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Workforce/Population, Economy, Infrastructure, Geography, Hierarchy, and Time (WEIGHT): Reflections on the Plural Dimensions of Disaster Resilience

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The concept of resilience and its relevance to disaster risk management has increasingly gained attention in recent years. It is common for risk and resilience studies to model system recovery by analyzing a single or aggregated measure of performance, such as economic output or system functionality. However, the history of past disasters and recent risk literature suggest that a single-dimension view of relevant systems is not only insufficient, but can compromise the ability to manage risk for these systems. In this article, we explore how multiple dimensions influence the ability for complex systems to function and effectively recover after a disaster. In particular, we compile evidence from the many competing resilience perspectives to identify the most critical resilience dimensions across several academic disciplines, applications, and disaster events. The findings demonstrate the need for a conceptual framework that decomposes resilience into six primary dimensions: *workforce/population*, *economy*, *infrastructure*, *geography*, *hierarchy*, and *time* (WEIGHT). These dimensions are not typically addressed holistically in the literature; often they are either modeled independently or in piecemeal combinations. The current research is the first to provide a comprehensive discussion of each resilience dimension and discuss how these dimensions can be integrated into a cohesive framework, suggesting that no single dimension is sufficient for a holistic analysis of a disaster risk management. Through this article, we also aim to spark discussions among researchers and policymakers to develop a multicriteria decision framework for evaluating the efficacy of resilience strategies. Furthermore, the WEIGHT dimensions may also be used to motivate the generation of new approaches for data analytics of resilience-related knowledge bases.

KEY WORDS: Disaster risk assessment; disaster risk management; engineering analytics; resilience

1. INTRODUCTION

Recent research studies and applications in the field of disaster risk management have emphasized the importance of managing system resilience (Abe & Ye, 2013; Biedrzycki & Koltun, 2012; Carpenter, Brian, Marty, & Nick, 2001; Committee on Increasing National Resilience to Hazards and Disasters, 2012; Rose, 2009). In particular, applications of resilience have markedly grown in the field of disaster risk management, motivating the enhanced ability of organizations to adapt, reorganize, and efficiently recover from disruptive events (Santos, Herrera, Yu, Pagsuyoin, & Tan, 2014). However, most of the available literature sources treat the dimensions of resilience as isolated concepts across multiple disciplines (MacAskill & Guthrie, 2014). Few of these

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sources harness the power of data analytics and adaptive artificial intelligence for managing resilience using current technologies. There is a need for the risk field to learn from the many perspectives on system resilience, as informed by a wide variety of academic disciplines, applications, and disaster events. The objective of this article is to leverage findings from multidisciplinary research to identify the most critical resilience dimensions, and compile these aspects into a comprehensive framework that acknowledges the plural dimensions of resilience, specifically in the domain of disaster risk management.

Previous publications on the topic of resilience typically focus only on a particular or limited set of resilience dimensions (Lucini, 2014). Nonetheless, there are notable discussions in previous literature suggesting the need for decomposing resilience into multiple components. MacAskill and Guthrie (2014) discussed the issues associated with the multiple interpretations of resilience according to four categories: precision, circularity, context, and completeness of knowledge. They developed a conceptual framework of resilience in disaster risk management in which the application and context of resilience were decomposed into secondary factors (i.e., application is broken down into perspective and object; while context is broken down into societal, chronological, and scale). They also decomposed the secondary factors into tertiary factors (e.g., chronological is broken down into predisaster and postdisaster, among others). Furthermore, the concept of resilience has also been suggested in the literature to comprise several components such as ecological, environmental, institutional, infrastructural, organizational, economic, social, community, familial, and individual (Lucini, 2014). Hosseini, Barker, and Ramirez-Marquez (2016) performed a review of resilience definitions according to four different subject domains (organizational, social, economic, and engineering), paving the way to a system for classifying resilience into qualitative and quantitative categories. Similarly, Cimellaro, Renschler, Reinhorn, and Arendt (2016) propose a PEOPLES framework that identifies seven dimensions of resilience: population and demographics; environmental and ecosystem; organized governmental services; physical infrastructures; lifestyle and community competence; economic development; and social-cultural capital (Renschler, 2013). The proposed WEIGHT framework and its associated dimensions encompass the PEOPLES framework but they have several fundamental differences. For example, the *workforce* dimension is emphasized since disaster recovery hinges heavily on workforce availability in the aftermath of disasters to reduce business interruption losses and to immediately restore economic livelihoods. Also, we believe that the term *infrastructure* is a better alternative to *physical infrastructure* in order to encompass both physical (e.g., transportation, electric power, etc.) and "soft" (e.g., cyber networks, finance, etc.) infrastructure systems. Furthermore, *hierarchy* and *time* are explicit dimensions identified in the WEIGHT framework, which are an important consideration in resilience and disaster risk management.

Hence, this article offers an alternative multifaceted view of resilience that not only captures the decompositions described above, but also focuses on the primary dimensions that are deemed to be critical in the domain of disaster risk management. In particular, the six primary dimensions of disaster resilience explored in this article are as follows: *workforce/population*, *economy*, *infrastructure*, *geography*, *hierarchy*, and *time*. Another distinct advantage of our proposed resilience decomposition is that these keywords form the acronym WEIGHT, which coincidentally and conveniently emphasizes the "weight" (i.e., importance) of resilience in disaster risk management. The sequence of the acronym also implicitly suggests an inherent distinction of the *systems* and *contexts* associated with resilience. The first three (workforce/population, economy, and infrastructure) comprise primary categories of systems that need to be resilient against disasters, while the last three (geography, hierarchy, and time) can be construed as contexts relevant to the management of resilience.

This article aims to provide a detailed documentation and review of resilience in the context of disaster risk management. The overarching objective of this review is to stimulate discussions towards a more cohesive and multidisciplinary recognition of the plural dimensions of resilience across various scientific communities, public-policy-making agencies, disaster relief organizations, and other relevant stakeholders. Brief descriptions of the six dimensions of resilience follow. Our intent is to discuss the essence of each dimension; literature sources supporting these preliminary claims are pursued in detail in the main sections of the article.

- Workforce/Population (W): Recent articles on disaster preparedness emphasize the criticality of workforce in sustaining the continuity of regional activities in the aftermath of disasters (Santos et al., 2014). The workforce is not only at the forefront of achieving regional prosperity; it also directly supports disaster preparedness and recovery. Without loss of generality, the "workforce" dimension also encompasses the general population and demographic attributes, which in its entirety can be deemed as vulnerable to the consequences of disasters. Disasters disrupt workforce mobility and limit access to workplaces, consequently resulting in significant economic losses. Furthermore, disasters also create adverse social/psychological effects to vulnerable populations, which could further exacerbate regional productivity. Relevant data in modeling this dimension may include census estimates, labor statistics, incomes, and population surveys.

- Economy (E): The economy dimension encompasses the interdependent economic sectors of a region (e.g., agriculture, manufacturing, commerce, service, and government, among others). Related literature underscores the significance of both direct and indirect effects of disasters across interdependent sectors. In particular, several studies have demonstrated the significance of resilience enhancement policies (e.g., inventories) in decreasing economic losses and shortening the recovery period in the aftermath of disasters (Resurreccion & Santos, 2012). Relevant data may include regional economic metrics, such as GDP, income, industry-specific GDP, spending, and consumption.
- Infrastructure (I): The infrastructure dimension describes lifeline infrastructure systems (e.g., transportation, electric power, communication) as well as critical service systems (e.g., finance, medical services, and health). Furthermore, this dimension generally captures the critical infrastructure and key resources (CIKR) as identified by homeland security policymakers in the United States. Relevant data may include infrastructure condition, demand, performance, and usage patterns.
- Geography (G): The geography dimension refers to location-specific attributes of a region. It includes factors pertaining to ecology and environment, as well as spatial factors that relate to the likelihood of disasters and the severity of their consequences. Relevant data may include topography, proximity to coastlines, climatological characteristics, and vulnerability to specific types of disasters such as earthquakes, hurricanes, and man-made events.
- Hierarchy (H): The hierarchy dimension of resilience describes the current state and issues pertaining to how disaster management policies and decisions flow across different organizational levels (global, national, regional, and local). This dimension also encompasses the complexities associated with both vertical and horizontal coordination of roles, stakeholder involvement, and the availability of technologies that can enhance the efficiency of disaster recovery. Relevant data may include a mapping of decision-making processes for various types of critical resources and coordination linkages across the different levels of decision-making entities. As these processes likely differ among nations, states, localities, and organizational types, this dimension is the most challenging to document.
- Time (T): The time dimension refers to various stages of disaster risk management ranging from preparedness planning to mitigation activities leading to recovery. It also encompasses other temporal uncertainties pertaining to disaster occurrence such as time of day or seasonal variations. Within the time dimension, it is important to recognize how the severity of consequences and the efficacy of associated mitigation measures could vary with respect to specific timing of arrival (e.g., day vs. night, idle vs. rush hours) as well as duration of exposure to disasters (e.g., slow vs. rapid onset). Relevant data include time-series information regarding all of the data types described in the other dimensions.

The WEIGHT dimensions of resilience as proposed in this article are depicted in Fig. 1. This illustration is intended to provide the reader an overview of the categories of the WEIGHT dimensions and their subdimensions; for figure clarity, the linkages and interrelationships across these dimensions are not shown. We underscore that the resilience dimensions are not mutually exclusive entities; rather, they are overlapping, interdependent, and involve coordination across system functions, owners, stakeholders, and users. There have been risk studies that attempted to monetize some of the WEIGHT dimensions. In some instances, these dimensions may be noncommensurate; overperformance in one

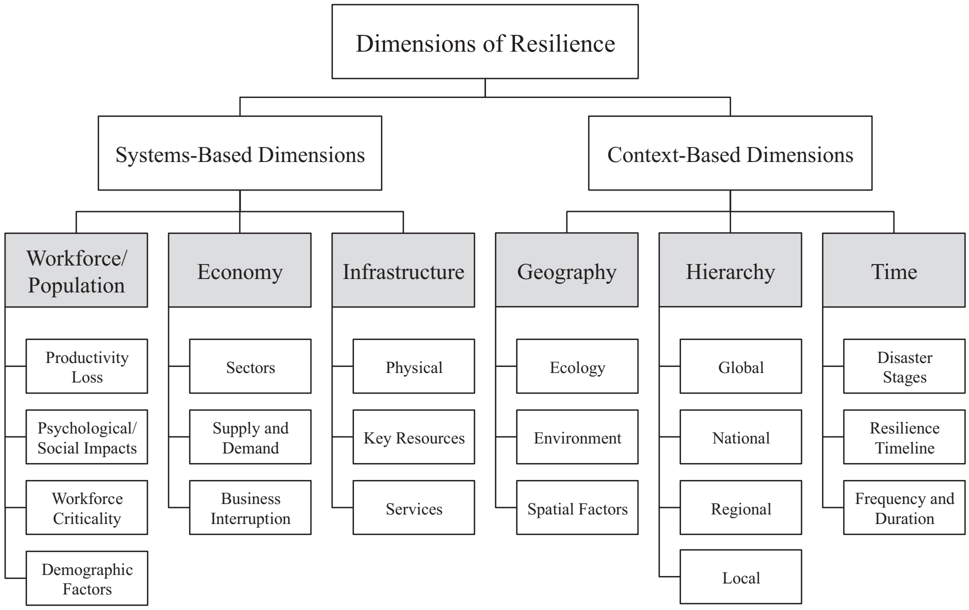

Fig. 1. Overview of WEIGHT dimensions of resilience.

dimension cannot necessarily compensate for underperformance in another dimension (Multihazard Mitigation Council, 2005). However, we do acknowledge the practical need for monetization and also recognize that monetization does not imply fungibility of resilience dimensions. In a practical setting, quantification in monetary terms may be necessary for decision making. Consequently, we recognize and emphasize the plural dimensions of resilience, which, when integrated, provide a multidisciplinary interpretation that advances the current frontiers of disaster risk management.

Although single performance metrics or dimensions allow for ease of mathematical modeling and decision making, we acknowledge that no single performance metric is sufficient for measuring system performance and system resilience. We also acknowledge that some resilience dimensions described in this article are not commonly measured or quantified, thereby requiring synthesis of both quantitative and qualitative knowledge management (Aven, 2017). This philosophy paves the way for a more structured approach for collecting, archiving, and mining of resilience-related information and knowledge bases. For example, there is an emerging field known as “engineering analytics,” which can be described as a structured approach for problem solving via systems thinking and analytical techniques to translate information into actionable decisions.

We study the WEIGHT dimensions within the context of disaster risk management. We adopt the U.N. Office for Disaster Risk Reduction definitions of “disaster” as “a serious disruption of the functioning of a community or a society at any scale due to hazardous events interacting with conditions of exposure, vulnerability and capacity, leading to one or more of the following: human, material, economic and environmental losses and impacts.” Similarly, we define “emergency” as “sometimes used interchangeably with the term disaster, as, for example, in the context of biological and technological hazards or health emergencies, which, however, can also relate to hazardous events that do not result in the serious disruption of the functioning of a community or society” (U.N. Office for Disaster Risk Reduction, 2017). The definition of “risk” is evolving and can have many interpretations depending on the application. While we refer the reader to the Society for Risk Analysis glossary of risk terms for the many nuanced definitions of risk, we adopt common interpretation of risk that studies “the effect of uncertainty on objectives” (Society for Risk Analysis, 2015)

The subsequent sections of this article are organized according to the order of the dimensions of disaster resilience in the WEIGHT acronym and subdimensions as depicted in Fig. 1. The final section includes reflections on how the WEIGHT dimensions can be integrated into a comprehensive risk management and resilience paradigm.

2. RESILIENCE DIMENSION 1: WORKFORCE/POPULATION

This section focuses on the relationship between disasters and workforce sectors. Available and productive workforce sectors are critical for sustaining the operability and functionality of vital systems. Disasters often cause irreversible damage to infrastructure systems and other impacts that have profound economic consequences, including strained market growth and workforce interruption. There are inherent obstacles to the effective and timely implementation of efforts to return all systems to predisaster functionality. Recovery efforts rely on an operating workforce, the absence of which can slow the recovery process. Disasters can also induce psychological impacts on targeted populations. Hence, strategies for mitigating disruptions to the workforce and the general population should be explored to better understand its disaster-related resilience.

2.1. Workforce/Population Subdimension 1: Productivity Loss

The disruption of the workforce sector is an inevitable impact of a disaster. Workforce absenteeism related to disasters triggers productivity losses that contribute to the decrease of a sector's output, and could further exacerbate the efficiency of the supporting production factors (e.g., machines, capital, labor, etc.) (Akhtar & Santos, 2013). In most cases, many other resilience dimensions are critically dependent on the workforce (e.g., the workforce sectors are central to the management of economy, infrastructure, geography, hierarchy, and time). Regions typically have limited budgets to address day-to-day operations. When a disaster occurs, the diminished workforce and productivity further constrain the ideal path to recovery. Many studies emphasize the need for more resilient infrastructure systems; however, research is lacking in the area of workforce-centric impact management and recovery (Santos et al., 2014).

Diseases caused by pandemics are an example of a major impact of a disaster that primarily impedes the workforce. A pandemic can be described as a slow-onset disaster that expands rapidly when a significant percentage of the population across a vast region gets infected by a disease, instigating prolonged periods of absenteeism (Santos et al., 2014). For instance, the 1918–1919 H1N1 influenza pandemic that claimed an estimated 50–100 million lives worldwide is recorded as one of the deadliest disasters in human history (Taubenberger & Morens, 2006). More recently, the 2003 severe acute respiratory syndrome (SARS) pandemic began in a small region in mainland China and rapidly spread to over 28 other countries, resulting in 700 deaths and over 8,000 cases. (World Health Organization, 2017). This pandemic led to major workforce disruption over the ensuing weeks, causing economic havoc for tourism and over $30 billion in losses (Peiris, Yuen, Osterhaus, & Stöhr, 2003). These examples demonstrate that workforce disruptions and absenteeism can directly impact economies and related sectors, and also cause indirect impacts throughout the system.

Disasters may also be indirectly associated with extended workforce absenteeism. For example, employees may take time off to care for sick relatives who are unable to care for themselves (e.g., disabled, children). A study conducted in the United Kingdom reports that, on average, 4.4 days are missed per worker due to workforce absences caused by illness within the family (Office of National Statistics, 2016). This absenteeism is considered to be time missed from performing work and other related duties. Although this average is lower than the earlier estimate from the same study (7.2 days per worker in 1993) as a result of advances in identifying health-related risks, the time missed can lead to indirect economic impacts.

In addition to pandemics, disasters (such as hurricanes and acts of terrorism) can inevitably lead to workforce absenteeism. Workforce disruptions contribute to losses in economic output and productivity. While this section focuses on absenteeism within the workforce dimension, it draws upon other dimensions (i.e., economy, infrastructure, geography, hierarchy, and time) to explain its effects on interconnected regions, further emphasizing the need for a multifaceted approach to managing disaster-related events.

2.2. Workforce/Population Subdimension 2: Psychological and Social Impacts

Although the psychological well-being of the general population in itself could be considered a separate dimension, we included it within the workforce/population dimension because disasters have historically caused adverse impacts on the morale and productivity of the working populations (Reifels et al., 2013). The mental health of affected populations following a disaster is an emerging topic of research interest. In comparison, the direct and indirect losses attributable to the psychological impact of disasters on the workforce could be as significant as the financial value of lost or damaged physical infrastructure systems. Comprehensive and critical surveys such as those conducted by Norris, Byrne, Diaz, and Kaniasty (2002) as well as Reifels, Naccarella, Blashki, and Pirkis (2014) increase public awareness on disaster-related mental health and its significance in disaster impact mitigation. By addressing this subdimension of workforce, overall community resilience can be strengthened.

Empirical studies of public mental health following the September 11, 2001 attacks on the United States ("9/11 attacks") found a surge in post-traumatic stress disorder (PTSD) cases (Susser, Herman, & Aaron, 2002). While PTSD existed prior to the 9/11 attacks, Galea et al. (2002) were able to distinguish PTSD specifically attributed to the attacks. This single disastrous event triggered ripple effects within the society; mental health was affected not only within the workforce, but also within the general population. The Federal Aviation Administration (FAA) also reported that following the event, the general public exhibited apprehension about using airline transportation and therefore lowered demand for air travel (Federal Aviation Administration, 2002). The 9/11 attacks demonstrate the interconnected response of economic sectors to a disaster. To perform a comprehensive evaluation of the effects of a single disaster to an economic region, robust evaluation tools are needed to model how these sectors are linked. Santos (2006) developed an extension of the economic input–output model to assess the impact of disruptive events on regional systems (Santos, 2006). In a five-year economic loss model, Santos concluded similar findings to those published by the Government Accountability Office where the air transportation sector lost close to $40 billion over the same time period (U.S. Government Accountability Office, 2002). Similar to resilience dimensions and their subdivisions, disasters are a multifaceted issue that extends to multiple interdependent sectors. In the case of the 9/11 attacks, the psychological impact of this event burdened a large portion of the airline industry.

In order to formulate effective disaster resilience policies, logistical barriers surrounding the mental and psychological well-being of the population must be addressed to strengthen the relief efforts for reconstruction after a disastrous event. When the Sichuan Earthquake of 2008 struck China, it directly affected a portion of the region's population of 160,000. In particular, 990 out of 1,591 government officials engaged in disaster relief lost family members in the disaster (Wang, Chan, Shi, & Wang, 2012). Many of these officials were placed on suicide watch; symptoms of depression and PTSD began to develop in the following months. Wang et al. (2012) interviewed a number of local officials to evaluate their stress and coping mechanisms in an effort to discover best practices for combating compounded mental health issues. The researchers concluded that many officials who engaged in meaningful relief work contributed to better coping efforts while defining a key work-life balance.

Mental health and the psychological effects of disasters are prevailing issues that must be addressed for the workforce. As with many problems associated with other resilience dimensions, these effects are not an isolated concern, but one with far reaching impacts on other interconnected dimensions and sectors.

2.3. Workforce/Population Subdimension 3: Workforce Criticality

In examining the workforce dimension, absenteeism and psychological/social well-being are identified as areas for key research in previous sections. Parallel to the impacts of disastrous events on a population and its workers, the prioritization of the workforce based on its criticality to the affected region must also be emphasized (Perry & Lindell, 2003). It is critical to have a functional staff to maintain the operations of systems that support basic human necessities. Disaster preparedness and response efforts must include a prioritization strategy for organizing relief and continued recovery (Chen, Sharman, Rao, & Upadhyaya, 2008). During nondisaster conditions, a community workforce will function according to established patterns, with individuals performing defined tasks. In a disaster situation, there may be a shortage in workforce to fulfill those tasks until overall system functionality is restored.

Workforce prioritization includes identifying tasks that are crucial to response and recovery, while also identifying other tasks that are not absolutely necessary during a disaster. Kaufman et al. (2014) conducted a study to expose the challenges facing the public health workforce and to better understand emerging priorities for state and local government agencies. The study found that while discipline-specific initiatives have been the focus in recent years, the workforce should be viewed with respect to its independent functions, and prioritization should take place for cross-cutting workforce development. It was postulated that the coordination of workforce efforts will occur no matter the circumstance, but the success of these efforts will rely on creating a balance between core- and specialty-based training to enhance fundamental skills. By combining the different categorical work structures in local and state governments a better formation of resources can be allocated for overall disaster response and recovery.

From a disaster management perspective, Brewer (2015) conducted a comprehensive study on the preparedness considerations emergency managers make to ensure disaster readiness for community collaboration. Three major themes emerged for emergency managers: (1) constant planning, (2) incorporation of public outreach, and (3) cross-cutting collaboration across the workforce. By organizing the community, potential chaos can be further diminished. Therefore, both government officials and emergency response staff are critical in mitigating risk and in aiding in response efforts. Other occupations, albeit vital to the community (e.g., educators), will not be a prioritized workforce in order to best respond to disasters. By understanding the ordering and management structure in the event of a disaster, Biedrzycki and Koltun (2012) proposed that a whole community approach can be an effective strategy for enhancing resilience.

2.4. Workforce/Population Subdimension 3: Demographic Factors

Regional demographic factors in the context of disaster resilience include occupation, income, marital status, age, gender, education level, and population density, among others. Social vulnerability is not evenly distributed among social groups or regions. Different areas are more susceptible to hazards depending on the characteristics of the local population (Cutter & Emrich, 2006). The human aspect of social vulnerability stems from the quality of life and the livability within a region based on the following dependencies (Nelson, 2018): proximity to a possible hazardous event, population density, education and awareness of the hazard, existence of early-warning systems and channels of communication, and availability and preparedness of emergency infrastructure. In general, low-income countries can be more vulnerable to disastrous events because of the factors, that could be attributed to lack of access to public education on hazards and disaster risk reduction programs. In some cases, high-income nations are more prone to disasters due to industrialization, deforestation resulting in erosion, construction of infrastructure that increases landsides, or severe weather associated with climate change (Yin & Li, 2001). In the United States, nearly 80% of the population resides and works in urban areas, resulting in congestion and dense infrastructure (Donner & Rodríguez, 2011). Other regions and countries face similar issues where sustained population growth and increasingly dense urban areas increase vulnerability and also introduce challenges to disaster preparedness and response plans.

Within the first dimension of WEIGHT, we decomposed the workforce/population category into several subdimensions to draw attention to areas of key research and existing gaps as identified in the literature (Santos et al., 2014). In the event of workforce disruptions, there are expected cascading effects to interrelated economic sectors. While this section focuses primarily on impacts to the workforce and strategies to better enhance resilience, the economic dimension is shown to also be impacted, both directly and indirectly. A coupled response to disasters must be undertaken. The subsequent discussions of the WEIGHT dimensions will continue to emphasize how disasters do not only affect isolated structures, sectors, or communities, but also have far-reaching effects. As such, the strategies for enhancing disaster resilience and mitigating long-term impacts must be formulated with a broader economic perspective in mind.

3. RESILIENCE DIMENSION 2: ECONOMY

This section encompasses the interdependent economic sectors, including agriculture, manufacturing, trade, service, and government, among others. Such sectors are vulnerable to disasters. Disasters limit the availability of required inputs and disrupt the delivery of outputs from producers to consumers. Significant economic consequences caused by disasters and business interruptions propagate across interdependent sectors. In order to better assess the economic risks triggered by disasters, it is necessary to decompose the different sectors of the economy, sector-specific disaster management strategies, and several modeling tools to demonstrate the complexity of the economic dimension. By exploring these key areas, resilience may be better understood for evaluating and enhancing the efficacy of disaster resilience strategies.

3.1. Economy Subdimension 1: Sectors

Disasters cause significant challenges and consequences that could generate lasting impacts on the population and the economy. The economy encompasses a wide range of sectors, such as agriculture, manufacturing firms, financial services, trade, and government agencies, that are crucial to continued growth and development. A regional economy can be examined as a set of interconnected sectors that are vulnerable to direct and indirect impacts from disasters, either directly from the disaster itself or from cascading supply chain disruptions to the flow of goods and services. Business interruptions triggered by disasters can lead to costly economic losses. The inherent interdependencies across economic sectors further exacerbate the direct effects of disruptive events, often resulting in significant ripple effects. A survey by Webb, Tierney, and Dahlhamer (2000) indicated that the direct and indirect losses triggered by disasters are as significant as the magnitude of the resulting physical infrastructure and property damages. In estimating such losses, it is essential to understand the magnitude and extent of linkages that exist across interdependent sectors of the affected regional economy.

In December 2004 a tsunami caused by the Sumatra-Andaman earthquake ravaged Indonesia (Aceh Province), India, Sri Lanka, and other proximate nations (Lay et al., 2005). The Institute for Economics and Social Research at the University of Indonesia (LPEM) estimated a total loss of U.S. \$4.6 billion in Aceh province alone, where over one-third of the road networks, schools, and hospitals were destroyed (Nazara & Resosudarmo, 2007). The total cost of the disaster nearly equaled Aceh's GDP (2% of Indonesia's GDP); the majority of the economy is centered on agriculture and oil and gas industries, which were each reduced by almost 35% (Athukorala & Resosudarmo, 2005). In particular, the agriculture sector suffered greatly from pollutants caused by the tsunami. Approximately 30,000 hectares of land for rice were impacted by salinity that will take time to flush through natural means (e.g., rainfall) (Jayasuriya & McCawley, 2010). The lack of rice cultivation has affected the supply of goods for the people of Aceh, who consume 60% of the crop output. Due to the magnitude of devastation to the local economy and infrastructure, disaster management is still working to repair long-term growth and development. The economy of Aceh, which relies on key production sectors, suffered greatly from the tsunami. Direct impacts immediately following the disaster could be quantified through infrastructure degradation and loss. The indirect impacts stemmed from underlying economic concepts of supply and demand for goods and services. These issues contributed to slower growth and development in that region until the local systems were restored to predisaster functionality. While the Aceh province is a small percentage of Indonesia's entire GDP, this event and the effect on the area highlight the apparent disruptions to a local economy.

Another example is the 2011 catastrophic earthquake and tsunami in the northeast coastal region of Japan. Several months following the disaster, disruptions to global supply chains adversely affected the automotive sector and set off a complex chain of global business interruptions. In assessing the global supply chain disruptions triggered by this disaster, MacKenzie, Santos, and Barker (2012) have demonstrated the use of economic analysis and modeling to estimate the breakdown of economic losses suffered by specific sectors in different countries. It was also observed that although a significant number of sectors incurred economic losses in the aftermath of the tsunami, the same study also identified positive impact to sectors involved in recovery operations (e.g., construction industry).

While a myriad of studies focus on the aggregated economic losses to a region due to a disaster, it is important to assess the loss breakdown across different sectors. Through the use of modeling and analysis tools, sector-specific preparedness plans can be undertaken to further enhance economic resilience.

3.2. Economy Subdimension 2: Supply and Demand

Disasters are often associated with both short- and long-term economic losses to regions. Long-term consequences involve slowed economic growth, delayed economic development, and poverty. The displacement and effect on people can be devastating in the period following a disaster. Most of these impacts are well-documented in literature pertaining to the economic modeling and analysis of disasters (Kellenberg & Mobarak, 2011; Rose, Benavides, Chang, Szczesniak, & Lim, 1997). By coupling a historical understanding with potential future scenarios, better practices and decision-making strategies can be applied in order to strengthen economic resilience. The economic responses to a disaster are predicated on reactions of the affected population and the changes in demand and supply patterns after the disaster, as well as policies that could impact the duration of disaster recovery.

While the direct supply and demand impacts of a disaster are commonly estimated within the scope of the affected region, there are challenges in the assessment of spillover effects in broader multiregional settings. Many industries, such as electronics, automobiles, and apparel, have become highly integrated into global supply chains in which products, supplies, and manufacturing processes have expanded across national boundaries (Christopher, 2011). With the growth and expansion of global supply chains, the ability to contain and manage the consequences of disasters is expected to become increasingly more cumbersome.

In 2011, heavy flooding caused damage in multiple South-East Asian countries. Thailand incurred over U.S. $40 billion in losses and crippled manufacturing capabilities (Centre for Research on Epidemiology of Disasters, 2016). This flooding caused a major supply chain disruption and price fluctuations in the hard disk drive market. Because Thailand is the second largest producer of hard disk drives in the world, the resulting production disruption further led to a spike in pricing across the world market due to the changes in purchasing behaviors of wholesalers and redistributors (Abe & Ye, 2013). Automobile manufacturing processes were also halted due to the flooding. While Nissan and Toyota plants elsewhere were not physically and directly harmed, both companies suspended production because of increased difficulty in procuring parts from suppliers in Thailand (Haraguchi & Lall, 2015). Toyota (2011) also realized the effects of supply shortages, thereby causing facilities in countries including Pakistan, the Philippines, and the United States to adjust their production accordingly. The effect of flooding not only impacted technology and automobile companies alike, but the rest of the world and the global markets reliant on such production. This disastrous flooding event not only effected Thailand; the impacts began to take effect on a global scale in multiple industries. The economic patterns such as supply and demand are not random occurrences nor are they new to disaster impacts. By collecting data on economic responses and trends, historical information and "lessons learned" will contribute to quantitative and qualitative analysis for future disaster preparedness planning.

3.3. Economy Subdimension 3: Business Interruption

In order to understand the financial impacts of disasters, the availability of data and statistical tools help to estimate the magnitude of business interruption losses. While there are many models that are widely used for assessing business interruption, this section will highlight three models that are most commonly used: input–output, econometric time-series, and computable general equilibrium (CGE). Although these models broadly encompass both economic and statistical-based approaches, this listing is not exhaustive. Other models are available, such as agent-based and behavioral simulations, that capture higher-resolution interactions across local firm and household units.

Input–output model analysis is one of the most widely used methods in economics for analyzing the interdependencies across industries in an economy (Baumol, 2000). The I–O model is a useful tool in economic decision-making processes used in many countries—it presents a framework that is capable of describing the interactive nature of transactions among economic systems (Miller & Blair, 2009). For the purpose of disaster preparedness and economic loss assessments, an I–O model can be utilized in order to calculate different amounts of labor, materials, and other resource inputs needed to rebuild hospitals or repair bridges (Greenberg, Lahr, & Mantell, 2007). This model is able to provide impact analysis of business interruption losses, notably those that are triggered by disruptions to demand and supply levels. Among its limitations are (i) the assumption that technology and productivity are fixed proportions and (ii) the lack of accounting for the time-value of money. Extensions to the basic I–O model remedy part of these limitations by factoring seasonality or economic cycles relative to the occurrence of an event, hence providing better estimates of the impact of demand/supply perturbations (Santos & Haimes, 2004). I–O models supplemented by dynamic analysis can be made scalable and adaptable to local, state, and national needs.

The second broad modeling category is the development of econometric time-series models given a disastrous event. This type of modeling differs from I–O models in that it captures information within an economic sense pertaining to historical trends (Conway, 2001). It is advantageous for use in factoring of forecasts for employment, wages, and pricing that may influence the economy's temporal reaction from the time of investments to the full yield of their benefits (Greenberg et al., 2007). With this advantage, it also presents a limitation of being "backward" looking, meaning that the information pertains to previous economic relationships and may not always provide accurate information for future events. Although there may be limitations to the econometric model, it is able to test for a variety of scenarios and factors for assumptions in the amount of predisaster mitigation needed and the extent of economic resilient behavior that must be undertaken. Most importantly, like the I–O model, it allows for a functional forecast that enables policymakers and organizations to better plan and act for disasters.

Lastly, CGE models are inherently I–O models but with modifications to explicitly consider resilience within the mathematical formulation (Rose & Lim, 2002). Rose (2009) provides detailed reviews of economic resilience definitions, categories, and enhancement strategies such as production recapture and inventories, among others. CGE analysis offers a more complex modeling framework for assessing the impacts of economic and disaster resilience policies (Rose & Liao, 2005). It shares the capabilities of I–O models in itemizing the effects of a disruptive event across interdependent sectors. In addition, CGE's explicit inclusion of distribution and elasticity parameters has the potential to more accurately describe the efficacy of strategies for allocating constrained resources with the aim of minimizing the business interruption losses. This form of economic analysis approaches disasters in a multifaceted perspective and is able to model a myriad of responses to impacts that feature shortages and changing market conditions (Rose & Liao, 2005). Okuyama, Ewing, and Sonis (2004) developed and implemented a dynamic model that include spatial and temporal effects of disasters to the Hanshin, Japan earthquake of 1995. This application of the model demonstrates additional analytical insights that may be used in conjunction with CGE analysis.

The concepts of economic relationships to disaster impacts are complex in nature and no single model will be able to forecast a comprehensive analysis of disaster consequences. Each scenario is inherently different and presents a variety of challenges when estimating and planning a viable strategy. In many situations for the use of tools, the iterative process will continue to improve estimation and analysis. Recently, Rose proposed a framework for business interruption assessment to consider public–private partnerships and their impact on property damage and economic loss estimation (Rose & Huyck, 2016). Although the challenges are numerous, the use of the economic models supports the formulation of risk management policies and strategies.

4. RESILIENCE DIMENSION 3: INFRASTRUCTURE

Infrastructure functionality is one of the key considerations for defining effective disaster preparedness and response. It presents a financial burden for recovery, while also intensifying workforce disruptions, leading to greater disastrous effects across multiple dimensions. In the context of disaster resilience, this article adopts a definition for infrastructure as any large-scale public system, services, and assets of a country that are essential to security, safety, economic activity, and way of life (Baren, 2009; The White House, 2013). Infrastructure is viewed by many organizations as both critical infrastructures and key resources (CIKR) that can be further separated into physical systems, resources, and services that support an entire region or country. Physical infrastructure is critical to a region's economy and it affects the daily life of an individual, from the movement of goods to providing transit. These types of assets include aviation, rails, bridges, and roadways that all must balance between increased demand and strained reliability in the event of a disaster (U.S. Government Accountability Office, 2008). Key resources can be separated into crucial systems for food, water, energy, communication, and other sectors that are needed for a system or community to maintain the most basic functions. A third component of CIKR comprises sectors that provide emergency, financial, and security services. As the world continues to change in complexity while increasing its interconnectedness, it is important to reinforce the resilience of CIKR. The complete integration of the services, systems, and sectors provides the support for the well-being of society.

4.1. Infrastructure Subdimension 1: Physical Infrastructure

In recent years, there have been several research advances in understanding infrastructure interdependencies (for example, the fundamental work by Rinaldi, Peerenboom, and Kelly, 2001). Furthermore, Sharkey et al. (2016) provided a framework for identifying and classifying interdependencies in the context of restoring critical infrastructure systems in the aftermath of Hurricane Sandy. The loss or reduction of the functionality of a critical infrastructure not only intensifies the impact of a disaster on a community, it also produces long-term secondary impacts on other dimensions such as workforce, economy, and interconnected infrastructures. Physical infrastructures may be categorized as all tangible assets that arise from the systems and services supporting a community. For example, following an earthquake disaster, the surge of seismic damage may overwhelm a region, a household, other facilities, and physical structures, potentially leading to long-term effects on the regional and national economy (Tesfamariam & Goda, 2013). Hence, it is important to assess how the magnitude and extent of interdependencies across various systems can be leveraged to improve the process for prioritizing resilience policies to minimize the impact of disasters.

In 2010, Haiti endured a 7.0 magnitude earthquake that resulted in thousands of fatalities. Residents were trapped in collapsed and poorly reinforced buildings; electric power systems failed; telecommunication channels faltered; and roads were blocked by debris (Encyclopædia Britannica, 2016). Damages were estimated at $7.6 billion in a nation that previously had a GDP of $11.9 billion (The World Bank, 2010). The impacts to the community underscore the severe need for improving the quality of resilient systems. During and in the aftermath of an earthquake, a collapse of physical infrastructure initiates a chain reaction of strained emergency services, a lack of key resources for relief, and economic losses that will be felt over the long term.

A comparable catastrophic aftermath of a strong earthquake was experienced in Japan due to the 2011 Tohoku Earthquake and Tsunami. The National Police Agency of Japan (NPAJ) reported over 15,000 casualties and over 300,000 buildings completely destroyed, with a further 1 million damaged (BBC News, 2012). Other secondary impacts include the disruption of supply chains, effects of rebuilding and growth within the economic sector, and the emergence of a national power supply crisis resulting from a nuclear power plant shutdown (Reuters, 2011). The estimated total cost of the disaster is 16.9 trillion yen (U.S. $160 billion) (BBC News, 2012). Regarded as one of the costliest natural disasters on record, the loss and destruction of physical infrastructures amounted to over two-thirds of the calculated damages.

4.2. Infrastructure Subdimension 2: Key Resources

The inoperability of vital utility systems delays recovery efforts and also leads to secondary consequences across dimensions, such as public health problems (Cretikos, 2007). When considering disaster impacts, resilience, and assessment strategies for key resources, the interdependencies of these resources must be highlighted. Resources such as water, energy, fuel, and food are fundamental assets for community survival and also for maintaining basic functions.

The capacity to provide key resources to a community is directly related to the survival of a community during and after a disaster. For example, the lack of access to safe drinking water leads to a notable rise in incidences of waterborne diseases that would otherwise be minimal had it not been for a disastrous event. When a tsunami ravaged Indonesia in 2004 and damaged a majority of drinking water infrastructure, many survivors drank from unprotected wells, causing over 85% of the community to suffer from diarrhea (Brennan & Rimba, 2005). In similar natural disasters, waterborne diseases like gastroenteritis, hepatitis, cholera, and leptospirosis have been found to increase when susceptible populations are overexposed to poor sanitation and unsafe water sources (Jafari, Shahsanai, Memarzadeh, & Loghmani, 2011; Watson, Gayer, & Connolly, 2007; World Health Organization, 2006). Crowding in evacuation centers can also give rise to secondary disasters in the form of diseases spread. Evacuation centers are perceived as sanctuaries for displaced individuals partaking of scarce key resources but they can also act as epicenters for various illnesses (Khalakdina, 2005). In the 2017 Hurricane Harvey that struck the state of Texas, historic floods caused failure of municipal water pumps in Beaumont City. Early estimates indicated that approximately 118,000 people lost access to water, causing a large hospital to shut down and evacuate its patients (Sanchez, Yan, & Simon, 2017).

Key resources that support mobility and communication are also essential in maintaining function while the disastrous event is in progress and in the ensuing recovery phase. The efficiency of recovery efforts as well as the delivery of aid are severely compromised when these resources are rendered unavailable during a disaster. When Typhoon Haiyan ravaged the Philippines in 2013, critical transportation and power networks were severely damaged, making rescue operations and communications extremely difficult (Santos et al., 2014). When Hurricane Sandy struck northeast U.S. in 2012, power and Internet service were nonfunctional for several days. Although multimodal transport systems maintained mobility, commute times were up to three times the normal commute (Kaufman, Qing, Levenson, & Hanson, 2012).

4.3. Infrastructure Subdimension 3: Services

Services are essential to maintaining security, public health and safety, and economic stability throughout an effected community. Economic sectors and physical infrastructure systems provide outputs in the form of tangible products (i.e., goods and commodities), as well as intangible outputs, particularly services. Translating quality of service in monetary terms is often difficult to accomplish. Critical infrastructure systems such as those identified by DHS (e.g., transportation, electric power, water, telecommunication, finance, emergency response, etc.) provide services that are essential in sustaining practically all the activities of various households, business sectors, and government agencies. Short-term outages of an essential service may cause inconveniences, but a prolonged outage duration may pose a significant threat to public safety. Disruptions to services provided by critical sectors also lead to significant ripple effects. For example, the 9/11 terrorist attacks in the United States caused securities markets and several financial exchanges to close until the financial services for communication and IT-related business could be relocated and restored (U.S. Department of Homeland Security, 2015b). In addition to the devastating impacts on surrounding physical infrastructures, this disastrous event led to an economic impact that materialized as a reduction of real GDP growth in 2001 by 0.5%, and a workforce impact due to an increased unemployment rate of 0.11% (loss of 598,000 jobs) (Roberts, 2009). The adverse impacts to both the economy and workforce dimensions were immediately felt across the country in the aftermath of the 9/11 terrorist attacks.

The emergency services sector (ESS) is responsible for protecting the public and the nation's critical infrastructures by providing preparedness, response, and recovery services (U.S. Department of Homeland Security, 2015a). These services facilitate coordination and partnerships across all hierarchies of governmental and nongovernmental partners, enabling stable and reliable operations following a disaster. Studies have shown that emergency services contribute to resilience related to socioeconomic and demographic factors (Flanagan, Gregory, Hallisey, Heitgerd, & Lewis, 2011). Without these services, the socially vulnerable are less likely to have an effective response and recovery from a disaster. Emergency services directly impact the well-being and daily life of the entire community, including elements of public health and financial security.

It is common for disaster preparedness and response strategies to include sector-specific documentation. For example, the U.S. Department of Homeland Security documents sector-specific plans for emergency preparedness and risk reduction within the financial services and ESS. Although it is practical to include sector-specific plans, there is continued need for integration. As mentioned previously, disasters do not solely impact one dimension, a singular community, or even a specific sector. Disasters are multifaceted and complex. Thus, risk mitigation plans should integrate sector-specific plans, allowing for increased collaboration among sectors, people, and geographies in the event of a disaster.

5. RESILIENCE DIMENSION 4: GEOGRAPHY

The geography dimension involves understanding how natural and social systems combine to improve resilience. There are several subdimensions that represent the location-specific factors pertaining to the likelihood of disasters and their associated severity. Most available literature sources pertaining to the geographic dimension of disaster risk management focus on the spatial attributes (Kendra, 2007). Expanding on this restricted view, we propose two other subdimensions: ecology and environment.

Geography is defined as "the study of places and the relationships between people and their environments." Furthermore, ecology is a subset focusing on particular interactions within the broader domain of geography (National Geographic, 2012). In addition to ecology, we consider environment as a another subset of geography, comprising the built and natural landscapes. Finally, we also include the spatial attributes of a region as a subdimension of geography.

5.1. Geography Subdimension 1: Ecology

Disaster resilience encompasses the magnitude and extent of disruption that can be tolerated before a given socioecological system collapses. Carpenter et al. (2001) state that resilience is directly linked to sustainability. The degree of resilience of a system depends on how well it can withstand catastrophic events without incurring significant degradation. In defining resilience, it is critical to understand the dynamic interactions between natural and social systems. Socioecological and economic–ecological interactions are major relationships that span multiple dimensions centered on the ecological subdimension of geography. As such, these linkages are highlighted in the following sections.

Resilient socioecological interactions are predicated on incorporating diverse mechanisms for living through and learning from unexpected shocks and change (Adger, 2005). Within ecosystems, biodiversity and spatial patterns adapt over time to contribute to resilience. Biodiversity is a mechanism where species and other functional groups respond and react differently to environmental fluctuations (Bellwood, Hughes, Folke, & Nyström, 2004). Conservation of resource theory has been used as a framework to study individual and community resilience for displaced disaster survivors (Docena, 2015). Examples include the rebuilding of affected areas in Louisiana (e.g., New Orleans) after Hurricane Katrina and also in the aftermath of Typhoon Haiyan in the Philippines. Such mechanisms sustain the socioecological relationship of being resilient to disasters within this geographic dimension.

Another notable relationship is the linkage between economy and ecology, and the resilience related to the interaction of the economic and geographic dimensions. The globalization of trade in commodities, goods, and services has connected areas more closely than before (Brown, Kerry, Hameed, & Bateman, 1997). For example, coastal regions, where tourism is a primary livelihood, are vulnerable to tourism demand and tourist characteristics. Tourists may carry infectious diseases that are not native to the region, potentially leading to an epidemic (Allison & Seeley, 2004). In some coastal regions, economic mechanisms have been created to recover and strengthen the resilience and economic–ecological relationship. For example, after Hurricane Ivan in 2004, private-sector interests accelerated recovery by rebuilding public infrastructure such as roads found in the Caribbean (Tompkins & Adger, 2004). The relationship between people and their surroundings became inevitably linked and relief was made possible, with economic impacts serving as the motivation to provide financial services. This demonstrates that resilience can be enhanced further by addressing the interaction of society with its environment.

5.2. Geography Subdimension 2: Environment

The environment subdimension refers to region-specific climates and types of potential disasters. It is characterized by distinct biomes and climates that are classified by predominant vegetation, adaptation of organisms, and long-term weather patterns (Campbell, 2009). Each biome has its own climatological influences and can be grouped into five major spheres: aquatics, deserts, forests, grasslands, and tundra. Although this listing is not exhaustive, this categorization allows for more directed strategies to improve resilience among those spheres. Also, it is known that particular regions are predisposed to certain types of disasters. As these disasters span across diverse environments, there is a need to examine climatological influence and vulnerability to specific types of disasters.

It is important to understand the relationship between environments and disasters. Environmental degradation reduces the capability of ecosystems to provide resources and services to communities, such as food, medicines, and protection from hazards (International Union for Conservation of Nature, 2015). While natural events can lead to environmental degradation, degradation can also result from human-caused events, such as intentional damage and human error. For example, historical agricultural practices have led to catastrophic environmental impacts and displacement of communities. In the early 1930s a dust bowl crisis resulted from intensive farming of fertile soil and a lack of crop rotation (Schubert, Suarez, Pegion, Koster, & Bacmeister, 2004). This led to years of drought, high winds, and the transformation of once productive lands into desert environments. The topic of dust bowls is reemerging as new evidence suggests that temperature and annual precipitation are shifting in opposite directions in many regions (Romm, 2011).

Climatic shifts are impacting environments around the world, causing secondary impacts to workforce, economies, and other dimensions. These climate shifts have been attributed to greenhouse gas (GHG) emissions from anthropogenic activities (Intergovernmental Panel on Climate Change, 2014). Greenhouse-gas mitigation policies, such as the Paris Agreement, aim to reduce human influence on these potential climate shifts. Without these policies to mitigate the climatological influence and strengthen resilience to disasters, dust bowl era effects may rise again and once more displace hundreds of thousands of lives (Seager et al., 2007). A broader consequence of climate shifts may introduce unsustainable living conditions at a global level.

5.3. Geography Subdimension 3: Spatial Factors

The third subdivision of geography involves the analysis of spatial factors related to the intersection of environment, ecology, and human aspect of disasters. The interdependencies across natural and social systems allow for identification of human vulnerabilities that are pivotal for developing resilient communities. The human aspect involves dimensions such as the workforce and hierarchical management structures, as discussed in Section 2. It is also central to the provision and receipt of support during disasters. Furthermore, the spatial component is a common theme even within environment and ecology; nonetheless, the emphasis of subsequent discussions is on the location of people relative to the location of environments. The proximity to locations of historical disasters is important for understanding the potential severity and impact of future events. For instance, about 23% of the world's population (1.3 billion) lives within 100 km of a coast, and this is projected to increase to 50% by 2030 (Small & Nicholls, 2003). These groups are more vulnerable to coastal flooding, tsunamis, and hurricanes. Sea level rise, frequent large hurricanes, and coastal submersion possibly resulting from climate change may cause these individuals to eventually abandon their homes (National Geographic, 2016). Climate change and other global environmental and socioeconomic changes may expose these geographies to unfamiliar risks, such as unexpected hurricane patterns and unprecedented weather patterns. For example, consider the post-Harvey rainfall due to unexpected jet stream patterns and other climate-related factors (Fischetti, 2017).

Without proper education and awareness on disaster-related events, risk reduction plans may prove ineffective. Given the diversity of spatial factors that affect the vulnerability of populations to disasters, a one-size-fits-all solution to preparedness, response, recovery, and mitigation may be ineffective in reducing vulnerability or improving local resilience to hazards. While it is important to encompass all aspects of geography including its drivers and external factors, an effective strategy must draw upon the other dimensions as well. The growing likelihood and magnitude of disasters should further motivate a paradigm shift of preparing for disasters from a multidisciplinary perspective.

6. RESILIENCE DIMENSION 5: HIERARCHY

This section addresses societal structures for mitigating disasters. During emergency response in disaster situations, hierarchies of management provide necessary stability and reliability of services. Disaster management has traditionally been fragmented across global boundaries and within local, regional, and national entities. The form of governing risk has been directed to mainly emergency management departments or agencies with little interaction among other key stakeholders, such as corporate partnerships and other dedicated nongovernmental organizations (NGOs). Within the hierarchy dimension, various nonstructural factors need to be considered when formulating policy plans across decision-making hierarches (global, national, regional, local). In particular, factors such as laws, culture, religion, education, and risk perception (among others) need to be recognized when designing region-specific resilience management policies.

In order to understand and better influence a successful management structure, Bissell (2013) identifies key weaknesses in the following areas that must be addressed in preparation for an event: leadership, collaborative organizational structures with outlined command chains, common technology, and joint communication, as well as logistics and resource-priority-setting systems. These weaknesses suggest that effective planning, guidance, and cooperation across all involved stakeholders and sectors are key to mitigating prolonged effects of disasters. For example, consider the Sendai Framework for Disaster Risk Reduction 2015–2030, an internationally recognized framework adopted by the U.N. International Strategy for Disaster Reduction (2015). This framework outlines a multidimensional view of resilience that supports risk governance across the global, regional, national, and local levels.

Recently, the subject of humanitarian logistics has received significant research attention, inspiring the rise in the development of optimization and decision support models in fields such as disaster and emergency management. In the last four decades, Kent (2004) concluded that humanitarian operations have grown to become a big network and serve as a major opportunity for global collaboration. Organizations such as the Red Cross have now extended their boundaries to include cross-country collaboration. The efficiency and effectiveness of providing relief to disaster-stricken populations can be directly attributed to the logistics of humanitarian operations (Bonney, 2005). The transboundary scope of humanitarian logistics highlights the hierarchy and application from global coordination to local aid (Kovács & Spens, 2007).

Technological advances have also substantially improved the ability for stakeholders, individuals, and communities to communicate following a disaster. For example, rapid communication can allow for organizations such as the United Nations and World Health Organization (WHO) to coordinate efforts in real time. Mobile technologies such as cell phones and social media allow for reliable communication with the public both before, during, and after a disaster. There is also a recent rise in the use of social media as an effective platform to expedite information flow across the victims, emergency responders, volunteers, and other disaster risk management stakeholders.

6.1. Hierarchy Subdimension 1: Global Disaster Management

With the lack of an international governing board, global disaster management (GDM) is focused on policies, relief, and plans to be adopted to enhance transboundary collaboration. Organizations such as the U.N. Development Programme (2015) and the U.N. Office for Disaster Risk Reduction (2017) are shaping GDM policies. By promoting the integration of disaster risk reduction and overall global resilience, a broad form of global governance can be achieved. For example, disaster management policies from the Sendai and Hyogo Frameworks have been adopted by the United Nations and other international organizations. There are three characteristics that influence governance: stakeholder involvement, cooperation and collaboration, and flexibility (Gall, Cutter, & Nguyen, 2014). These characteristics exist on the global scale and thereby become interwoven drivers for all governance levels.

The most complex policy coordination issues exist at the global level due to aspects of culture, global dynamics, and location. It is important to emphasize the importance of horizontally overlapping collaboration at the global level. Due to the importance of GDM, the flexibility and coordination of both governing and public–private partnerships is key to better disaster management (Djalante, Holley, & Thomalla, 2011). To simplify the complexities, global organizations such as the United Nations, WHO, and the International Federation of Red Cross (IFRC) establish broad policies to address both national and regional-specific needs. For example, the IFRC Strategy 2020 includes other national societies to develop a responsive framework to changing circumstances (International Federation of Red Cross and Red Crescent Societies, 2010). This plan is a combination of previous policies and strategies by the IFRC and other partnerships to develop better practices for improving GDM.

GDM, through agencies outside of a government setting, is able to offer aid and support without the constant challenges found in a political landscape. Aside from policy suggestions and broad outlines for disaster management, relief is managed at the global level through worldwide response agencies. The WHO is one such organization that prioritizes relief in order to build a better future for everyone around the world. Like the United Nations, WHO staff work side by side with governments and other public–private partners to ensure the highest attainable level of public health (World Health Organization, 2016). The relief offered enables resilience governance to all those in need of medical and health assistance. Working on every continent and almost every country, these resources are able to diminish the operational complexities found at the global level while inducing transboundary collaboration.

6.2. Hierarchy Subdimension 2: National Disaster Management

The national level of disaster management forms a combination of the actionable policy influence and organizational relief. The role of governance becomes more clearly defined as a major aim for national management to create a more country-specific scope for disaster risk reduction. In the United States, for example, a committee formed by the national academies published a 200+ page report emphasizing the need for a nationwide resilience imperative (Committee on Increasing National Resilience to Hazards and Disasters, 2012). The report highlights the following needs: public awareness, establishing the economic value of resilience, resilience metrics, government policies, capacity assessments, and effective communication across national and regional stakeholders. With each country having unique governing structures, the National Disaster Management Office (NDMO) or some form of governmental disaster management aligns itself accordingly. The countries of Tanzania and Columbia, for instance, have their NDMO within the prime minister's office (U.N. Development Programme, 2014). This approach enables both countries to provide overarching support throughout these countries.

In nations like the United States, a combination of multiple organizations is the most suitable system for handling the various types of disasters. The Federal Emergency Management Agency (FEMA) is the leading disaster response agency that collaborates extensively with public–private partnerships and contracting agreements in order to aid in emergency management (Federal Emergency Management Agency, 2018). This structure of management is a combination of policy and aid because FEMA is part of the Department of Homeland Security (DHS), a cabinet department of the federal government that works to prepare and respond to disasters. As the organizational rigidity and complexities diminish at the national level in comparison to the entire world, there is better movement horizontally across the government and within policy making.

As an example of both horizontal and vertical integration across hierarchical levels, FEMA publishes strategic frameworks for disaster management within regional and local communities. Four major publications of interest are the National Incident Management System, National Preparedness Goal, National Response Framework, and National Recovery Framework (Federal Emergency Management Agency, 2018). Each publication identifies risks, adaptable coordinating structures, key stakeholders, and strategies to minimize impact depending on the time period for a given disaster. These policies act as rubrics for how to develop a resilient community. The horizontal integration occurs within policy making that is agreed upon by various organizations at the national level while vertical interaction takes place within stakeholder incorporation. At the country level, many organizations such as FEMA have begun to collaborate by sharing resources and by actively communicating in order to create a flexible hierarchical structure that can withstand the increasing number of disasters.

The national policies support both the strengthening of related disaster management organizations and also reduction of key weaknesses. A gradual shift from fragmenting government agencies to external partnerships arises so that the best possible aid may be given to any affected area. As disasters occur, lessons may be learned to improve preparedness and build more effective future strategies.

6.3. Hierarchy Subdimension 3: Regional Disaster Management

While global and national management are responsible for global disaster preparedness and response, little progress will be accomplished without regional coordination. Effective planning through this lens brings focus to regions such as states or provinces. Countries with large land areas such as the United States and Canada are in a unique position. Because types of disaster events may vary by regions and geographic conditions, disaster management plans must address region-specific needs.

In the United States, there are specific responsibilities for the state governments to follow that are defined for specific locations: enact emergency management policy, enforce national policies and laws, assist local governments, coordinate with other state-level agencies, and allocate necessary resources for disaster management (National Governors Association, 2016). Each state also maintains a state office of emergency management that is responsible for developing and maintaining state disaster operations. The regional level acts as the liaison between local communities and the national government. This broad form of responsibilities acts to influence each region or state to better define what resources are necessary and what policies should be established. For example, in a state like Florida, more specific responsibilities are centered around building the statewide resilience to hurricanes or pandemics such as the Zika virus (Florida Division of Emergency Management, 2001). A state in northern United States, e.g., Massachusetts, will develop resilience plans for blizzards and other region-specific disasters (Massachusetts Emergency Management Agency, 2016).

Regional disaster management underscores the locality of disaster resilience. Moreover, governance at the state level works to bridge the vertical gap between the national and community level of disaster risk reduction. For example, in 2016–2017 the northeast United States was hit by widespread drought so severe that it was compared to historic multiyear drought in the 1960s (U.S. Geological Survey, 1991). Many local industries were affected, prompting several federal and state agencies, including the National Oceanic and Atmospheric Administration (NOAA) and the National Integrated Drought Information System, to initiate dialogues among affected states to identify gaps in drought preparedness and strengthen regional drought resilience.

6.4. Hierarchy Subdimension 4: Local Disaster Management

When focusing on a local-level disaster and emergency management, very specific community-based action relies upon established groups such as police departments, fire departments, and medical centers (Waugh & Streib, 2006). Given the nature of individuals responding to and absorbing the impact of a disaster, an emphasis on community organization must be stressed (Sutton, 2006). While preparation is crucial for disaster management, responses during a disaster and immediately afterward directly impact the community, thus leaders must emerge to avoid chaos. The strategy to reinforce community resilience is reliant on local preparedness that is coordinated with regional and national plans.

Community planning for disaster management is often overlooked yet it is vital to saving lives and preventing further damage (Burnham, 2008). There are three major components that are important to mention: organization of local response, implementation and mitigation plan, and community analysis. Local response must be organized prior to an event in order to maximize effectiveness. It is generally under the jurisdiction of the local government or disaster committee to establish a functioning hierarchal structure. The implementation and mitigation plan is the backbone for the organizational structure. This component contains responsibilities, timelines, physical resources, and personnel coordination necessary for being disaster resilient. The foundation of the hierarchical dimension for disaster resilience is local disaster management. It is imperative for localities, region, nations, and the international community to collaborate with one another to develop policy, relief strategies, and manage any gaps along the disaster management chain.

7. RESILIENCE DIMENSION 6: TIME

As the final dimension in WEIGHT, time acts as a resource and as a factor that applies across all dimensions of resilience. All dimensions are dependent on the passage of time and can only accept its effects and formulate resilient strategies based around timing. A common theme in many of the differing elements has been the stages of the disaster timeline. With every disastrous event, there are distinct phases before, during, and after that are relevant to preparation and recovery. The timeline of a disaster fits along a framework defined as the loss triangle where the functionality of a given system is plotted over time. This framework better aligns and creates a more accurate decision-making process for designing resilient strategies. The timing and occurrence of disaster can determine the relative magnitude of destruction and recovery efforts required. At the onset of a disaster, the rapidity and duration of an event will categorize the decision-making process formulated through the loss triangle framework. The previously discussed resilience dimensions, in one form or another, are influenced by time; as such there is an interconnectivity among the dimensions that must be addressed.

7.1. Time Subdimension 1: Disaster Stages

Resilience covers a wide-ranging spectrum of time that can be dissected into three distinct stages: prior to the event, during the event, and post-event. Resilience is defined as the ability of a system to resist, absorb, accommodate, and recover. The final stage of a disaster-related event is split into the recovery and response portion of the resilience definition. By understanding the fundamental relationships associated with the different stages of resilience, better planning tools can be designed and implemented.

Colten, Kates, and Laska (2008) also proposed a consistent temporal decomposition of resilience elements (anticipating multihazard threats, responding to hazard events, recovering from disasters, and reducing vulnerability to hazard threats) and specifically applied it to the case of Hurricane Katrina.

Prior to the onset of a hazardous event, the community that will be affected must establish a level of preparedness; otherwise, the event may cause irreparable damages. In the case of Gujarat, India, an earthquake with the strength of 7.7 on the Richter scale occurred on January 26, 2001, killing nearly 20,000 people and injuring over 170,000 (Rastogi et al., 2001). This catastrophic event has been studied extensively by the global community to develop risk mitigation strategies for similar events. In the wake of similar disasters, disaster preparedness and the allocation of aid must be prioritized to optimize the effectiveness of scarce resources (Bremer, 2003). While the local community must establish prior management strategies, the global community must continue to monitor and aid those in need.

The second stage of resilience occurs in the chaotic moments during a disaster. By the time a hazardous event is underway, the resilience of a community can be categorized into the action of absorption and reaction of response. Some of the impacts and effects to the system will be lost, but critical functions may remain. The capacity to absorb a disastrous event depends on how adaptable a community may be depending on their initial preparations (Walshe, 2014). After preparations have been made, it is up to the community to absorb disastrous events and proceed to function. Response works as the reaction that immediately follows the absorption period. During this period of disaster resilience, immediate threats of the event and the establishment of humanitarian efforts will be coordinated. Following preparation and absorption, the ability to respond in the face of a chaotic event will define the survival of a system.

Drabek (1989) defines the stage of recovery to be a long-term impact assessment of the disaster onto individuals and the community. This stage of disaster resilience should not be seen as the end of disaster resilience but a continuum extending until the next event occurs. Recovery encompasses all actions of the system to return to normalcy, the beginning preparations for any future incidents, and a constant iteration of improvement.

7.2. Time Subdimension 2: Resilience Timeline

In the face of catastrophic events, a succession of management must assume control and vital systems must be evaluated for functionality or else a fallout larger than anticipated may occur. Fig. 2 illustrates the framework of disaster resilience based on time and system functionality dimensions. This framework has been used to model single-event disasters and then applied over multievents to better understand the resilience for various types of physical and organization-based systems (Bruneau et al., 2003). The time required and the rapidity to return the system to pre-event functionality are based on the organization and actions orchestrated by disaster managers. The robustness of a system is the ability to withstand misfortune without significant degradation (Tierney & Bruneau 2007). By minimizing the loss triangle, the impact of the time dimensionality may be diminished. Time is a vital dimension for resilience.

According to the loss triangle framework, returning a system back to its preparatory phase functionality before a disaster is directly related to the decision-making process before and during an event (Withanaarachchi & Setunge, 2014). While it is difficult to create a practical model for the decision-making process during disasters, a framework may be generated in order to best handle an event. The loss triangle can be minimized with proper planning in the decision-making process. For example, Golden-Hour is a term used in trauma care where the initial 60 minutes of care are a large determinant of a successful outcome (Lerner & Moscati, 2001). While it is mainly reserved for emergency management, the concept is similar in disaster-related situations. The more drawn out a response is, the longer it will take to recover and return to the level of functionality prior to the event.

Many communities use past disaster experiences to more effectively prepare for future disasters. For example, the experience of the 2005 Hurricane Katrina enabled a much improved response to the 2008 Hurricane Gustav. With proper preparation, decisions were made to place states on hurricane watch, emergency shelters were prepared, and nearly 2 million residents evacuated Louisiana (The Economist, 2008). While the storm diminished after making landfall, it ranked as a category 2 storm (able to uproot homes and cause severe flooding). It can be inferred

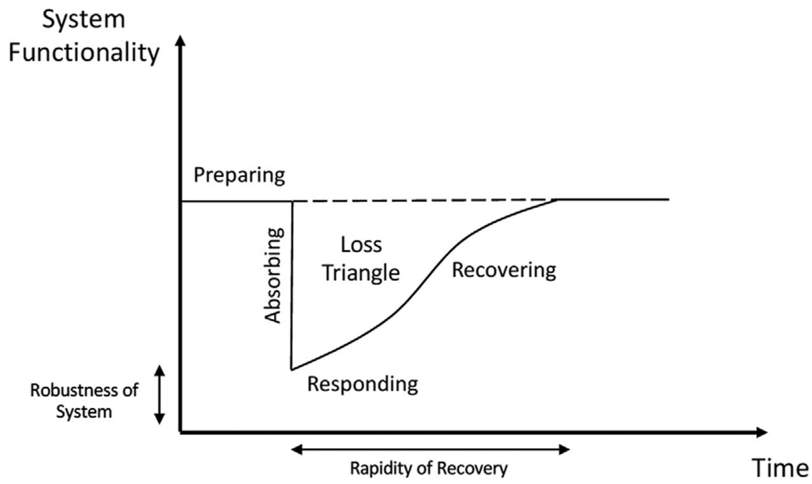

Fig. 2. Resilience loss triangle.

that without proper decision making and planning, the losses would have been more significant.

7.3. Time Subdimension 3: Frequency and Duration

The factors surrounding the influence of time from the decision-making process to the stages of disaster timeline contain a common theme—occurrence. The incidence of disasters can be as broad as the seasonality and time of year, or even as specific as the time of day. Whether or not an event takes place in the summer or in the winter will lead to vast differences of preparations and reactions within the stages of the disaster timeline. For this reason, discussing the occurrence of disasters and understanding temporal variations are essential to administering effective resilience.

Naumova (2006) states that seasonality is a systematic periodic occurrence of events over the course of a year. We lack adequate methods and sufficient analytical tools to comprehensively explain timing associated with some types of natural disasters, such as earthquakes (Geller, 1997). However, patterns of occurrence emerge in relation to other types of natural disasters. For example, predictive modeling of riverine flood risk (Milly, Wetherald, Dunne, & Delworth, 2002) and coastal inundation risk (Poulter & Halpin, 2008) has improved dramatically in recent years, allowing for more effective understanding about time and duration of disaster events.

The seasonality of some disaster events may be cyclical; as seasons progress, there is a need for strategies to prevent and control emerging diseases and events. Patterns of disease outbreaks can be linked to changing seasons. There is a strong relationship between climate and human health; certain climatological conditions are favorable to pathogen growth and transmission (Cooke & Hill, 2001). As seasons shift, some strategies may be implemented to prevent or minimize disease outbreak, e.g., flu during transition from summer to fall. By developing the awareness on changing seasons and the recurring patterns of outbreaks, the efficacy of resilience against epidemics and disasters may be better addressed.

A more specific application of the dimension of time can be deconstructed further to the occurrence relative to the time of day. Less variable and cyclical than the change of seasons, the time of day for an event to occur can also have adverse effects. For instance, when a natural or man-made event occurs during rush hours, emergency response will be delayed. The consequences of this delay will contribute to adverse effects. This impact is seen daily in emergency response incidents. As mentioned previously, the Golden Hour right after an incident is the most critical period of time that directly correlates to determining whether or not there is a high chance for a successful outcome.

While the timing of disaster events is widely studied, the duration of these events is primarily studied in the context of disasters that occur over an extended period of time. For example, the field of hydroclimatology involves modeling the duration of flooding behaviors (Poff, 2002). There is growing interest in also studying the duration of recovery within the context of resilience modeling. For example, as the electric grid recovery following Hurricane Maria in Puerto Rico extended over several months, there is impetus for building electricity systems that can more quickly recover (Bueno, 2017).

While time is identified here as one of the dimensions of resilience, it is also a common factor that cuts across all the other previous dimensions. Managing the adverse effects of disasters to workforce, economy, infrastructure, geography, and various organizational hierarchies whether separately or in combinations will directly impact the disaster recovery timeline.

8. SUMMARY AND AREAS FOR FUTURE RESEARCH

The concept of disaster resilience has received significant attention in recent years. The number of research and policy-related publications that study resilience has grown dramatically, given the increasing recognition of its value in mitigating the consequences of disasters. A case in point, a highly cited study by the Multihazard Mitigation Council (2005) has estimated the significant benefits that can be attributed to mitigation investments—"for every $1 the public sector spent on mitigation, society saves $4." In this article, we underscore not only the importance of disaster resilience but also the plurality of its dimensions.

Six primary dimensions have been explored in this article, namely: *workforce/population*, *economy*, *infrastructure*, *geography*, *hierarchy*, and *time*. Collectively, these dimensions form the acronym WEIGHT, which not only serves as a potentially effective mnemonic but also emphasizes the important "weight" (i.e., contribution) of each dimension of resilience. The "workforce/population" dimension is concerned with maintaining labor availability as well as minimizing the psychological effects of disasters on the general population, which could directly and indirectly disrupt workforce productivity. The "economy" dimension encompasses the various sectors (e.g., agriculture, manufacturing, service, trade, and government) that directly support regional livelihoods and are also essential in expediting recovery. The "infrastructure" dimension encompasses physical infrastructure systems, key resources, and services that are arguably important in the deployment of critical functions (e.g., transportation, information, and medical care), which are necessary in managing the consequences of disasters. The "geography" dimension is concerned with the spatial, environmental, and ecological features of the affected region as well as the distribution of populations and resources. The "hierarchy" dimension captures the decision-making structures, flow of information and resources, and various types of interfaces across global, regional, national, and local organizations that are involved in disaster risk management. Finally, the "time" dimension represents the various stages of disasters from preparedness to recovery and also recognizes various temporal factors including disaster frequency and seasonality, as well as duration (i.e., slow vs. fast onset).

This article has illustrated the interconnectedness of the WEIGHT dimensions. For example, the "time" dimension permeates all other dimensions and is a vital element in mathematical notions of resilience. The dimension of "geography" is also commonly studied in risk management applications, but there is need for further research to understand how geographic resilience can be modeled using noneconomic dimensions. The dimension of "economy" is well-studied in both engineering and finance disciplines as it involves measurable indices of performance that can be combined with large quantities of data and analytic methods. As "infrastructure" supports both safety and economic activities over time, it is a critical element of disaster risk management research. In contrast, the "workforce" dimension is less frequently studied in a disaster risk management context due to insufficient data and understanding of workforce dynamics. However, there is no precedent for existing resilience regimes to concurrently model all of the dimensions studied in this article.

As no single dimension is sufficient for a comprehensive risk management regime, interdependent WEIGHT dimensions motivate new approaches for data analytics of resilience-related knowledge bases. There is opportunity to adapt single-metric approaches, such as a resilience triangle, to include a multidimensional perspective of performance. Given the multiobjective nature of this pursuit, there is also need to include these multidimensional resilience measurements in decision support for allocating resources towards system investments. Tools such as multiperspective analysis using multicriteria decision analysis or multiobjective optimization models provide the ability to concurrently analyze multiple dimensions that often involve both qualitative and quantitative information.

Fig. 3 shows a simple visualization tool using radar charts and Likert scales to evaluate the efficacy of two hypothetical risk management

Fig. 3. Multicriteria decision analysis for evaluating the efficacy of two hypothetical risk management strategies.

strategies in minimizing the impact of disasters on the six WEIGHT resilience dimensions. However, care should be taken to acknowledge interdependencies among the WEIGHT dimensions. If decision-making methods involve the weighting or preference ranking of parameters, the analyst should ensure that independent criteria are used.

Even with models that include all of the studied dimensions in a resilience assessment, there is also need to consider system uncertainties. For example, some dimensions (such as economics) are relatively well understood compared to other dimensions (such as workforce). There is also opportunity to leverage expertise on WEIGHT dimensions for building simulation models that can recognize these types of uncertainties and uncertain future conditions (scenarios) within decision-making models. As system-related data become more readily available to researchers, there is opportunity for data-analytic resilience models to be adaptive to changing conditions and new knowledge sources. Using these innovations, there is opportunity for new technologies and the growing field of artificial intelligence to further advance the management of system resilience. In the longer term, these types of modeling advances can help guide investments toward initiatives that are able to improve resilience across multiple dimensions. These models can ease and possibly even promote stakeholder collaboration for identifying mutually beneficial system improvements. Future scientific advances that leverage the WEIGHT dimensions may then allow for more effective trade-off analysis among these dimensions.

In conclusion, this article presents an integrated view of disaster resilience by identifying the WEIGHT dimensions. While the ideas presented in this article aim to provide a holistic picture of resilience, the authors also envision that the WEIGHT framework could spark subsequent discussions to emphasize the need for a more cohesive framework in utilizing relevant models, approaches, and technologies. Having explored the individual WEIGHT dimensions that influence and are affected by disaster management, the subject of disaster resilience must be viewed from a multidisciplinary perspective. Each dimension on its own has underlying critical challenges that must not be addressed independently, but rather synergistically through effective coordination of disparate efforts from scientific communities, policy-making agencies, affected communities, and other relevant stakeholders. Hence, an unwavering pursuit of relevant research, as well as development of effective strategies and technologies, to enhance disaster resilience is urgently needed to combat the rising frequency and intensity of disasters (Bueno, 2017).

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