OVERVIEW OF A FRAMEWORK TO ENGINEER INFRASTRUCTURE RESILIENCE THROUGH ASSESSMENT, MANAGEMENT AND GOVERNANCE

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An international infrastructure resilience framework developed collaboratively by the American Society of Civil Engineers (ASCE) Infrastructure Resilience Division (IRD) and the Japan Society of Civil Engineers (JSCE)

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SUMMARY

Infrastructure system resilience prior to or following disruptions due to natural or technological hazards is intimately linked with and supports community resilience. This paper presents a framework, consisting of eight key elements, connecting processes and tools for assessment, management and governance related decisions and the community outcomes. It recognizes infrastructure as interdependent socio-technical systems capable of achieving resilience through optimized flow and provision of services to users that satisfy community-level objectives by reducing social and economic losses while enhancing community wellbeing. In this paper an overview of the framework is provided, drawing upon more detailed descriptions presented in Davis et al. (2021a, 2021b).

INTRODUCTION

An international framework is presented that supports the engineering of resilient infrastructure systems, provides opportunities for improved efficiency through standards, improves the global understanding of what makes infrastructure systems resilient, and focuses institutions on common research, development, and implementation goals. The Japan Society of Civil Engineers and American Society of Civil Engineers Infrastructure Resilience Division (IRD) led the development of this framework to enable others to create resilient infrastructure systems that in turn supports community resilience. The framework identifies processes, tools and outcomes for system assessment, management and governance useful for analyzing and designing systems prior to or following actual disruptions. Its structure does not dictate any specific computational models and allows numerous other processes to be utilized and interact.

An infrastructure resilience framework covering all infrastructure systems and hazards, incorporating planning, mitigation, response, recovery, and rebuild for the complete set of elements needed to create resilient networks has not previously been fully conceptualized. This paper proposes such a framework that focuses on research, development and implementation of infrastructure resilience with an understanding of its role in overall community resilience through optimized flow and provision of services to users. It has an emphasis on infrastructure systems and is intended to be applicable to all possible hazards. The framework incorporates the important concept of operability and its relation to system functionality (Davis, 2021). It further stresses the continuity of infrastructure system services, through the network or by alternative means, as a principal interface with social and economic resilience, and the need to derive target infrastructure system performance objectives incorporating community expectations. The critical inter-relations between assessing infrastructure resilience and the need to manage and govern the systems with an understanding of the economics or financing of resilience as well as potential social and economic losses, all in support of community resilience, are brought together within this framework. This paper overviews the framework drawing upon more detail descriptions of Davis et al. (2021a; 2021b).

INFRASTRUCTURE RESILIENCE FRAMEWORK

Figure 1 diagrams the infrastructure resilience framework identifying processes, tools and outcomes for system assessment, management and governance useful for analyzing and designing systems prior to or following actual disruptions. For this framework, infrastructure is defined as the physical and organizational structures and facilities needed for the operation of a society or enterprise (Lexico.com, 2020), including the physical components and human agency interaction (i.e., they are socio-technical systems).

Figure 1 is broken into two sections vertically through the middle. The left portion is designated as 'System Assessment' and the right portion as 'Management and Governance'. These sections are inter-related as shown by the arrows in Figure 1 linking elements on either side of the line. The 'System Assessment' portion identifies the framework processes for evaluating existing or proposed systems. The 'Management and Governance' portion identifies the processes and tools needed for proper resilience management and governance to provide the outcomes to ensure resilient infrastructure systems. Infrastructure resilience management and governance utilize system assessments and incorporate other tools to engineer, manage, and govern resilient systems that properly support the resilience of the communities they serve.

Figure 1 shows elements numbered 1 to 8 making up the infrastructure resilience framework processes. Each of these elements, as well as their connection to other elements, is described in subsections below. Elements 1 to 6 collectively describe the system assessment. Elements 7 and 8 are important to managing and governing infrastructure resilience. Elements 1 to 4 represent the core infrastructure system resilience. Elements 4 to 6 represent the core community resilience elements. Element 4 is a key crossover element linking infrastructure systems and community resilience as further explained in the section describing this element. As shown in Figure 1 by the direction of the process arrows, proper assessment of these elements results in social and economic outcomes for the infrastructure systems in terms of policy, economics of resilience, and communities in relation to social and economic losses.

Tools useful for managing infrastructure resilience. These include the data collection (Ayyub, 2001; Ayyub, 2002), and understanding its range of uncertainty, in support of all resilience elements. Data collection and sharing improves adaptive capacity, decision-making, and situational awareness. Data processing and utilization provides means for communicating need for, or results of, assessment, management, or governance actions and where policy measures may improve infrastructure resilience.

The Figure 1 processes are applicable for a hypothetical event or scenario, or an actual event. In both cases opportunities exist for learning and making improvements based on the results. The framework is useful for identifying effective resilience investment strategies that community leaders and system owners can carry out over time.

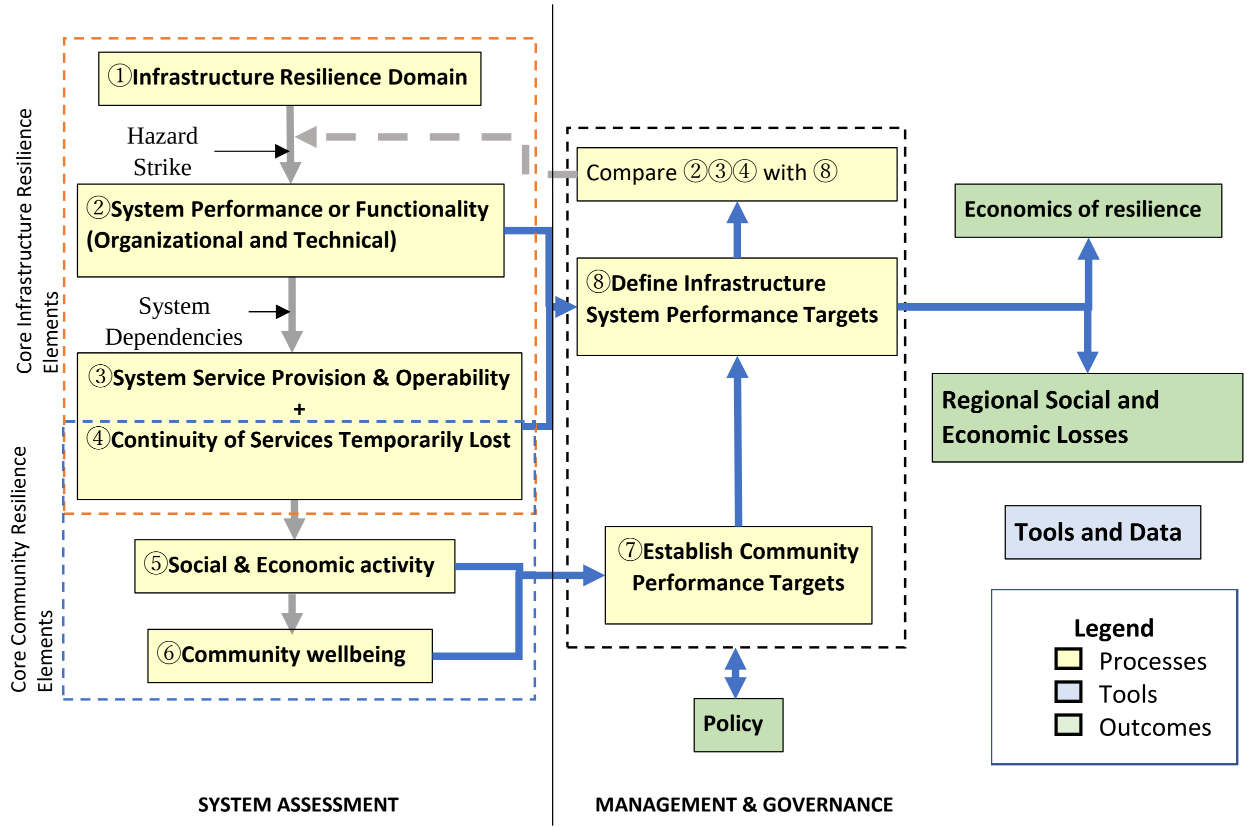

Figure 1. Infrastructure Resilience Framework. Gray arrows show flow for system assessment processes. Blue arrows show flow for management and governance processes. The infrastructure resilience elements are identified by circled numbers.

Figure 1 indicates infrastructure resilience is achieved through the interlinking of all process elements, tools, and outcomes, while system enhancement through any single element can make important improvements. The framework can be applied in part or in whole using conceptual or advanced computational models. It incorporates the targeted infrastructure system resilience level for the communities being served. As a result, this framework can be greatly enhanced when utilized in conjunction with broader community level frameworks which can properly capture Elements 5 and 6, some of which are summarized in Davis et al. (2021a).

Element 1: Infrastructure Resilience Domain

Figure 2 identifies the infrastructure resilience domain of Element 1 and its dimensions. The IRD defined this infrastructure resilience domain (Davis et al. 2018) to be structured around: Infrastructure Systems (shown on vertical axis), Hazards (shown on horizontal axis to right), and the Adverse Event Cycle (shown on the horizontal axis pointing out of the plane of paper). These three primary dimensions make up a matrix of resilience cubes having a System-Hazard-Event Cycle locus. Figure 2 explicitly outlines the cube for Communication System-Flood-Preparation. Each cube addresses contextual dimensions needed to achieve infrastructure resilience for each system, all hazards of importance, and every step in the event cycle. Davis et al. (2018) explains the infrastructure resilience domain depicted in Figure 2 in more detail.

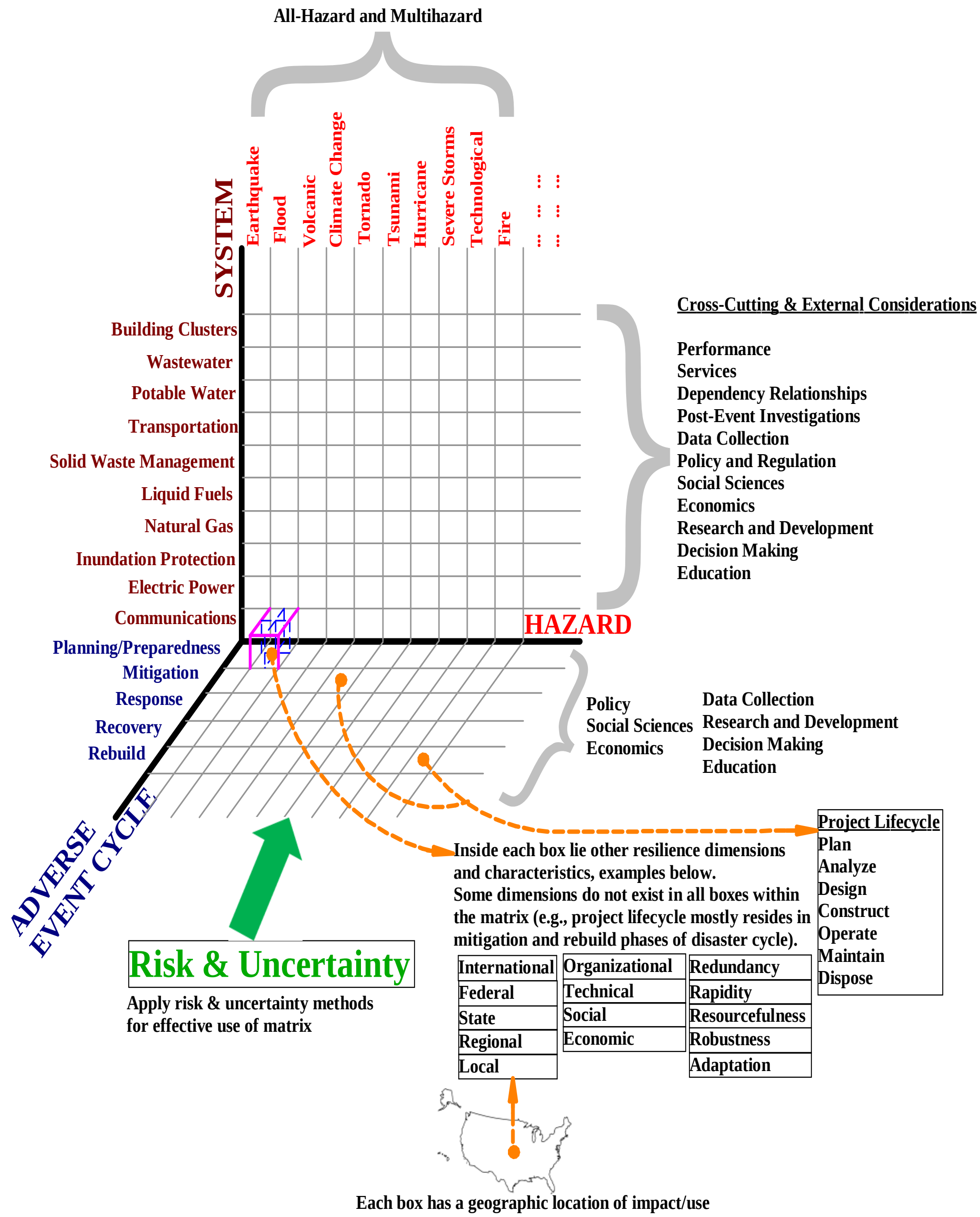

Figure 2. ASCE infrastructure resilience domain (modified from Davis et al, 2018). The axes label the three primary infrastructure resilience dimensions. The geospatial hierarchy and other resilience dimensions may reside within each cube. Cross-cutting and external aspects are identified on right and above most applicable planes. Risk and uncertainty permeate throughout.

The infrastructure systems in Figure 2 are categorized as lifeline systems and building clusters. The traditional lifeline systems (Duke and Moran, 1975) are itemized on the vertical axis in Figure 2. Building clusters are a set of one or more buildings providing services for common function such as housing, healthcare, retail, etc. Clusters perform as a system but are not necessarily geographically co-located and may be distributed throughout the community (NIST, 2015). All engineering disciplines are needed in support of these systems.

Element 2: Building and Lifeline System Performance or Functionality

Element 2 describes the building and lifeline system performance or functionality. Figure 3 shows the performance of a system over time, which is commonly equated to quality of infrastructure or functionality (Bruneau et al, 2003; Ayyub, 2014; Cimellaro, et al. 2010; Tierney and Bruneau, 2007; Croope and McNeil, 2011). The terms performance and functionality are used interchangeably in this paper. However, the performance measure of a system is the aggregate of the entire set of component performances, their connectivity, and how the organization interacts with and manages them at the component and system levels. The Figure 3 curves capture the technical and organizational dimensions requiring the physical systems and the managing organizations to withstand hazard-related impacts and recover quickly from them. The organizational and managerial aspects are supported by the data and tools, as well as policy and other outcomes from the managerial and governance portion of the framework.

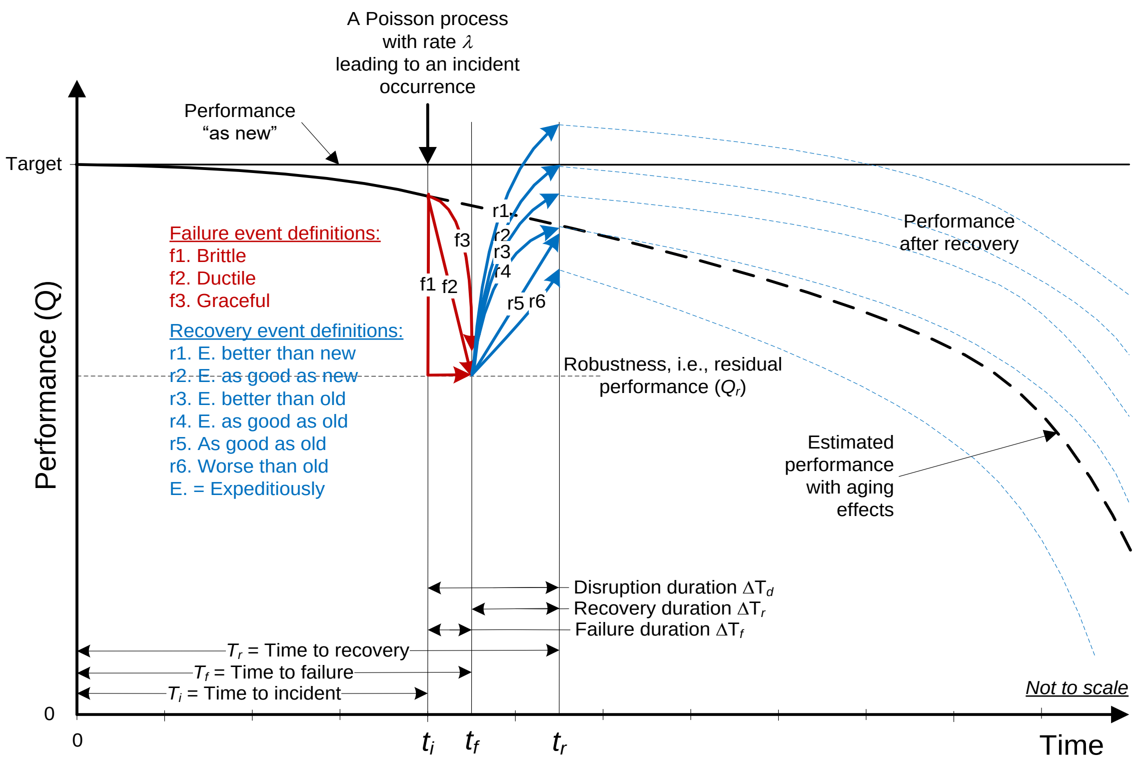

Figure 3. Infrastructure (building or lifeline) system performance over time (Ayyub, 2015)

The Element 1 infrastructure resilience dimensions of system, hazard, and adverse event cycle, shown in Figure 2, link with and are also represented in the Element 2 curve shown in Figure 3. Ayyub (2015) suggests the curves in Figure 3 represent any system performance and provides analytical and computational frameworks. Earlier, Bruneau et al. (2003) used a simpler resilience curve to represent the four R's: *robustness*, the capacity to minimize the initial losses, which is a function of the systems' and its components pre-event condition, and *rapidity*, the time to recover, a function of preparedness and *resourcefulness*, and *redundancy* which are not shown explicitly. The time to recovery following an abrupt performance loss is a result of planning, preparedness, response, recovery, and rebuild capabilities and capacity, and strongly associated with available resources and the emergency and crisis management competencies.

Infrastructure system performance over time may take a multitude of trajectories. As indicated in Figure 3, performance gradually changes over time, for better or worse, and sometimes abruptly. Gradual change may come from chronic stressors such as deterioration or financial constraints, and slow onset hazards like sea level rise or global temperature variation. Abrupt change results in some level of functional loss within the socio-technical system associated with a significant incident or disastrous event such as a hazard strike. The event may be of any size. The rate and amount of functional loss is related to the level of organizational and physical damage as a function of its vulnerability, fragility, and hazard exposure. The system failure may be brittle, ductile, or graceful. Recovery may be to a performance level identified in Figure 3. In extreme cases recovery may include complete abandonment and rebuild. The infrastructure system functionality is restored once all repairs and construction associated with the event that caused the initial or any cascading losses are completed (Bruneau et al., 2003; Cimellaro et al., 2010; Davis, 2021).

The performance of each infrastructure system depends upon other systems' performances. Loss of performance may result from direct system impacts as a result of a hazard strike, or from loss of dependent services even if the system was not damaged (e.g., loss of electric power may impact water system performance due to inability to pump).

Element 2 also considers the potential for secondary losses resulting from cascading effects of the primary losses inflicted by an initial hazard strike. For example, if an earthquake or flood were to cause a dam to break, then the massive flood wave from the reservoir causes severe secondary losses in the inundation zone; or a radiation release from a nuclear power plant contaminating the environment in the region. Illness from an epidemic or pandemic reduces human resources resulting in functionality loss while also effecting the regional economy. The financial impacts can cause long-lasting secondary functionality losses; this indicates impacts from natural hazards affecting system resilience may not always be related to physical damage.

Element 3: System Service Provision and Operability

Element 3 identifies the system service provision and operability. Every infrastructure system provides services to the community. For hospital and health care building clusters, the infrastructure services include space, heating, cooling, electricity, etc. allowing health care social institutions to provide medical services. For water systems, services are related to water usage. Similar for other infrastructure systems. Each system's services are definable in terms of the basic service categories essential for supporting community resilience. The ability to continue providing these service categories, or rapidly restore them if lost after a hazard strike, is related to the Element 2 system performance or functionality and dependent upon the technical and organizational dimensions.

Post-event functionality is measured relative to pre-event normal functionality, which is assumed to be 100% (a system or building may have less than 100% functionality before an event if it is not working completely proper). As shown in Figure 3, post-event functionality loss results in a measure less than 100% until completely restored to pre-event or another acceptable level. In this context, as an example, loss of power to a hospital is a reduction in functionality below 100%, even if the power is temporarily supplied through emergency generation; the hospital building system is not 100% functional until power is restored.

The system has 100% operability when all the basic services are met, which for a highly resilient system occurs prior to returning to 100% functionality. Using the same example for power loss to a hospital, the building system is 100% operable when using the generator to provide power if it can achieve the provision of all basic services to users prior to restoring the electric power service. Similar to functionality, post event operability may be permanently less than 100%.

Figure 4 presents a more complicated example of the Los Angeles Water System following the 1994 Northridge Earthquake. The water system basic service categories, treated as performance dimensions per Figure 3, are defined as (Davis, 2014):

<u>Water Delivery</u>: This service is fully achieved when the system can distribute water to customers, but the water delivered may not meet quality standards (requires public notification), pre-event volumes (requires water rationing), or fire flow requirements (impacting firefighting capabilities).

<u>Water Quality</u>: This service is fully achieved when water quality at customer connections meets pre-event standards. Potable water meets health standards (public notices for water use are removed), including minimum pressure requirements to ensure contaminants do not leach into the system.

<u>Water Quantity</u>: This service is fully achieved when water flow to customers meets pre-event volumes (water rationing removed).

<u>Fire Protection</u>: This service is fully achieved when the system can provide pressure and flow of a suitable magnitude and duration to fight fires.

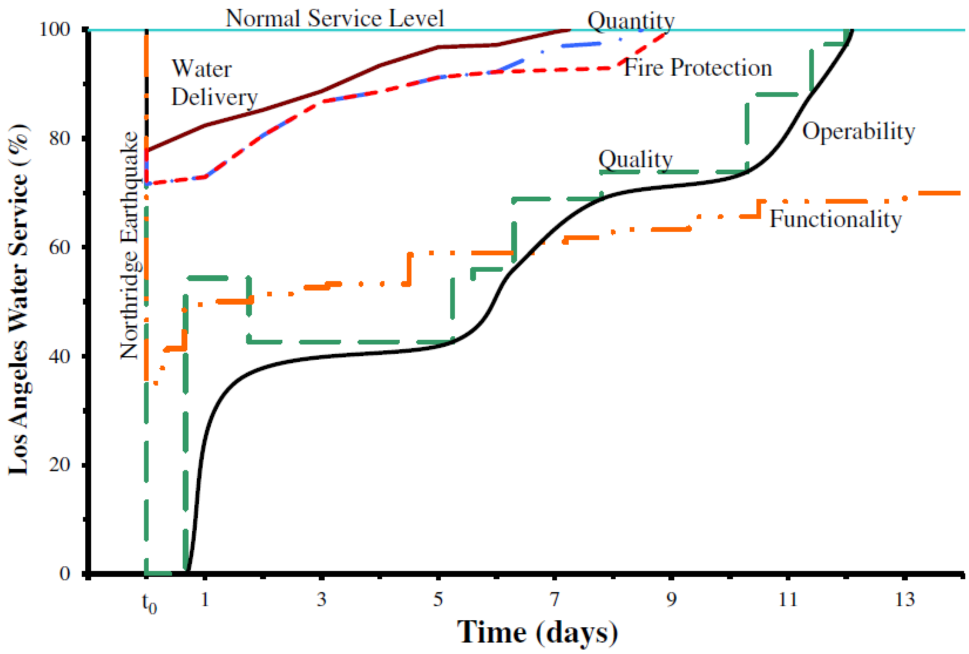

Figure 4. Los Angeles water system service restorations following the 1994 Northridge Earthquake. Operability is not a service; it is a milestone delineating collective restoration of water delivery, quality, quantity, and fire protection services (Davis, 2014).

Figure 4 plots the service category and functionality losses and restorations. Functionality is calculated (Davis, 2013) by directly accounting for customer service restorations resulting from damage repairs while incorporating system interdependencies. Operability is plotted as the fulfillment of all the basic service categories. As seen in Figure 4, full operability was returned in 12 days after the earthquake, but full functionality was not restored for another 6 years (Davis, 2014). At 12 days after the event all customers were able to resume normal use of water services even though the water system was not functioning as it did prior to the event. Davis (2014, 2021) initially identified the inter-relation between functionality and operability and expanded it with definitions and proposed basic service categories for all infrastructure systems.

Element 4: Continuity of Services

Element 4 describes the continuity of temporarily lost services. Understanding the lost services is supported by Element 3. Resilient communities have the capacity to manage without normal infrastructure services during the time they are lost. This requires the social units within communities to understand and integrate the infrastructure systems technical and organizational resilience into their planning. Preventing loss of services from significant hazard strikes for large complex infrastructure systems is unlikely. Resilient infrastructure systems can accommodate service losses and restore them to the community when they are needed relative to the size and likelihood of events and uncertainty of system performance and recovery. This requires the infrastructure systems and their operating organizations to understand and integrate the social and economic resilience of communities into their planning (i.e., community needs, expectations, and adaptability to temporary service modifications). Continuity of lost services can be achieved by using alternatives, substitution, maintaining stockpiles, curtailing or going without, and other means (Rose, 2016). Planning for continuity of lost services should be accomplished collaboratively between the community and infrastructure system operators in coordination with government and non-government organizations who can provide aid until all services are returned. Continuity of services may be achieved through system modifications or independent of the infrastructure systems (bottled water, generators, portable toilets, etc.). Rose (2009; 2016) describes business strategies. When the potential loss of services from the infrastructure systems are adequately planned for by the community, Element 4 is the key cross-over link between infrastructure system and community resilience filling any service gaps to ensure needs are met.

Element 5: Social and Economic Activity

Element 5 describes community social and economic activity. As related to infrastructure resilience, this element pertains to those social and economic aspects supported directly and indirectly by the infrastructure systems. Without infrastructure system services social and economic functionality is, in general, diminished. This element is supported by Elements 3 and 4. The increased ability to maintain services and rapidly restore any lost services from Element 3, and provision of continuity during service losses in Element 4, improve the resilience of social and economic systems. Additionally, the planning, preparedness, mitigation, emergency response, recovery, and rebuild capabilities of social and economic institutions along with financial mechanisms (insurance, loans, public assistance) is essential to assessing community resilience. Understanding Element 5 is vital to establishing community performance targets in Element 7.

Element 6: Community

Element 6 describes the community, wellbeing, livability, equity, etc. Community wellbeing is the combination of social and environmental conditions (see Davis et al., 2021a) essential for individuals and their communities to flourish and fulfill their potential (modified from Wiseman and Brasher, 2008); this includes providing infrastructure system services and social institutions.

Element 6 focuses on understanding the communities' environment, economic, health, equity, cultural, security, education, and political components contributions toward maintaining itself and fulfilling the various residents' needs (Kusel and Fortmann, 1991; What Works Wellbeing, 2017). This is supported by Element 5. The amount of infrastructure service losses and their durations can significantly impact a communities' wellbeing and livability. Understanding the local components making up Element 6, community, and its wellbeing is vital to establishing the Element 7 community performance targets.

Element 7: Establish Community Performance Targets

Element 7 establishes community performance targets. Identifying target community performance objectives is essential to determining target infrastructure performance for Element 8. The performance objectives define measurable community resilience indicators in terms of acceptable losses, including casualties, and social and economic function and pre-event community wellbeing. The targets are developed relative to the community's exposure to hazards, their intensity, potential return periods, and consequences, which vary with community capacity.

Element 8: Define Infrastructure System Performance Targets

Element 8 defines infrastructure system performance targets consistent with Element 7. Identifying target performance objectives in terms of lost services and time to restore them is essential to creating resilient infrastructure systems. Without target objectives it is difficult to design resilience into the systems and impossible to predict if the systems can provide the anticipated support for community resilience relative to the hazard exposure. Element 8 is the link to developing outcomes for economics of resilience and social and economic losses. This includes establishing reasonable and affordable performance objectives.

Feedback

As shown in Figure 1, the Elements 2, 3, and 4 system performance results are compared with the Element 8 target infrastructure system performance objectives. If the performance is better than the target objectives, then the system meets the desired resilience. If the performance is less than the target objectives then modifications may be needed and the system reassessed as shown by the dashed arrow in Figure 1. Modifications may include pre-event mitigations to the infrastructure system (e.g., hardening components, adding redundancy, or reducing interdependencies) or improvements to the management and governance structures (e.g., modifying regulations or implementing management processes such as emergency preparedness exercises). The social, economic and community performances from Elements 5 and 6 along with the community performance targets from Element 7 may also need to be re-evaluated but this is not directly shown in Figure 1. The feedback process provides an opportunity to learn and incorporate beneficial actions into institutional policy (Cutter et al., 2008).

OUTCOMES OF THE INFRASTRUCTURE RESILIENCE FRAMEWORK

Policy Outcomes

Policy is a course or principle of actions to create resilient systems adopted at the governmental and regulatory level or within the corporate or system organizational level. This framework provides a platform enabling effective communication for regulating harms, redistributing risk, assigning liabilities, and privatizing responsibilities to meet target losses and recovery times.

Elements 7 and 8 and the compare/feedback process are the key links to supporting policy for improving community resilience through infrastructure systems.

Social and Economic Loss Outcomes

Social and economic losses include all direct and indirect potential impacts to communities resulting from infrastructure system damage and service losses using macro-economic principles. These include, but are not limited to: property and infrastructure, persons, households, and businesses, including business interruption and unemployment; non-economic losses to/from people (casualties, physical or mental health impacts, etc.), key governmental services, social networks and systems including loss of social capital, cultural heritage and artifacts, standard of living, and the environment (pollution, greenhouse gas emissions, loss of environmental capital) (Gilbert et al., 2015; Rose 2004, 2009, 2016; Gilbert and Ayuub, 2016). The infrastructure system contributions toward these losses are to be minimized. The framework enables losses to be propagated through elements and communicated to show how they may be cost-effectively reduced in a single or across multiple infrastructure systems, and the communities they serve.

Economics of Resilience Outcomes

The economics of resilience informs decisions relating to enhancing infrastructure system resilience and addresses the question of how much should be invested at the present and throughout the system's life in order to reduce consequences of failure and resulting losses in a cost-effective manner using principles of micro-economics (Gilbert and Ayyub, 2016). Benefit/cost evaluations and cost effectiveness measures (Gilbert et al. 2015; Gilbert and Ayuub, 2016; Rose, 2016; Multihazard Mitigation Council, 2018; McNeil et al., 2019) are examples of the many tools used to determine resilience actions to undertake. The costs to provide continuity of lost services for Element 4, restore basic services for Element 3, and completely repair/rebuild the damaged socio-technical system for Element 2 after basic services are restored, need to be accounted for. The economics of resilience helps determine which cost-effective strategies are to be taken before a hazard strike and if it is potentially better to not undertake pre-event mitigation measures and instead manage infrastructure damage and associated losses using response and restoration actions or other coping mechanisms.

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