005)	The ability of systems following disasters to self-organize, with the capacity to learn from and adapt to disruptions
UN/ISDR (2005)	Resilience is the capacity of a system, community, or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures
Resilience Alliance (2007)	Ecosystem resilience is the capacity of an ecosystem to tolerate disturbance without collapsing into a qualitatively different state that is controlled by different set of processes. Thus, a resilient ecosystem can withstand shocks and rebuild itself when necessary. Resilience in coupled social-ecological systems, the social systems have the added capacity of humans to learn from experience and anticipate and plan for the future
Maguire and Hagan (2007)	Social resilience is the capacity of social entity e.g. group or community to bounce back or respond positively to adversity. Social resilience has three major properties, resistance, recovery, and creativity
Cutter et al. (2008)	The ability of a social system to respond and recover from disasters and include those inherent conditions that allow the system to absorb impacts and cope with an event, post-event, and adaptive processes that facilitate the ability of the social system to reorganize, change, and learn in response to a threat
Presidential Policy Directive 8 (PPD-8, 2011)	The ability to adapt to changing conditions and withstand and rapidly recover from disruption due to emergencies
National Academies (2012)	The ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events
Presidential Policy Directive 21 (PPD-21, 2013)	The ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions, including the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents