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Abstract

Ever increasing density of population and wealth increases the consequences of natural disasters. The recent natural disasters, the 2012 Hurricane Sandy, the 2011 Tohoku earthquake and tsunami, the 2011 Thailand floods, the 2005 Hurricane Katrina, just to name a few of the most devastating events, point to the increasing vulnerabilities of our society. The consequences of such disasters are not only immediate casualties and damage, and pain and suffering of the population, but also long-lasting changes in how people individually adapt to the post-disaster situation, and how the societies change to cope, recovery, rebuild and grow again. The deep setbacks disasters can cause, and the spring-back of the affected communities point emphatically to the importance of societal resilience for sustainable development of societies. For the purpose of this report *societal resilience* is defined as "the ability (of social entities: individuals, organizations or communities) to prepare and plan for, absorb, recover from and more successfully adapt to adverse events" (The National Academy 2012). The role of the community built infrastructure in societal resilience to natural disasters crystalized in the engineering community during the formulation of the principles of performance-based seismic design. Given the civil infrastructure system (CIS) focus of the STREST project, the link between societal resilience and the CISs of the community affected by a disaster is established first. Then, a time-varying metrics of resilience of a system is adopted in order to represent the pre-event state of the community, the phases of disaster-induced loss accumulation and absorption, followed by the recovery phase and finishing with the post-event adapted state of the community. This system resilience metric is investigated in detail, focusing on the types of metrics relevant for CISs. Then, a novel compositional supply/demand resilience quantification framework is presented. The novelty is separate tracking of the evolution of the supply of services provided by a CIS and the demand for these services by the community throughout the post-event loss accumulation, absorption and recovery phases of the community resilience process. The notion of *Lack of Resilience* is defined as the state when the CIS supply does not satisfy the community demand. The framework is probabilistic, in that the *Lack of Resilience* is a time-dependent random variable. The compositional nature of the framework stems from the bottom up process used to evaluate the instantaneous supply and demand. The process comprises the evaluation of hazard (building on outcomes of Work Package 3), evaluation vulnerability of CIS and community built infrastructure components (building on outcomes of Work Package 4), and evaluation of the operation of the CIS and community integrated system using the CIS operations model. The report concludes by a discussion on how the proposed CIS stress test methodology, ST@STREST, the principal outcome of Work Package 5 of this project, can be integrated into the regulatory framework aimed at evaluating and societal resilience and designing resilient communities in Europe.

Keywords: community resilience, societal resilience, stress tests

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Table of Contents

List of Figures

List of Tables

1 Societal Resilience

Sustainable development of our civilization, nations, economies and societies and communities is imperative. As stated by Brundtland Commission Report (WCED 1987):

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts:

- The concept of **needs**, in particular the essential needs of the world's poor, to which overriding priority should be given; and
- The idea of **limitations** imposed by the state of technology and social organization on the environment's ability to meet present and future needs."

There are many challenges to achieving sustainable development: political, economic, societal, cultural, technological... Nature itself poses challenges through low-intensity but persistent processes, such as climate change, as well as through high-intensity but rare events with extraordinary consequences: natural disasters.

Ever increasing density of population and wealth increases the consequences of natural disasters. The recent natural disasters, the 2012 Hurricane Sandy, the 2011 Tohoku earthquake and tsunami, the 2011 Thailand floods, the 2005 Hurricane Katrina, just to name a few of the most devastating events, point to the increasing vulnerabilities of our society. The consequences of such disasters are not only immediate casualties and damage, and pain and suffering of the population, but also long-lasting changes in how people individually adapt to the post-disaster situation, and how the societies change to cope, recovery, rebuild and grow again. The growing risks posed by natural disasters increase the needs and emphasize the limitations, thus posing and increasing challenge to sustainable development.

The deep setbacks disasters can cause, and the spring-back of the affected communities point emphatically to the importance of societal resilience for sustainable development of societies. Here, we define *societal resilience* as "the ability (of social entities: individuals, organizations or communities) to prepare and plan for, absorb, recover from and more successfully adapt to adverse events" (The National Academy 2012).

Definitions, aspects, dimensions, and attributes of resilience have been rehashed extensively between around the mid 1970's (Holling 1973) and today. The more recent, and thus, more comprehensive, reviews show the diversity of fields (from ecology and psychology to engineering and sociology), areas (from individuals, organizations, communities to the environment), and applications (from individuals' health, organization change management to societal civil protection, risk governance, economy, and policy planning) *resilience* pertains to. Cutter (2016) examines the resilience as fundamental societal mechanism to overcome vulnerability, and extends the scope towards societal equity and fairness. Alexander (2013) examines the origins of the word and the societal aspects it has come to denote. Keck and Sakdapolrak (2013) comprehensively review the many definitions of resilience in general and societal resilience in particular. Meerow et al. (2013) review urban resilience, emphasizing the complexity of the system of systems that is an urban area today and pointing to the socio-technical dimensions of resilience. Thus, in this report we take a systemic view of the community.

Fundamental to these analyses of societal resilience is the distinction between the static and the dynamic nature of resilience. We consider societal or community resilience as a process (after Norris et al. 2007), shown in Fig. 1.1. The time dimension of the resilience process is key. The community is adapted and functions before the adverse event in the presence of low-intensity persistent (small-consequence high-probability) processes that degrade the ability of the community to function. In contrast, an adverse event or set of coincident or cascading events, i.e. a crisis, is a high-consequence low-probability event. The community takes actions to counteract the persistent stressors, engineers the capacities to counteract the effects of a crisis, and plans the post-crisis actions. If the resistance of the community is high, the effects of a crisis are not appreciable. Otherwise, the community is vulnerable, and a temporary dysfunction ensues. Resilient communities recover, over time, and adapt to the post-event conditions, while the vulnerable ones fail to re-establish themselves. The capacities (attributes) of community resilience, robustness, rapidity and resourcefulness, are adopted from Bruneau et al. (2003) and explained in Table 1.1. One of the key aspects of the adaptation of the community to the post-event conditions is the learning from the crisis experience that goes into actions to remake and re-engineer the capacities to counteract the effects of a crisis. In this sense, we consider resilience as a dynamic process.

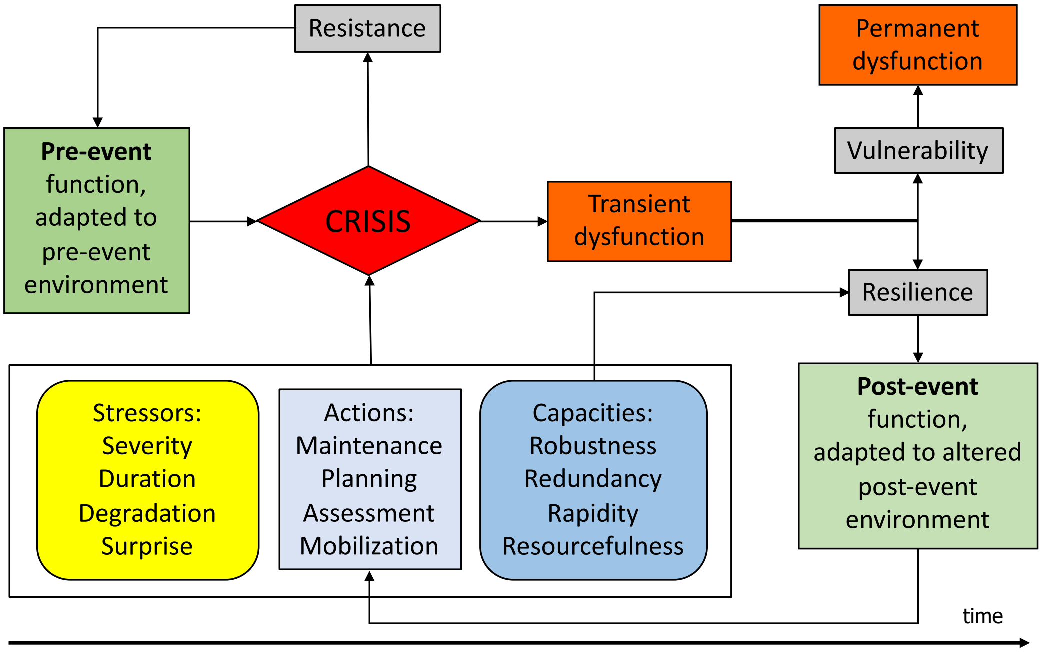


Fig. 1.1 Community resilience as a process (Mieler et al. 2013).

The role of the community built infrastructure in societal resilience to natural disasters crystalized in the engineering community during the formulation of the principles of performance-based seismic design (SEAOC 1995) by the US Earthquake Engineering Research Centers (PEER, MCEER and MAE) as well as the EU-based SYNER-G (e.g. SYNER-G Reference Report 5, Khazai 2013) and OpenQuake projects, and the ongoing US FEMA Hazus project. Given the CIS focus of the STREST project, we will elaborate the link between societal resilience and the CISs of the community affected by a disaster in Chapter 2 of this report.

Table 1.1 Four properties of resilience (adapted from Bruneau et al. 2003)

Property	Description
Robustness	The ability of systems, components, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function
Redundancy	The extent to which systems, components, and other units of analysis exist that are substitutable
Resourcefulness	The capacity to identify problems, establish priorities, and mobilize resources when faced with conditions that threaten to disrupt some system, component, or other unit of analysis
Rapidity	The capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption

Closure of the feedback loop, where post-disaster adaptation informs about building of new community resilience capacities, enable engineering of resilient communities. Quantification of community disaster resilience is fundamental to the iterative engineering process as it provides the design acceptance criterion. Cutter (2016) provides a review of community disaster indicators and frameworks for their evaluation. However, another comprehensive review of resilience, focused on engineered systems, is presented by Hosseini et al. (2016). Ayyub (2014, 2015) goes in the same direction, but focuses on the role of the built infrastructure of communities in their resilience to natural disasters, while Francis and Bekera (2015) drill further down into engineering resilience frameworks and metrics.

In this report we adopt a time-varying metrics of resilience of a system in order to represent the pre-event state of the community, the phases of disaster-induced loss accumulation and absorption, followed by the recovery phase and finishing with the post-event adapted state of the community shown in Fig. 1.1. A graph of the community resilience process, shown in Fig. 1.2, draws heavily on the original formulation by Bruneau et al. (2003), and expands it by indicating possible post-even community states, following Kröger (2013) and Heinimann (2013). The time-varying measure of community resilience is the “quality of performance” of the community systems. We elaborate this system resilience metric in detail in Chapter 3 of this report, focusing on the types of metrics relevant for CISs.

In Chapter 4, we present a novel compositional supply/demand resilience quantification framework. This framework leverages the systemic notion of a community and the interaction between the higher-level community functions and its built infrastructure that includes the civil infrastructure systems (CISs). Here, the novelty is separate tracking of the evolution of the supply of services provided by a civil infrastructure system (CIS) and the demand for these services by the community throughout the post-event loss accumulation, absorption and recovery phases of the community resilience process. We define the notion of *Lack of Resilience* as the state when the CIS supply does not satisfy the community demand. The framework is probabilistic, in that the *Lack of Resilience* is a time-dependent random variable. The compositional nature of the framework stems from the bottom up process used to evaluate the instantaneous supply and demand. The process comprises the evaluation of hazard (building on outcomes of Work Package 3), evaluation vulnerability of CIS and community built infrastructure components (building on outcomes of Work Package 4), and evaluation of the operation of the CIS and community integrated system using the CIS operations model.

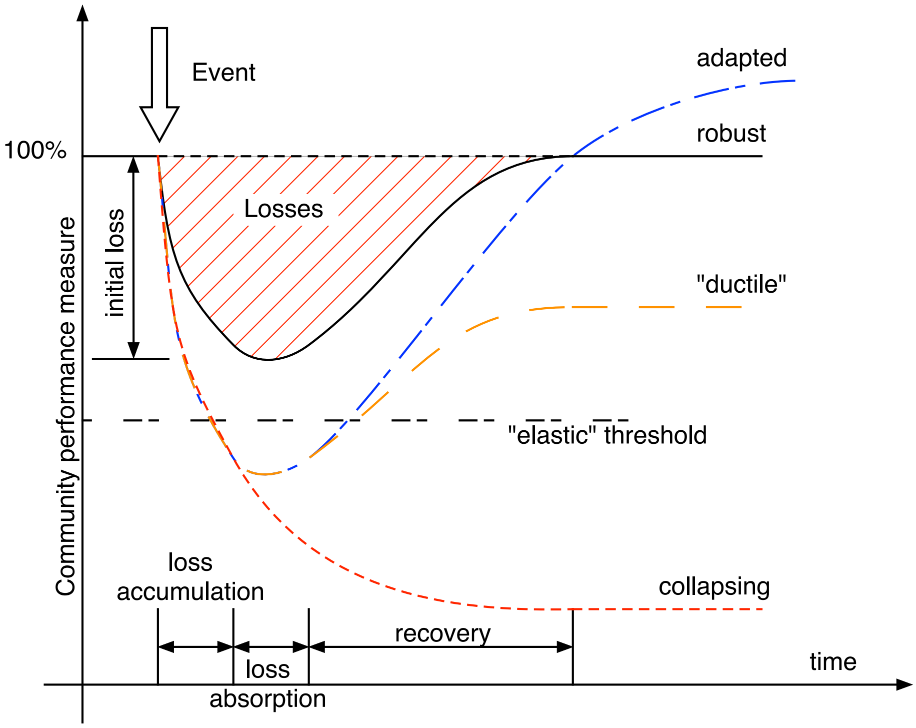


Fig. 1.2 Quantification of community resilience (modified from Bruneau et al. (2003) and Heinimann (2013))

We conclude this report by indicating how the proposed CIS stress test methodology, ST@STREST, the principal outcome of Work Package 5 of this project, can be integrated into the regulatory framework aimed at evaluating and societal resilience and designing resilient communities in Europe. We also examine possible future research objectives to further develop the proposed societal resilience quantification framework and operationalize it in practice.

2 From Societal Resilience to Resilience of CIS

The material in this Chapter is adapted from the work of Dr. Michael Mieler (Mieler et al. 2013, Mieler et al. 2015).

Modern societies comprise social entities: individuals, organizations or communities. A community is a dynamic system of people, organizations, and patterned relationships and interactions (Alesch 2005). A system is a dynamic entity comprising a collection of interacting, potentially correlated components assembled to perform an intended function (adapted from Buede 2000, ISO and IEC 2008, Kossiakoff et al. 2011). As such, a community can be considered a system, albeit an incredibly large and multi-faceted one. Unlike other types of systems (such as nuclear power plants or commercial aircraft), no two communities are identical. However, many share similar characteristics and configurations.

2.1 COMMUNITY COMPONENTS

Bea (2007 and 2008) defines seven general types of components in a system: structures, hardware, people, organizations, procedures, environments, and interfaces. These seven categories are used to guide the discussion of the numerous components that comprise a typical community (note that components within a system can themselves be systems (Buede 2000)):

- Structures refer to those components that physically support a community and its vital functions. There are two primary categories of structures: buildings and lifelines (or CISs). Buildings support a wide range of functions, including residential, commercial, industrial, and governmental. Lifelines refer to the systems and facilities that provide services necessary to the function of an industrialized society and important to emergency response and recovery activities after a disaster. Lifelines can be grouped into the following five categories (adapted from Rinaldi et al. 2001, ALA 2016, O'Rourke 2007): water; telecommunications; energy (electric power, natural gas, oil, and solid fuels); transportation (roads and highways, mass transit, ports and waterways, railways, and airports); and waste disposal (wastewater and solid waste).
- Hardware refers to those components that physically enable the vital functions of a community to be performed. Typically, hardware works in conjunction with structures to perform these functions. For example, by themselves, structures like electric transmission towers and lines do not make a community's electric power network functional; equipment like generators and transformers are required in order for the power grid to operate successfully. In general, hardware has moving parts whereas structures do not. Taken together, structures and hardware form the built environment.
- People refer to the residents of a community. Residents can serve many different roles simultaneously, including that of operator, user, and/or member of the general

public. Operators are those residents who actively participate in or enable the vital functions of a community. They include service and industry workers like truck drivers, firefighters, electricians, custodians, bankers, city planners, and doctors, to name only a few. Operators typically rely on a specific subset of structures and hardware to perform their duties successfully. In addition, their behavior can be strongly influenced by the organizations, procedures, and environments in a community. For example, firefighters not only require functional communication, transportation, and water infrastructure in order to extinguish fires successfully, but also extensive training and rigorous command structures. In addition to operators, residents can also serve as users or customers. In general, users do not directly participate in the operation of a particular system or service; however, because they use or consume the service or product, they can be affected if the system or service is disrupted. For example, an ophthalmologist who relies on public transportation may be unable to commute to and from work if bus service is disrupted. An especially important group of users within a community is students, as they have little control over how their community’s education system is run. Lastly, residents can serve as members of the general public. Members of the general public neither operate nor use the service or system under consideration; however, they can still be affected by its operation. For example, a chemical factory may emit pollutants into the surrounding environment that affects nearby residents who do not use the chemicals produced by the factory. In this example, the nearby residents are neither operators nor users, but are still affected by operation of the factory.

- Organizations refer to the groups or teams of people that actively participate in the vital functions of a community. There are two main types of organizations: businesses and institutions. Businesses provide goods and services to customers for a profit. They include grocery stores, banks, restaurants, engineering firms, and private utility providers. Institutions provide vital public services to the residents of a community. They include public and other non-profit entities like schools, universities, churches, and government agencies (*e.g.*, police and fire departments, post offices, transit authorities, public utility providers). Certain types of organizations specify and enforce the procedures that dictate how people and other organizations behave. For example, the building department specifies and enforces the procedures (*i.e.*, building codes) that engineering firms must follow when designing and constructing buildings. In addition, engineering firms typically specify additional procedures their engineers must follow; for example, a particular process for analyzing the response of a building to an earthquake.

- Procedures refer to the formal and informal laws, regulations, guidelines, and customs that govern a community and its vital functions. They include, for example, legally adopted statutes, bills, and ordinances, codes and standards, operating manuals, and emergency response plans. Procedures, which are typically developed, implemented, and enforced by organizations, dictate the way people and organizations behave. They can also influence how structures and hardware perform. In light of this discussion, a regulatory framework includes both procedures (*i.e.*, regulations and guidance) and the organizations that develop and enforce them.

- Environments refer to the conditions under which a community and its vital functions are performed. There are many different types of environments, including natural, economic, social, and political. Environments can strongly influence the behavior of structures, hardware, operators, and organizations. For example, the natural environment that surrounds a community determines the hazards for which its buildings and other structures must be designed. In addition, the economic environment influences the actions of investment firms, developers, and other businesses, which in turn can impact the size and condition of a community's building stock.

- Interfaces refer to those components in a community that link or connect other components together. Interfaces enable control in the sense of feedback control, making it possible for components to interact in a rational manner. An increasingly ubiquitous interface is the Internet, which can be used, for example, to connect a traffic engineer (*i.e.*, operator) to sensors, cameras, and other instruments (*i.e.*, hardware) that monitor traffic conditions and loads a bridge (*i.e.*, structure).

2.2 COMMUNITY INTERACTIONS, CORRELATIONS AND FUNCTIONS

The interactions among its many different components enable a community to perform its vital functions successfully. These interactions take the form of dependencies and interdependencies and can be extraordinarily complex, especially given the large number of components in a community. Fig. 2.1 portrays some basic interdependencies among the lifelines in a community. Note that SCADA stands for supervisory control and data acquisition. Evidently, electric power plays a central role in a community, supplying power to the essential functions of most other lifelines. However, as the figure also demonstrates, electric power in turn relies on a large number of other lifelines to operate successfully.

In general, interdependencies increase the vulnerability of lifelines to service disruptions. For example, telecommunications service can be disrupted on account of internal issues (*e.g.*, damage to a switches or cell phone towers); however, because of interdependencies, service can also be disrupted on account of issues beyond the control of the telecommunications provider (*e.g.*, power outages). Some of the vulnerabilities arising from these interdependencies can be mitigated through use of backup or emergency supplies of critical utilities. For example, a telecommunications center can install onsite diesel generators to supply emergency power to switches and other vital hardware if the electric power grid goes down. However, as a practical matter, not all interdependence-related vulnerabilities can be mitigated fully. Furthermore, under normal operating conditions, interdependencies can serve to increase the operational efficiency of lifelines.

Correlation measures the relationship between the responses of two distinct objects. In a complex system like a community, correlation arises when a large number of its components have similar design or configuration – for example, a neighborhood of identical apartment buildings. While modular design and construction allows for greater economies of scale and efficiency, it also increases the vulnerability of the community to the effects of correlated failures. By incorporating diversity into the design and configuration of its components, a community can mitigate the impact of correlation.

The Southeast Region Research Initiative (SERRI) and Community and Regional Risk Institute (CARRI) define three broad groups of community functions that healthy and vibrant communities provide to their residents (SERRI 2009). The first group includes infrastructure-based functions like energy, water, and transportation. The second group involves economic functions like employment opportunities, adequate wages, and affordable housing options. And the third group includes social functions like community ownership and participation, education and training opportunities, and a sense of community and place. Fig. 2.2 shows these three groups of functions and their interactions.

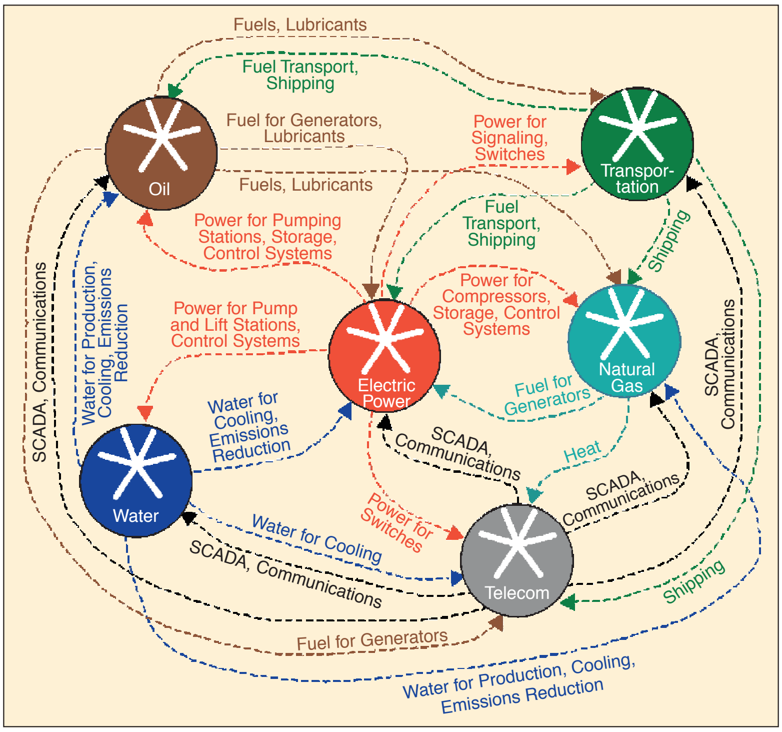


Fig. 2.1 Examples of lifeline interdependencies (Rinaldi et al. 2001).

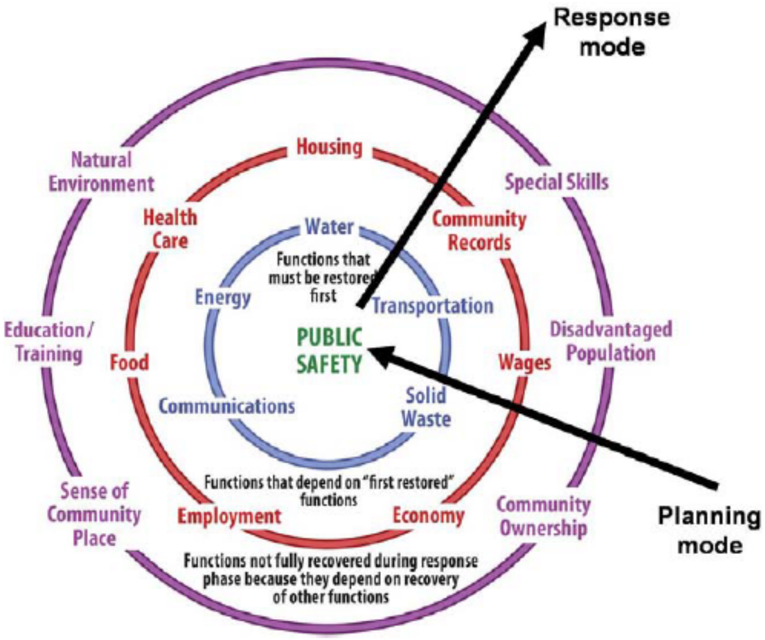


Fig. 2.2 Community functions (SERRI 2009)

Most of these relationships and interactions are physically supported by a community's built environment, which is a complex and interdependent network of engineered subsystems and components, including buildings, bridges, and lifelines. Subsequently, the built environment plays a crucial role in enabling a community to successfully function, providing the physical foundations for much of the economic and social activities that characterize a modern society.

2.3 HAZARDS

In the most general sense, a hazard is a potential source of danger. Typically, it refers to a threat that is unrealized but has potential to occur in the future. More specifically, US FEMA defines a hazard as "any event or condition with the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, environmental damage, business interruption, or other loss". Hazards can be either natural or human-made. Regarding this distinction, the Organization of American States writes (OAS 1991):

> *A widely accepted definition characterizes natural hazards as "those elements of the physical environment, harmful to man and caused by forces extraneous to him" (Burton et al. 1978). More specifically… the term "natural hazard" refers to all atmospheric, hydrologic, geologic (especially seismic and volcanic), and wildfire phenomena that, because of their location, severity, and frequency, have the potential to affect humans, their structures, or their activities adversely. The qualifier "natural" eliminates such exclusively manmade phenomena as war, pollution, and chemical contamination. Hazards to human beings not necessarily related to the physical environment, such as infectious disease, are also excluded from consideration here.*
>
> *Notwithstanding the term "natural," a natural hazard has an element of human involvement. A physical event, such as a volcanic eruption, that does not affect human beings is a natural phenomenon but not a natural hazard. A natural phenomenon that occurs in a populated area is a hazardous event… In areas where there are no human interests, natural phenomena do not constitute hazards… This definition is thus at odds with the perception of natural hazards as unavoidable havoc wreaked by the unrestrained forces of nature. It shifts the burden of cause from purely natural processes to the concurrent presence of human activities and natural events.*

Natural hazards such as earthquakes, hurricanes, and floods can damage a community's built environment, which in turn can disrupt the security, economy, safety, health, and welfare of the public.

In some instances, a natural hazard can produce multiple effects. For example, a hurricane can produce a combination of violent wind (including tornados), torrential rain, and damaging storm surge. Similarly, an earthquake can produce ground shaking, surface rupture, lateral spreading, liquefaction, tsunamis, and landslides. A natural hazard can also induce human-made hazards. For example, an earthquake can trigger large fires if gas lines rupture throughout a community (Scawthorn 2003). It can also produce extensive flooding if nearby dams or levees fail as a result of an earthquake. These induced hazards can have as much impact as the primary hazard and, therefore, should be accounted for when performing a hazard analysis for a system. Furthermore, the effects of a hazard can vary from location to location. For a spatially distributed system subject to earthquakes (like the electrical grid in Los Angeles), areas closest to nearby faults will likely experience stronger shaking than those farther away. Also, portions of the system founded on soft soil may experience amplified shaking relative to locations founded on rock.

Each community faces a unique set of hazards that depends on the surrounding natural and human-made environment. Community system designers and operators must carefully analyze the system's surroundings in order to properly identify and characterize the hazards that threaten it. Only after thoroughly evaluating potential hazards can operators plan and prepare accordingly.

A hazard analysis for a system identifies potential sources of hazard, as well as the range and frequency of hazard scenarios that each source can produce. A hazard analysis can be either deterministic or probabilistic. In a deterministic hazard analysis, one particular hazard scenario is evaluated. This scenario might, for example, postulate the occurrence of a hazard with a specific size and location (*e.g.*, a magnitude 7.6 earthquake on a particular fault segment). Such an analysis would be appropriate if attempting to establish a worst-case scenario for a particular hazard source. A deterministic hazard analysis, however, neglects to include uncertainties in the hazard such as its size, location, and frequency of occurrence. A probabilistic hazard analysis, on the other hand, provides a framework that identifies, quantifies, and combines these uncertainties to obtain a more complete picture of the hazard (Kramer 1996). A probabilistic hazard analysis includes all possible hazard scenarios and combines them using the frequency of occurrence of each scenario. For this reason, a deterministic hazard analysis corresponds to a particular scenario in a probabilistic hazard analysis (Thenhaus and Campbell 2003).

In this project, we focus primarily on the hazardous effects arising from earthquakes, including tsunami. The issues pertaining to seismic and tsunami hazards for CISs are presented in the deliverables of Work Package 3.

2.4 COMMUNITY PERFORMANCE AND VULNERABILITY

Performance refers to the ability of a community system or component to achieve objectives and targets pertaining to its functionality, safety, or costs. Typical performance measures for buildings include casualties, lifecycle costs, and time to restore functionality (*i.e.*, downtime). In contrast, response refers to the physical behavior of a system when subjected to a stress or stimulus (*e.g.*, earthquake ground shaking or liquefaction). Traditional response measures for buildings include forces, accelerations, displacements, and drifts.

As the definition above indicates, system performance is typically evaluated relative to specified targets or objectives. These performance targets or objectives can take many different forms, depending on the system or component being considered and the desired outcomes. For example, if a building owner is only concerned with protecting the safety of occupants during an earthquake, performance objectives for the building will seek to minimize casualties. These performance objectives can be achieved, for example, by assuring that the response of the building during an earthquake remains within certain thresholds (*e.g.*, peak inter-story drift ratios less than 2 percent). On the other hand, if a building owner is also concerned with maintaining functionality after an earthquake, performance objectives for the building will seek to minimize downtime in addition to casualties. It is important to note that performance objectives influence the scope of the evaluation required for a particular system. For example, if the performance objectives for a building specify that it minimize casualties during an earthquake, then only its structural system needs to be analyzed, as most earthquake-related casualties are caused by structural collapse. On the other hand, if performance objectives for the building specify that it remain functional following an earthquake, then both the building (including its structural and nonstructural systems) and any supporting lifelines need to be evaluated.

Communities are vulnerable to a wide range of natural and human-made hazards, including earthquakes, hurricanes, tornados, floods, economic downturns, pandemics, and terrorist attacks. Here, we focus primarily on earthquakes, which are especially challenging because of their unpredictability and widespread impact.

Earthquakes can produce many different effects, though the primary effect is ground shaking. Depending on the geology of the region, shaking can be felt at great distances – sometimes hundreds of kilometers – from the epicenter of an earthquake, though the intensity of shaking generally decreases as the distance from the epicenter increases. While ground shaking is typically the most widespread and devastating effect, earthquakes can produce additional harmful effects, including liquefaction, fault rupture, lateral spreading, landslides, and tsunamis. Furthermore, when an earthquake occurs, it usually triggers a series of aftershocks. Sometimes it can even induce additional earthquakes on nearby faults. These aftershocks and induced earthquakes, which themselves can be sizable, are particularly problematic because they strike when a community's built environment is in a weakened state.

2.5 DIRECT AND CASCADING CONSEQUENCES

The most direct consequence of earthquakes involves physical damage to the built environment of a community. For example, ground shaking can induce significant lateral displacements and accelerations that damage key structural elements in a building, possibly resulting in partial or total collapse of the structure. In addition, liquefaction can cause soil instability that ruptures buried pipelines and damages the foundations of structures. Furthermore, tsunamis can produce powerful waves that can obliterate entire city blocks. The extent of physical damage caused by earthquakes depends on many factors, including the location and magnitude of the earthquake and condition of the community's built environment. If the physical damage is severe, it can disrupt a large number of a community's vital functions and result in a significant number of casualties.

Cascading consequences refer to the sequences of events that result from physical damage to a community's built environment. Cascading consequences arise when the direct consequences of an earthquake cascade through a community, typically following the complex web of component interactions. For example, damage to gas pipelines can disrupt service to businesses and residences, and can even trigger large fires that destroy additional infrastructure, including the water, communication, and transportation systems that firefighters depend on to suppress fires. In addition, damage to a manufacturing facility can lead to costly downtime that could ultimately bankrupt the business and force workers to leave town in search of new employment. In turn, disruption to and potential closure of the plant can impact supply chains throughout the community, region, and even globe.

Due to an increasingly interconnected global economy, the cascading consequences caused by an earthquake can extend well beyond areas directly affected by it. The extent of these consequences depends on several factors, including the extent of the direct consequences and the importance of the affected community. For example, if an earthquake strikes a community and causes minor physical damage to its infrastructure, the cascading consequences will also likely be minor. On the other hand, if an earthquake strikes a city or region and causes extensive damage, the cascading consequences could be global, as they were following the Tohoku Earthquake that struck northern Japan in 2011.

If the consequences are severe enough, a community may never fully recover after an earthquake. The combined impact of losses to housing, jobs, schools, and other services may be too much for a community to handle. Instead of rebuilding, residents may simply choose to leave and start over elsewhere. Even if the community eventually repairs or rebuilds damaged infrastructures, the disruption caused by an earthquake may result in irreversible harm to local businesses as global supply chains shift production to (unaffected) locations, as it occurred in Kobe after the 1995 Great Hanshin-Awaji Earthquake (Olshansky et al. 2011). Before the earthquake, the port of Kobe was the sixth busiest container port in the world. It suffered heavy damage as a result of the earthquake and, by the time its facilities were fully reconstructed in 1997, the port had dropped to seventeenth busiest (Chang 2000). Nineteen years after the earthquake, the volume of containers handled at the port was only 87.6% percent of pre-earthquake levels (City of Kobe 2014).

In this project, we focus primarily on the performance and vulnerabilities of communities to earthquakes, including tsunami. Methods to evaluate and models of seismic performance and vulnerability of CISs are presented in the deliverables of Work Package 4.

2.6 COMMUNITY RESILIENCE AND CISS

A community is a dynamic system comprising a collection of interacting, potentially correlated components assembled to perform an intended function: to support the people, organizations, and patterned relationships and interactions that define a society. A community is a large, complex, multi-faceted system. Unlike other types of systems (such as nuclear power plants or commercial aircraft), no two communities are identical. However, many share similar characteristics and configurations.

Here, we adopt conceptual community functions configuration shown in Fig. 1.2. Further, we focus on four vital functions: public services, housing, employment, and education (adapted from Cutter et al. 2010, SERRI 2009, and Poland et al. 2009). It is important to note that these four items refer to the *functions*, not the physical infrastructure of a community. Here, we will divide the physical infrastructure that enables these vital functions into the frontline (Table 2.1) and the support (Table 2.2) systems. In general, in a community, frontline systems refer to buildings while support systems refer to lifeline CISs.

Both frontline and support systems of a community are vulnerable to seismic hazard. Their importance in the recovery process (the response mode in Fig. 1.2) is shown by their position. The fundamental function of the community, public safety, is in the innermost ring. During a disaster, it is provided by the community built environment (through structural design code provisions aimed at preventing collapse of structures), and must be restored first following a disaster. The middle ring represents the economic functions of a community, which cannot be restored until CIS-based functions are recovered. The outermost ring represents the social functions of a community, which cannot be restored until both infrastructure and economic functions are recovered.

The importance of CISs for community resilience was recognized clearing in the ResilUS conceptual model and framework proposed by Miles and Chang (2003, 2006, and 2007). Fig. 2.3 shows schematically the relationships among the built inventory (neighborhoods) and CISs (lifelines).

Table 2.1 Frontline systems for each vital function in a community (adapted from ASCE 2006, Poland et al. 2009)

Vital community function	Frontline systems
Public services	Hospitals, clinics, medical provider offices, and other health care facilities Fire, police, rescue, and ambulance stations Dispatch and emergency operations centers City hall and other administrative offices Military bases and other defense facilities Grocery stores and pharmacies
Housing	Permanent residences Single-family housing (including mobile homes) Multi-family housing (apartments, condominiums, dormitories, public housing) Institutional housing (nursing homes, assisted living facilities, correctional facilities, prisons, rehabilitation facilities) Short-term residences Transient housing (hotels, motels, boarding houses) Emergency housing (community centers, schools, convention centers, arenas, other designated emergency shelters) Interim housing (FEMA trailers, tents)
Employment	Commercial buildings (offices, retail shops, restaurants, banks, warehouses) Industrial buildings (factories, hazardous facilities)
Education	Preschools and day care facilities Primary and secondary schools (elementary, middle, and high schools) Post-secondary schools (universities, colleges, trade schools, institutes)

Table 2.2 Support systems in a community (adapted from Rinaldi et al. 2001, Barkley 2009, PCCIP 1997, ALA 2004)

Support system	Components
Electric power	Generation stations; transmission substations, towers, lines, and conduits; distribution substations, towers, lines, and conduits; control centers
Natural gas	Well facilities; processing plants; compressor stations; storage facilities; pipelines; control centers
Oil	Well facilities; pumping stations; refineries; storage facilities; pipelines; control centers
Solid fuels	Mines; processing/preparation plants; storage facilities
Roads and highways	Bridges; tunnels; roadways; traffic signs and signals; embankments; culverts; retaining walls; operation and control centers; maintenance facilities
Mass transit	*Buses*: stations; operation and control centers; fuel, dispatch, and maintenance facilities *Light rail*: tracks; bridges; tunnels; DC power substations; dispatch and maintenance facilities
Railways	Tracks; bridges; tunnels; stations; signs and signals; fuel, dispatch, and maintenance facilities
Airports	Runways; control towers; terminal buildings; hangars; fuel and maintenance facilities
Ports and waterways	Waterfront structures (docks, piers, wharves, sea walls, breakwaters, jetties); cranes and cargo handling equipment; warehouses; fuel facilities; locks and other engineered waterways
Water	Well facilities; desalination plants; dams; reservoirs; canals; pipelines; pumping stations; treatment facilities; storage tanks
Waste water	Pipelines; pumping/lift stations; treatment facilities
Solid waste	Transfer stations; materials recovery facilities; waste combustion facilities; disposal sites
Telecommunications	Central offices; data centers; network operations centers;

	transmitter stations; towers and poles; cables, lines, and conduits; satellite dishes

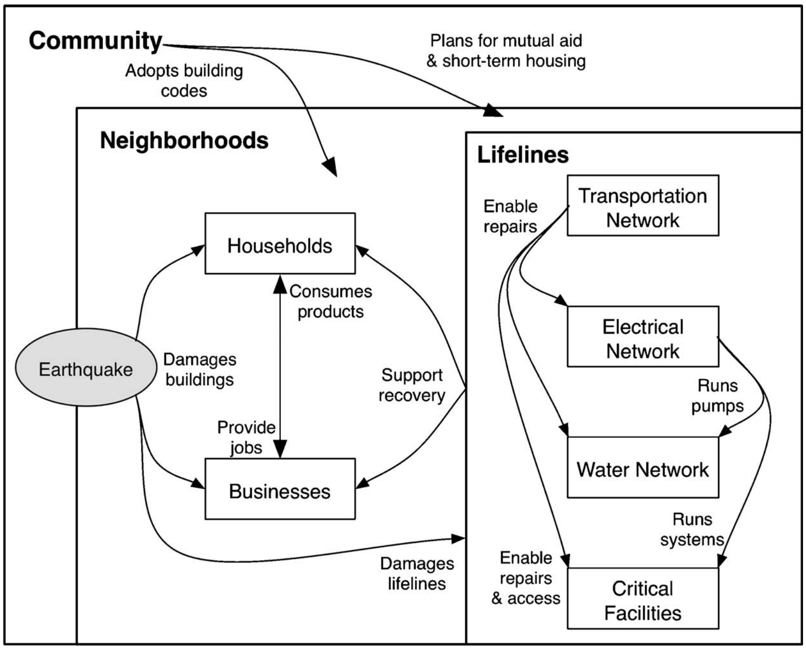


Fig. 2.3 ResilUS conceptual model of community recovery form earthquakes (Miles and Chang 2006).

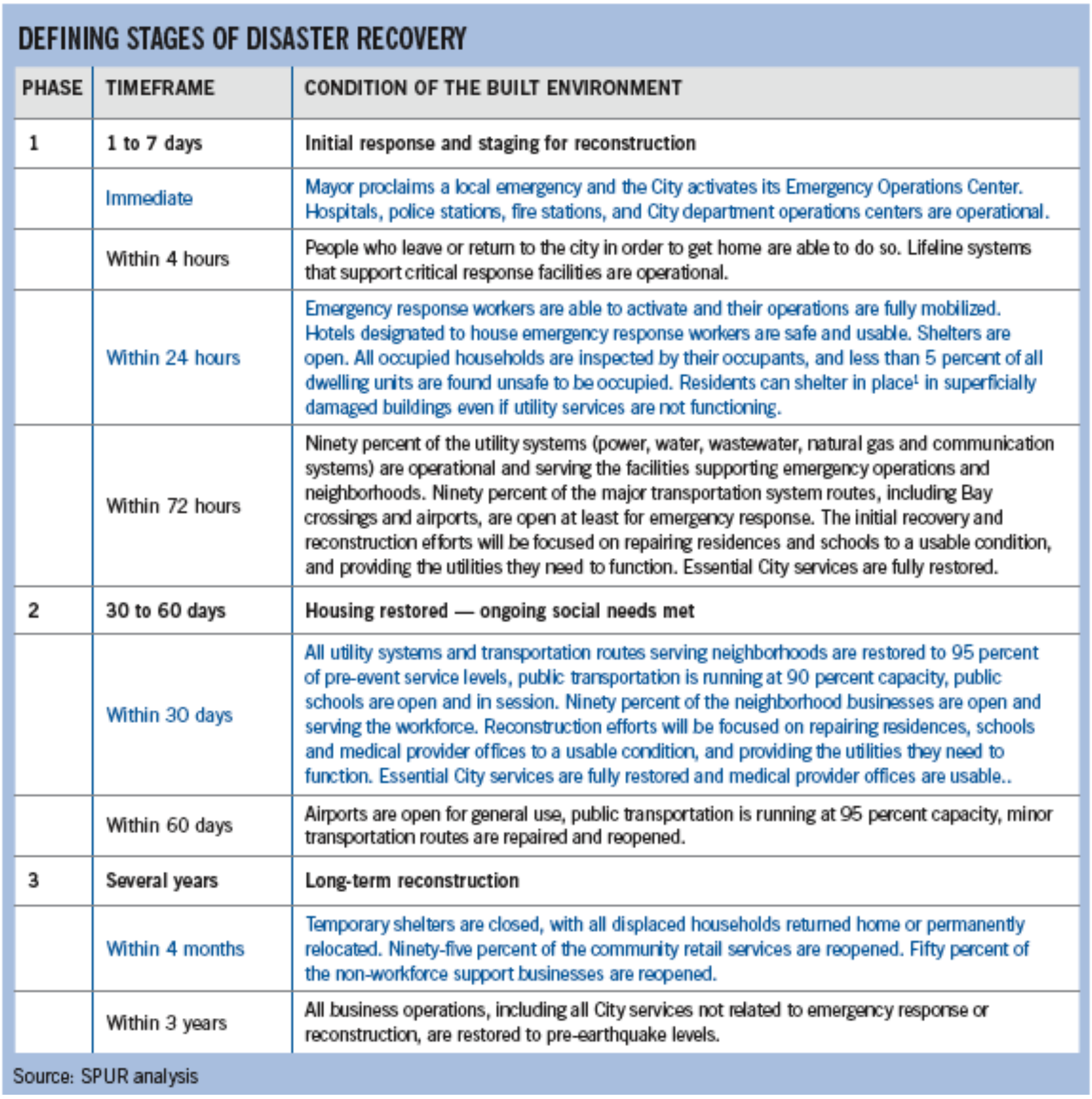
In this project, we focus on the role of CISs in facilitating community (and thereby societal) resilience to natural hazards. By adopting a conceptual representation of the evolution of community performance, shown in Fig. 1.2, we enable quantification of community resilience. By adopting the hierarchy of functions shown in Fig. 1.2 we focus on quantifying the resilience of CISs as the fundamental building blocks of community functions. Next, we select suitable CIS resilience metrics and propose a framework for CIS resilience quantification.

3 CIS Resilience Metrics

Bruneau et al. (2003) propose measuring resilience using three complementary metrics: probability of failure, consequences of failure, and recovery time. Referring to Fig. 1.1, the event of failure is associated with insufficient resistance of the community systems to the effects of the adverse natural hazard event, i.e. with vulnerability. Given the probabilistic nature of the hazard and the vulnerability, the probabilistic structure of the event of failure is described by integrating the conditional probability of vulnerability with the total probability of natural hazard event exceedance. Fig. 1.2 illustrates these metrics graphically, with the vertical axis measuring the consequences of failure in terms of a measure of community performance, and the horizontal axis measuring the time needed to accumulate (direct) losses, absorb (cascading) losses, and plan and execute the recovery of a community after an adverse event. Thereby defined community performance recovery path is, by itself, a function of random consequence and time variables.

The shaded area in Fig. 1.2 represents a conceptual integral measure of losses in terms of inadequate community performance over a period of time needed to for it to recover from the adverse event. Similarly, the amount of community performance loss at each point in time during the accumulation, absorption and recovery process is an instantaneous measure of the effect of the adverse event on the community performance. Numerous researchers proposed resilience metrics based on the instantaneous and integral measures of the community recovery path (Hosseini, 2016). Others, notably Bocchini et al. (2014), focus on modelling the parameters of the community performance recovery path function.

While much of the research in the community resilience field has, so far, focused on defining and measuring community resilience, less effort has gone into defining the particular measures of the consequences and time variables that define the community performance recovery path. Pioneering work in this direction was done by the San Francisco Planning and Urban Research Association (SPUR), which established a comprehensive set of performance objectives that, if achieved, would make the city of San Francisco more resilient to earthquakes. Specifically, this set of objectives aims to have the city “back on its feet” four months after a magnitude 7.2 earthquake on the Peninsula segment of the San Andreas fault (Poland et al. 2009). Fig. 3.1 displays the set of performance objectives for the entire city as a function of time, while Fig. 3.2 displays more performance objectives for important classes of buildings and lifelines. Fig. 3.1 also shows the current level of performance expected from each piece of infrastructure (the “X” mark) relative to its specified target (the shaded box). The work of SPUR and Poland et al. (2009) is unique because it establishes explicit performance objectives for the city in an attempt to improve its disaster resilience. Most resilience indicator studies conducted to date (Cutter 2015) focus on defining and measuring resilience, but stop short of establishing concrete targets to aim at, thereby leaving the following two questions unanswered: when is a community resilient enough and how resilient should the community components be to make the community resilient enough, i.e. if communities want to enhance or improve their resilience to disasters, exactly what level of performance is required from buildings and lifelines?



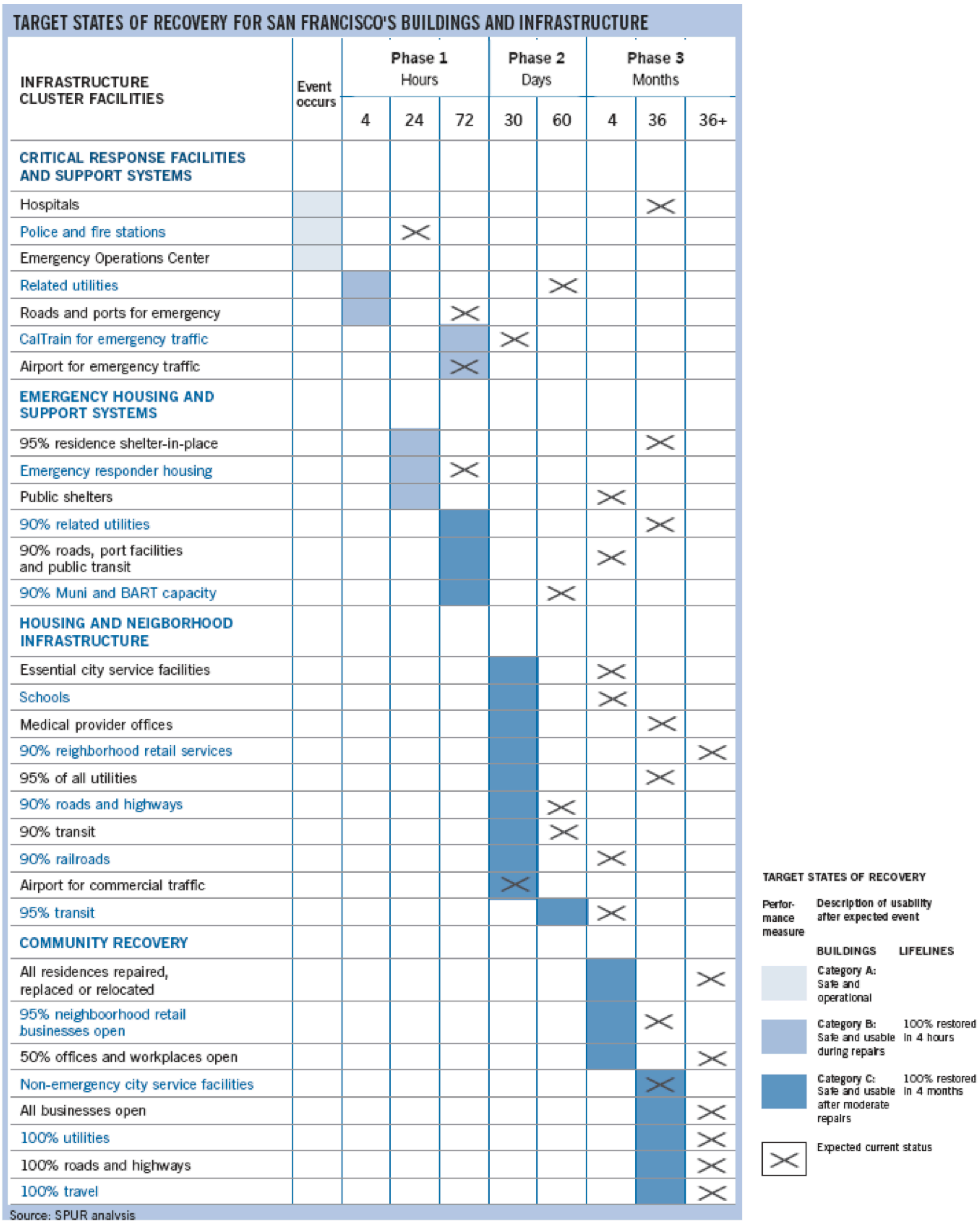
DEFINING STAGES OF DISASTER RECOVERY

PHASE	TIMEFRAME	CONDITION OF THE BUILT ENVIRONMENT
1	1 to 7 days	Initial response and staging for reconstruction
	Immediate	Mayor proclaims a local emergency and the City activates its Emergency Operations Center. Hospitals, police stations, fire stations, and City department operations centers are operational.
	Within 4 hours	People who leave or return to the city in order to get home are able to do so. Lifeline systems that support critical response facilities are operational.
	Within 24 hours	Emergency response workers are able to activate and their operations are fully mobilized. Hotels designated to house emergency response workers are safe and usable. Shelters are open. All occupied households are inspected by their occupants, and less than 5 percent of all dwelling units are found unsafe to be occupied. Residents can shelter in place[1] in superficially damaged buildings even if utility services are not functioning.
	Within 72 hours	Ninety percent of the utility systems (power, water, wastewater, natural gas and communication systems) are operational and serving the facilities supporting emergency operations and neighborhoods. Ninety percent of the major transportation system routes, including Bay crossings and airports, are open at least for emergency response. The initial recovery and reconstruction efforts will be focused on repairing residences and schools to a usable condition, and providing the utilities they need to function. Essential City services are fully restored.
2	30 to 60 days	Housing restored — ongoing social needs met
	Within 30 days	All utility systems and transportation routes serving neighborhoods are restored to 95 percent of pre-event service levels, public transportation is running at 90 percent capacity, public schools are open and in session. Ninety percent of the neighborhood businesses are open and serving the workforce. Reconstruction efforts will be focused on repairing residences, schools and medical provider offices to a usable condition, and providing the utilities they need to function. Essential City services are fully restored and medical provider offices are usable..
	Within 60 days	Airports are open for general use, public transportation is running at 95 percent capacity, minor transportation routes are repaired and reopened.
3	Several years	Long-term reconstruction
	Within 4 months	Temporary shelters are closed, with all displaced households returned home or permanently relocated. Ninety-five percent of the community retail services are reopened. Fifty percent of the non-workforce support businesses are reopened.
	Within 3 years	All business operations, including all City services not related to emergency response or reconstruction, are restored to pre-earthquake levels.

Source: SPUR analysis

Fig. 3.1 General performance objectives for San Francisco as a function of time (Poland et al. 2009)

Poland et al. (2009) provide a clear answer to the first question for the city of San Francisco. Mieler at al. (2015) attempt to provide the answer to the second question by proposing a transparent, performance-based, and risk-informed engineering framework and a quantitative methodology to establish a consistent set of performance targets for individual subsystems and components within the built environment (*e.g.*, buildings and lifelines) in order to enhance overall community resilience. This linkage is especially important in the context of improving community resilience for two reasons. First, a well-articulated set of performance goals for a community can make the concept of resilience more concrete in nature, giving communities tangible targets to strive towards. And second, an explicit set of community performance goals can serve as the basis for a more consistent set of performance objectives for individual components within the built environment, thus ensuring that individual components perform in a manner that is compatible with the best interests of the entire community. Currently, performance objectives for individual components are not tied to broader performance goals for the community, resulting in inconsistent and sometimes inappropriate performance targets for individual components within the built environment.



TARGET STATES OF RECOVERY FOR SAN FRANCISCO'S BUILDINGS AND INFRASTRUCTURE

INFRASTRUCTURE CLUSTER FACILITIES	Event occurs	Phase 1 Hours			Phase 2 Days		Phase 3 Months		
		4	24	72	30	60	4	36	36+
CRITICAL RESPONSE FACILITIES AND SUPPORT SYSTEMS									
Hospitals	░							☒	
Police and fire stations	░		☒						
Emergency Operations Center	░								
Related utilities		▒				☒			
Roads and ports for emergency		▒		☒					
CalTrain for emergency traffic				▒	☒				
Airport for emergency traffic				▒ ☒					
EMERGENCY HOUSING AND SUPPORT SYSTEMS									
95% residence shelter-in-place			▒					☒	
Emergency responder housing			▒	☒					
Public shelters			▒				☒		
90% related utilities				▓				☒	
90% roads, port facilities and public transit				▓			☒		
90% Muni and BART capacity				▓		☒			
HOUSING AND NEIGBORHOOD INFRASTRUCTURE									
Essential city service facilities					▓		☒		
Schools					▓		☒		
Medical provider offices					▓			☒	
90% reighborhood retail services					▓				☒
95% of all utilities					▓			☒	
90% roads and highways					▓	☒			
90% transit					▓	☒			
90% railroads					▓		☒		
Airport for commercial traffic					▓ ☒				
95% transit						▓	☒		
COMMUNITY RECOVERY									
All residences repaired, replaced or relocated							▓		☒
95% neighboorhood retail businesses open							▓	☒	
50% offices and workplaces open							▓		☒
Non-emergency city service facilities								▓ ☒	
All businesses open								▓	☒
100% utilities								▓	☒
100% roads and highways								▓	☒
100% travel								▓	☒

Source: SPUR analysis

TARGET STATES OF RECOVERY

Perfor-mance measure	Description of usability after expected event	
	BUILDINGS	LIFELINES
░	Category A: Safe and operational	
▒	Category B: Safe and usable during repairs	100% restored in 4 hours
▓	Category C: Safe and usable after moderate repairs	100% restored in 4 months
☒	Expected current status	

Fig. 3.2 Specific performance objectives for San Francisco's buildings and infrastructure as a function of time (Poland et al. 2009).

A careful examination of Figs. 3.1 and 3.2 shows that the community function performance objectives already have a well-defined time and consequence components. For example, some related utilities are expected to be operational within 4 hours after the event, while 90% of the CIS services are expected to be operational and providing service for emergency operations 72 hours after the event. Furthermore, 30 days after the event, utility services are expected to be restored to 95% of their pre-event levels. However, full restoration of pre-event utility services is expected only after 36 months. The current performance of the utilities is deemed to be much worse than the stated performance objective: for example, provision of utility services for emergency operations may take as long as 60 days after the event, restoration of 90-95% service as long as 36 months and restoration of the full pre-event service levels yet longer. Clearly, the question of how to improve the performance of CISs such that they meet the set community recovery performance objectives remains open.

3.1 SOCIETAL RISK METRICS

Another set of questions can be posed about the resilience metrics themselves. First, they are stated as deterministic, whereas a probabilistic formulation (in terms of high confidence in low probability of not meeting the stated performance objective) would be highly desirable. The use of pre- and post-event service levels to define the consequences of an event on community CISs (that provide utility functions) is convenient and consistent with the Bruneau et al. (2003) approach. Nonetheless, developing acceptance criteria for design (or retrofit, or emergency repair) of the CIS components based on a relative measure (a portion of the pre-event service level) is neither transparent nor practical. The pre-event service levels fluctuate with the seasonal and daily changes of supply and demand. The post-event service levels fluctuate even more violently, given the dynamics of CIS repairs, the interdependencies among the systems, and the fluctuations in demand. Finally, it is not clear at all where the community-required utility service levels are going to be 36 or more months after the event, given that the adaptation of the community to the post-event conditions may radically change the pre-event processes and interactions that characterized that community.

Therefore, it is instructive to briefly review the available societal risk metrics to select a better measure of adverse event consequences with respect to CISs. Jonkman et al. (2003) comprehensively review methods to quantify and limit risks from both natural and man-made disasters. They define a risk measure as a mathematical function of the probability of an event and the consequences of that event. They look at the following consequences: fatalities and injuries (in terms of individual and societal risk), economic damage, environmental damage, potential damage, and risk measures that amalgamate various types of consequences. Notably, Jonkman et al. (2003) also suggest the field of application of the particular risk metrics, discuss the acceptable values for that risk metrics, and provide examples from the Dutch risk governance experience.

The majority of the proposed risk metrics define a frequency of consequence. Thus, the acceptance criteria are, generally, based on defining regions of the frequency-consequence (F-C) diagram that represent risks viewed as tolerable, as unacceptable, and risks that should be reduced as practical or cost-effective, i.e. as low as reasonably achievable (ALARA), shown in Fig. 3.3.

Jonkman et al. (2003) define individual risk (IR) as the probability that an average unprotected person, permanently present at a certain location, is killed due to the effects of an adverse hazardous event. Societal risk (SR), on the other hand, expresses the risk that a group of people is simultaneously exposed to the consequences of an adverse hazardous event (Duijim 2009). The difference between the individual and the societal risk is illustrated in Fig. 3.4. While the individual risk levels are the same, the societal risk is larger in situation B because of a larger population density.

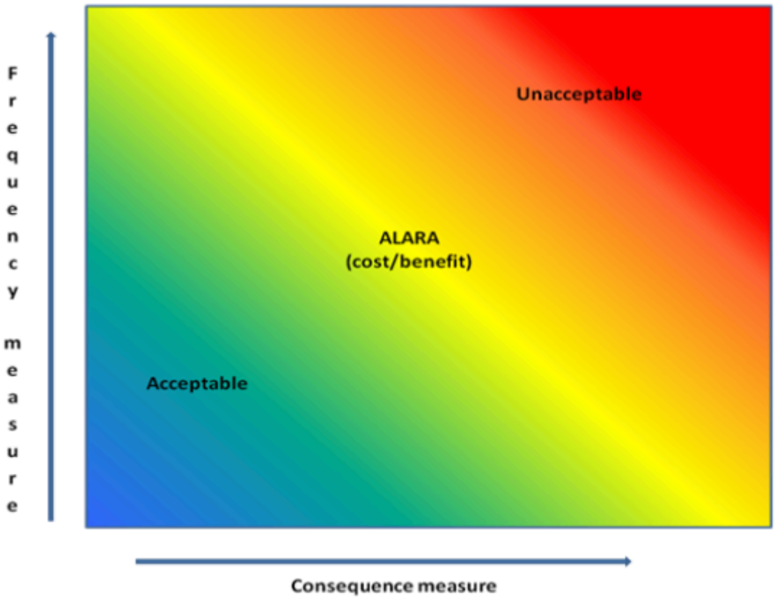


Fig. 3.3 Generic F-C curve, with the tolerable, ALARA and unacceptable risk regions (Apostolakis 2012)

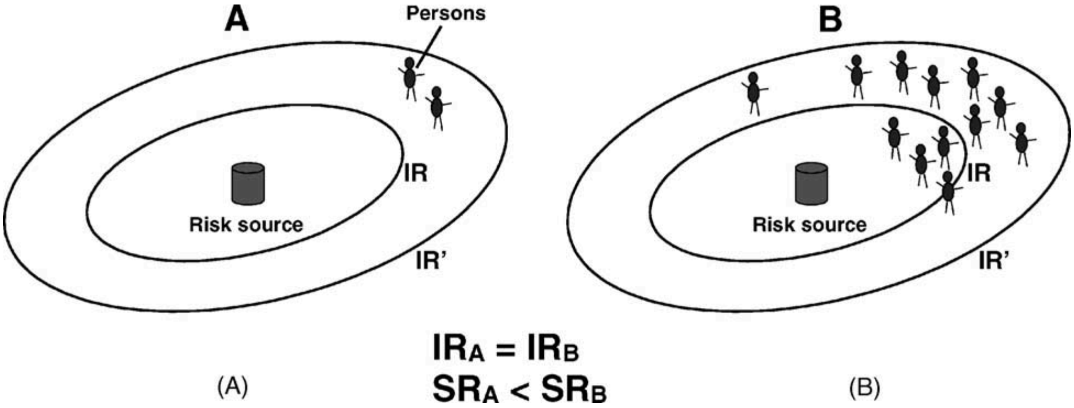


Fig. 3.4 The difference between individual (IR) and societal (SR) risks for two otherwise identical locations with different population densities (Jonkman 2003)

European practice has been converging towards a consensus regarding fatality risk acceptance criteria (Duijim 2009). Namely, individual risk shall be less than 10^{-6} per year; societal risk shall be less than 10^{-3} per year for major accidents with up to 1 fatality, and less than 10^{-5} for ten times larger accidents; and, the ALARA principle should be always applied.

Graphically, societal risk is often represented using the so-called F-N curves that plot the number of fatalities per year versus the corresponding probability of exceedance on log-log paper (Fig. 3.5 3.5). The area under the F-N curve, i.e. the expected value of the number of fatalities per year, also called the potential loss of life, is used often to simplify the information presented by the F-N curve.

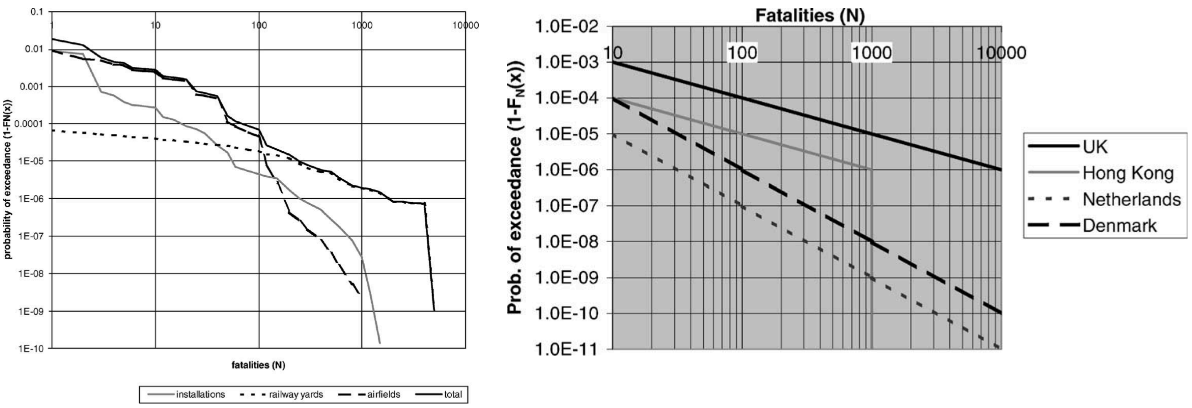


Fig. 3.5 F-N curve for the risk of various activities in The Netherlands in 1999 ((Jonkman 2003) source RIVM) (left) and Several international safety standards in F-N format (right) (Jonkman 2003).

Acceptance criteria for societal risk are often formulated using straight lines ($y=C/x^n$, where n is the steepness and C the abscissa intercept) in F-N curve space (Fig. 3.5), with the actual F-N curve expected to be under the line representing the acceptance criteria. The iso-risk line with steepness n=1 is risk-neutral, while steeper lines represent risk-averse standards, meaning that the consequences of larger adverse events are more heavily weighted and are therefore accepted with lower probability. Example of an acceptance criteria that are risk-neutral for accidents with smaller consequences and increasing risk-averse for accidents with larger consequences are the ones adopted by the US Nuclear Regulatory Agency shown in Fig. 3.6 (Apostolakis 2012).

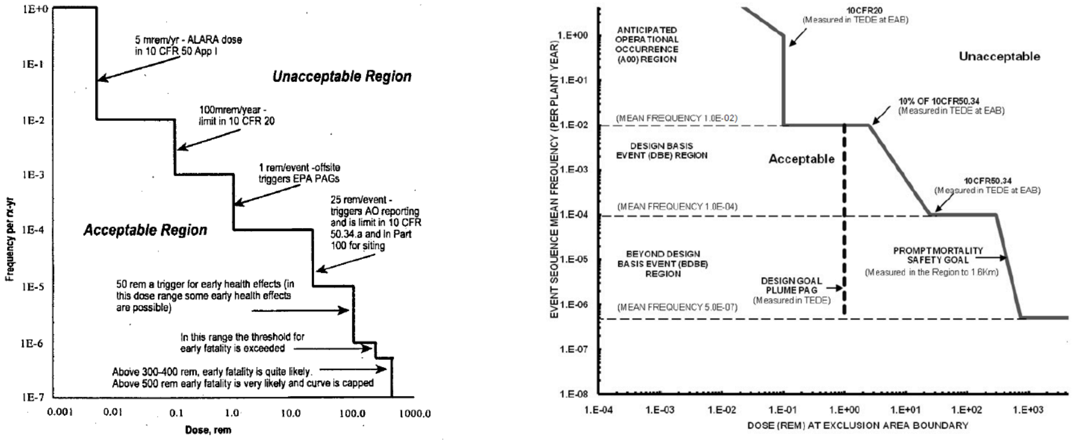


Fig. 3.6 Frequency-consequence charts with top-level regulatory criteria for (left) existing (ONRR 2007) and (righ) next-generation nuclear power plants (INL 2010))

Jonkman et al. (2003) also review the economic and environmental risk measures. Both measures are based on a cumulative assessment of the effects of the adverse event. Economic damage measures pertain to the community built environment, where the costs of the direct and cascading (indirect) damage are summed up. Environmental damage measures pertain to the community natural environment, where the effects of the adverse events are measured in terms of, for example, time to recover from an oil spill or the area lost to pollution. Both measures can be expressed in the form of F-L (frequency-loss) curves, or, simply, loss curves. Finally, the acceptance criteria for both measures are set in ways similar to F-N acceptance criteria.

The risk measures that address the potential consequences are, simply, loss curves integrated with probabilities of occurrence of the corresponding adverse events. These risk measures, therefore, represent total probabilities of loss. The integral risk measure build on the economic, environmental and fatality risk measures by first expressing the fatality and environmental consequences in monetary terms, and then defining a weighted sum of the measures. Acceptance criteria for the potential consequence and integral risk measures are often derived on the basis of cost-benefit analyses, through a comparison of the costs of risk mitigation to the monetary expression of losses.

3.2 COMBINED PERFORMANCE AND RISK METRICS

The metrics to quantify the resilience of CIS must reflect the dual role of the CIS in providing the essential aspect of public safety (as elements of the community built environment) and supporting the higher-level community functions (as elements of the community infrastructure). These metrics must also enable probabilistic expression of CIS performance as well as formulation of transparent and risk-informed acceptance criteria for CIS performance and, thus, community resilience.

With these criteria in mind, the societal risk metrics reviewed by Jonkman et al. (2003) offer a very solid starting point. One class of CIS resilience measures must address the fatalities. Another class of metrics should address the operation of CISs by looking at the quantities produced (e.g. volume of product refined by a refinery, quantity of electric power or water stored by a dam, or the value of goods produces in an industrial zone) or the rate of production (e.g. the flow of oil or gas in pipelines, or the number of handled containers in a port per day). Both metrics can be monetized, the fatalities using the actuarial value of life, and the production using the value of the product not delivered or produced. Once monetized, the metrics can be amalgamated.

In the following chapter we use the CIS performance metrics that measure the amount of service supplied by the system and the corresponding demand created by the community and track the supply/demand balance before, during and after the recovery process. Using this supply/demand approach we develop a compositional framework to quantify the resilience of CIS.

4 Civil Infrastructure System Resilience Quantification

The material in this Chapter is adapted from the work on the doctoral dissertation of Mr. Max Didier conducted with the assistance of Dr. Marco Broccardo and Dr. Simona Esposito (Didier et al. 2015, Sun et al. 2015, Didier et al. *in prep*).

Many resilience quantification frameworks impose an idealistic point of view that the objective is to recover (some portion of) the initial functionality of the CISs (utility,Fig. 1.2) as fast as possible after an adverse event. This assumption might however have only limited validity, especially in the case of major disasters. The CISs do not exist in a vacuum: they are built to deliver a service to a community. For this reason, the focus of a CIS resilience assessment should not only be on the impact of a disaster in terms of loss of their functionality (utility) over time, but on the ability of a CIS to supply the time-varying community demand for the services provided by the assessed CIS. A CIS resilience quantification framework needs to explicitly account for the evolution of the supply (i.e. the service supply capacity of the system) and for the evolution of the demand of the community and other CIS for its services in the aftermath of a disaster.

Since both the supply of the CIS and the demand for its service are local (i.e. governed by local damage), a holistic framework to evaluate and quantify the resilience of CIS must be compositional, a bottom-up one. Here, we propose a compositional demand/supply resilience quantification framework, linking the performance of a CIS to the demand for its services, and define a component-level and a system-level normalized *Lack of Resilience* measure designed to make it possible to directly compare the resilience of different CISs. Then, we propose a normalized measure of the reserve resilience margin as proxy for the redundancy and robustness of the CIS, and the notion of resilience time as a measure of the resourcefulness and the rapidity of the recovery process. Finally, we examine applications of the proposed framework to different possible post-event supply and demand scenarios.

4.1 COMPOSITIONAL DEMAND/SUPPLY RESILIENCE QUANTIFICATION FRAMEWORK

We propose a compositional demand/supply resilience quantification framework to evaluate the post-disaster resilience of CISs that supply their services to satisfy the demand of a community. The framework allows to account explicitly for the evolution of the demand of a community and the demand of other CISs during the post-disaster recovery process. The framework consists of three main elements:

1. The evolution of the potential demand for the service of the investigated CIS over time after a disaster. The potential demand is the amount of demand of all consumers of the service of the assessed CIS, if there were no limitations on the supply side (i.e. assuming an unlimited supply of service). Consumers include, for example, the community (composed by its residential building stock, industries, businesses and critical

facilities, used by the population) and all other CISs (e.g. electric power demand of the water supply system in order to run water pumps). Potential demand depends on:

- The vulnerability of the components of the set of demand systems (e.g. a community and/or another CIS) during the loss accumulation and absorption phase of a disaster; and,
- The recovery of the components of the set of demand systems during the recovery phase after a disaster.
- Potential extraordinary or high-priority needs in the aftermath of a disaster (e.g. hospital, telecommunications networks)

2. The evolution of the potential supply for the service of the investigated CIS over time after a disaster. The potential supply is the amount of service supply available to satisfy the demand of the system. Potential supply depends on:
    - The vulnerability of the components of the service supply and distribution systems during the loss accumulation and absorption phase of a disaster; and
    - The recovery of the components of the service supply and distribution systems during the recovery phase after a disaster.
3. A system operation model, regulating the allocation (or dispatch) of the service supply in order to satisfy the demand of the consumers. It accounts for the capacity limitations and interactions of the different elements of the CIS: the service production system, the distribution system, the technical functioning and control of the system, and the system or network effects. These include, for example, the topology of the system, operator service allocation policies, or possible demand distribution strategies.

The compositional resilience quantification framework allows the assessment of the resilience of a combined set of demand/supply systems. CIS resilience is the time-varying ability of a system to cover the demand for its services, while subjected to disruptive events that may occur over the system's lifetime. The framework allows, thus, to account for the impact of a disaster on both the demand and the supply side and to track the post-disaster evolution of demand and supply at both component and system levels.

4.1.1 Resilience at the component level

At the component level (local system node) a *Lack of Resilience* occurs when the demand exceeds the available supply of service. The component *Lack of Resilience*, LoR_i, is thus the amount of supply that cannot be provided by the damaged system to cover the demand over the given period of time. This is the amount of unsupplied demand or the supply deficit. To clearly outline the definition of the component *Lack of Resilience* the following variables are defined:

- $D_i(t)$ is the total potential demand of all consumers receiving their service from location (component, subcomponent or node) i at time t
- $S_{av,i}(t)$ is the available supply at location (component, subcomponent or node) i at time t
- $C_i(t)$ is the effective consumption, i.e. the supplied or consumed amount of service, at location (component, subcomponent or node) i at time t.

The $C_i(t)$ can match $D_i(t)$ or $S_{av,i}(t)$ based on this two different cases:

1. It is not possible to cover all of the demand. Then, the effective consumption is equal to the available supply:

$$D_i(t) \geq S_{av,i}(t)\colon C_i(t) = S_{av,i}(t) \tag{4.1}$$

2. The demand can be completely covered. Then, the effective consumption is equal to the total potential demand:

$$D_i(t) \leq S_{av,i}(t)\colon C_i(t) = D_i(t) \tag{4.2}$$

Thus: $C_i(t) = \min\left(S_{av,i}(t), D_i(t)\right)$.

Given the above definitions LoR_i is defined as

$$LoR_i = \int_{t_0}^{t_1} \langle D_i(t) - S_{av,i}(t)\rangle dt = \int_{t_0}^{t_1} \left(D_i(t) - C_i(t)\right) dt \tag{4.3}$$

where $\langle\cdot\rangle$ is the singularity function. The singularity function returns 0 for negative argument, otherwise it returns the argument itself. The start and the end time of the system resilience assessment are denoted as t_o and t_1, respectively. Notice that the resilience problem states in this terms is equivalent to a time dependent reliability problem. Eq. (4.1) is valid as long as the available supply at the node *i* is known and can be strictly delimited, i.e. all effects of other system elements are accounted for, negligible, or the available supply is independent and not influenced by other parts of the system. The compositional demand supply concept is schematically shown in Fig. 4.1 , where RM_i is the reserve margin, and T_R corresponds to the resilience time. Both are defined in subsequent sections.

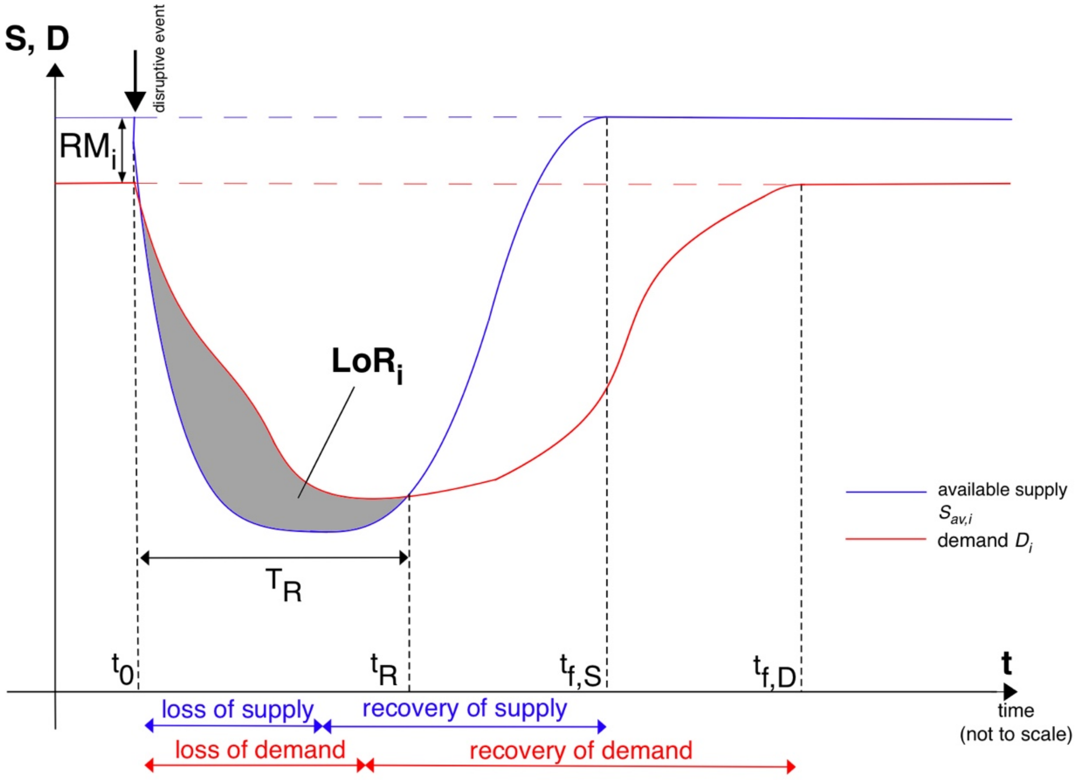


Fig. 4.1 Lack of Resilience at the component level

To illustrate this resilience concept, consider, for example, a local water well, where the small community obtains all of its potable water supply. For such a local well, $D_i(t)$ would be the water demand of the entire community. In the case of an electric substation of a city, $D_i(t)$ would be the power demand of all buildings and systems connected to that substation. Similarly, $S_{av,i}(t)$ would be the water supply capacity of the well or the electric power available at the distribution substation at time t.

Depending on the scope and duration of the resilience assessment, different values of t_0 and t_1 can be chosen. For the calculation of the disaster resilience of a CIS, the start of resilience assessment t_0 is often set to the moment of occurrence of a disaster. The end of resilience assessment t_1 can theoretically be set to infinite. For practical reasons, e.g. for strategic planning of the system operator, financial or insurance aspects, it might be set to the moment when the potential demand or the supply attain their pre-disaster levels, $t_{f,D}$ and $t_{f,S}$, respectively, or the moment when the supply again meets the demand (t_R), or to the control time, Cimellaro et al. (2010), or to the lifetime of the system.

Conditioning to a specific hazard level, statistical analysis of the LoR_i can be conducted in a classical Monte Carlo setting. The results of this approach would lead to component resilience loss curves. The single LoR_i can also be multiplied by a cost quantification or utility function q, which allows to monetarize the expected *Lack of Resilience*.

To obtain a dimensionless and comparable *Lack of Resilience* metric, the obtained LoR_i can be normalized by the cumulative service demand over the resilience assessment period, $\int_{t_0}^{t_1} D_i(t)dt$. This normalization is chosen for two reasons: 1) the proposed definition of resilience is demand-oriented: if all of the demand can be supplied, no *Lack of Resilience* is observed; and 2) at the system level, the total (potential) demand can be quantified, which is usually not the case for the available supply.

The normalized metric for the *Lack of Resilience* at a node *i*, $\widehat{LoR}_i$, over the resilience assessment period $t_0 \le t \le t_1$, is therefore given by:

$$\widehat{LoR}_i = \frac{\int_{t_0}^{t_1} \langle D_i(t) - S_{av,i}(t) \rangle dt}{\int_{t_0}^{t_1} D_i(t)dt} = \frac{\int_{t_0}^{t_1} \big(D_i(t) - C_i(t)\big)dt}{\int_{t_0}^{t_1} D_i(t)dt} \tag{4.4}$$

The (component) resilience R_i of node *i* is finally:

$$R_i = 1 - \widehat{LoR}_i \tag{4.5}$$

Note that $0 \le R_i \le 1$, where $R_i = 1$ signifies complete or full resilience of a node, meaning that even when subjected to the assessed disaster (or set of disasters), the demand for a service at node *i* can be covered at every moment, and $R_i = 0$ signifies that the service at node *i* has no resilience if subjected to the assessed event, i.e. none of the demand can be covered during the timeframe of the assessment.

4.1.2 Resilience at a system level

To compute the *Lack of Resilience* of a CIS at a system level, LoR_{sys}, different system and network effects and component interactions need to be consistently taken into account. The available supply at the different nodes depends, for example, on the damage and the recovery of the distribution elements (e.g. cables or pipelines). In some cases, it is possible that the supply from one node can only be distributed to a limited number of other nodes due to technical reasons such as island effects. If parts of the system are disconnected from each other, for example as a consequence of damaged links, separate sets of network components or islands are formed. In this case it is possible that on a system level the total supply still exceeds the total demand, but that there is unsupplied demand in some parts of the network or on a node level. It is, therefore, not possible to simply sum up the demand and the supply across all nodes of the system to obtain the supply deficit at the system level. Instead, supply and demand needs to be evaluated separately for the subsystems formed in the network using the CIS operation model. The *Lack of Resilience* of the entire CIS, LoR_{sys}, over a time period $t_0 \le t \le t_1$, is, thus, the sum of the LoR_i at the nodes of the investigated system:

$$LoR_{sys} = \sum_i LoR_i = \sum_i \int_{t_0}^{t_1} \langle D_i(t) - S_{av,i}(t) \rangle dt = \int_{t_0}^{t_1} \Big(D_{sys}(t) - C_{sys}(t)\Big)\, dt \tag{4.6}$$

where D_{sys} is the potential demand for the entire system and C_{sys} is the service consumption in the entire system. Notice that in general:

$$\int_{t_0}^{t_1} \left(D_{sys}(t) - C_{sys}(t)\right) dt \neq \int_{t_0}^{t_1} \langle D_{sys}(t) - S_{sys}(t)\rangle dt \tag{4.7}$$

Similar to LoR_i, the obtained LoR_{sys} for a given disaster can be multiplied by the probability of occurrence of that disaster and by a cost or a utility function *q* to obtain the expected LoR_{sys} over a given period, the incurred costs, or the (lost) utility, respectively.

The normalized value, $\widehat{LoR}_{sys}$, over a time period $t_0 \leq t \leq t_1$, is given by the aggregate demand D_{sys}:

$$\widehat{LoR}_{sys} = \frac{\int_{t_0}^{t_1} \left(D_{sys}(t) - C_{sys}(t)\right) dt}{\int_{t_0}^{t_1} D_{sys}(t) dt} \tag{4.8}$$

and the resilience R_{sys} of a CIS, over a time period $t_0 \leq t \leq t_1$, is therefore:

$$R_{sys} = 1 - \widehat{LoR}_{sys}, \text{ and } 0 \leq R_{sys} \leq 1 \tag{4.9}$$

The proposes *Lack of Resilience* measure is cumulative and follows conceptually the original resilience measure proposed by Bruneau et al. (2003) in that it represents the (normalized) area between the supply and demand evolution curves as shown in Fig. 4.2.

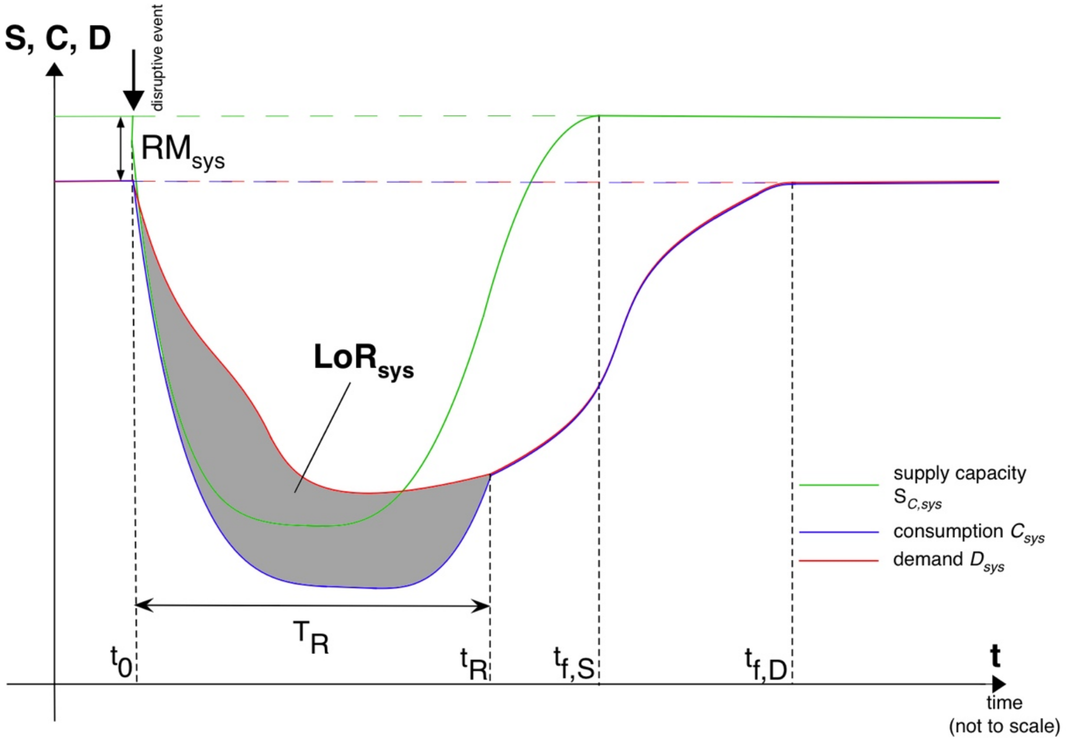


Fig. 4.2 Lack of Resilience at the system level.

Computing the supply, demand and consumption metrics to obtain the *LoR* is trivial only for an isolated node *i*. Such a node is not influenced by any other part of the system. In case of a small community water well discussed above, the service is offered or produced at the same node where the demand is present, making system-level resilience assessment trivial. However, CISs are composed of geographically distributed nodes. Furthermore, the origin of the supply is often disjoint from the demand. Different distribution nodes might compete for a limited supply capacity and influence, thus, the available supply at other nodes of the system. The consumption can, however, in no case exceed the demand, even in the case of redundant, cross-talking or overlapping demand/supply sets. The demand, in turn, can always be accurately evaluated at a distribution or demand node level. For example, a hospital that is connected to the normal electric power supply system and has as well an emergency power generator still presents a well-defined demand to a distribution node as its consumption is limited. If the entire hospital demand is supplied by the normal electric power system, it does not present any demand to the emergency power system and vice-versa.

Unlike the available supply, the consumption at a node is additive and can be aggregated on a system level: $C_{sys}(t) = \sum_i C_i(t)$. Similarly, $D_{sys}(t)$ is the total potential demand at all nodes of the system and $D_{sys}(t) = \sum_i D_i(t)$. The available supply at a node *i*, $S_{av,i}(t)$, corresponds to the actual time-dependent maximum capacity of the supply facilities at that node, $S_{C,max,i}(t)$, reduced by all losses at a supply node level, $S_{C.l,i}(t)$. $S_{C,max,i}(t)$ is for example the theoretical capacity of electric power generators in the case of an electric power supply system, or the capacity of a water well in a water supply system. $S_{C.l,i}(t)$ accounts for the reduction of the maximum capacity due to, for example, damage, ageing, corrosion, fatigue, efficiency losses and technical influences (e.g. due to changes in the available water flow for hydropower generation facilities or due to periodic or exceptional maintenance).

The system demand, supply and consumption are determined using a process schematically shown in Fig. 4.3. The supply produced or made available at supply nodes is transferred by a network of physical or logical links to different distribution nodes, where the service is distributed to the different consumers and, finally consumed. For example, in an electric power supply system the power is often generated at centralized generation plants and then transported by the transmission network to the different consumers. In addition to the effects of the distribution system (e.g. transmission losses), the interactions of the demand nodes and the allocation or dispatch of the service to different nodes made by the system operator needs to be taken into account. These effect, interactions and actions are included in the systems operation model. $S_{C,sys}(t)$ is, finally, the total service supply capacity of the supply nodes of the entire infrastructure system and can be expressed by:

$$S_{av,i}(t) = S_{C,sys}(t) - C_{sys\setminus i}(t) - S_{av,l,tr,i}(t) - S_{av,l,i}(t) \tag{4.10}$$

The system operation model determines the available supply to consume, $S_{av,i}(t)$, at the different distribution nodes, considering the allocation or dispatch strategy of the system operator. The dispatch strategy accounts for the technical functioning of the network and its components and the topology of the network (geographic locations of the distribution and generation nodes, the links in the network, and the capacities of the links and nodes).

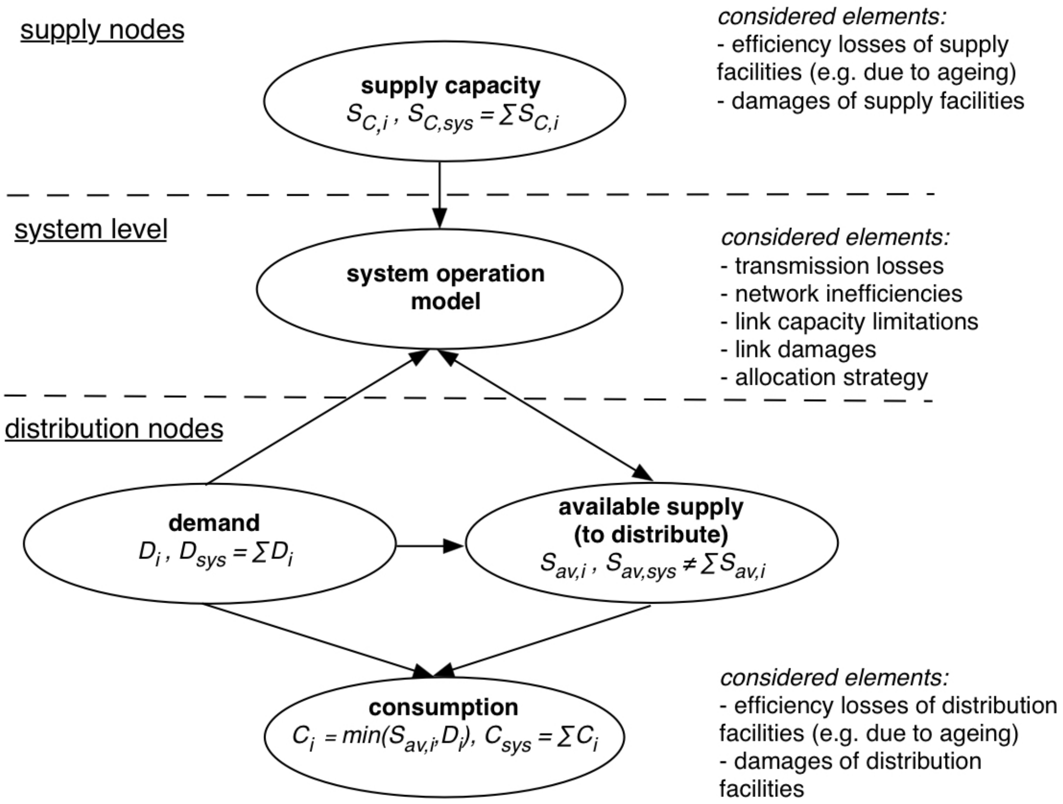


Fig. 4.3 A scheme to determine the demand, supply and consumption in a CIS at the system level.

4.2 ATTRIBUTES OF RESILIENCE IN THE COMPOSITIONAL SUPPLY/DEMAND QUANTIFICATION FRAMEWORK

Bruneau et al. (2003) defined different means and characteristics of resilience: robustness, redundancy, resourcefulness and rapidity. In the proposed compositional demand/supply resilience framework, robustness and redundancy describe the ability of a CIS to assure the coverage of the demand of a service under disaster loads. Resourcefulness and rapidity are closely linked in the proposed framework and are related to the amount of time needed after a disaster to reassure again at least full coverage of the demand.

The reserve margin (or safety margin) is defined as the reserve in supply capacity of a CIS, when compared to the actual demand for the provided service. It can be used as a proxy for the redundancy and robustness of the CIS, as the reserve could be used to substitute (at least in part) the supply capacity lost due to damage to some parts of the system. On a system level the reserve margin at time t, $RM_{sys}(t)$ (Fig. 4.2), is defined as:

$$RM_{sys}(t) = \frac{S_{C,sys}(t) - D_{sys}(t)}{D_{sys}(t)} = \frac{S_{C,sys}(t)}{D_{sys}(t)} - 1 \tag{4.11}$$

This measure accounts for both the redundancy in power supply capacity and the redundant connectivity of the system network. Similarly, on a node level, the reserve margin, $RM_i(t)$ (fig. 4.1), is defined as:

$$RM_i(t) = \frac{S_{av,i}(t) - D_i(t)}{D_i(t)} = \frac{S_{av,i}(t)}{D_i(t)} - 1 \tag{4.12}$$

If $RM(t) > 0$, the demand/supply system has a capacity reserve, in the opposite case, i.e. $RM(t) < 0$, the system has a supply deficit (e.g. an electrical power supply system is shedding load). If no service is available at all, then $RM(t) = -1$.

Using the reserve margin, the robustness RO_{sys} of a CIS can be defined as:

$$RO_{sys} = \min_t \left(\frac{RM_{sys}(t)}{RM_{sys}(t_0)} \right) \tag{4.13}$$

where the start of resilience evaluation t_0 coincides with the moment when the disaster hits the community.

The resilience time T_R is a proxy for the resourcefulness and the rapidity of a CIS system. It covers the duration of the loss accumulation, absorption and recovery phases after a disruptive event. Through a rapid and resourceful intervention losses can be limited or contained during the loss accumulation and absorption phase. Additionally, losses can be limited through a faster, more rapid, recovery during the recovery phase. Resilience time T_R is equal to the duration of the service deficit, i.e. when $C_{sys}(t) < D_{sys}(t)$ on a system level, and $C_i(t) < S_i(t)$ on a node level, corresponding to the duration between t_0 and t_R in Fig. 4.2 and Fig. 4.1, respectively. In the case of occurrence of several disastrous events j (e.g. an aftershock sequence for seismic hazard), shown in Fig. 4.4, T_R is the sum of the different resilience times $\mathrm{T_R} = \sum_\mathrm{j} \mathrm{T_{R,j}}$.

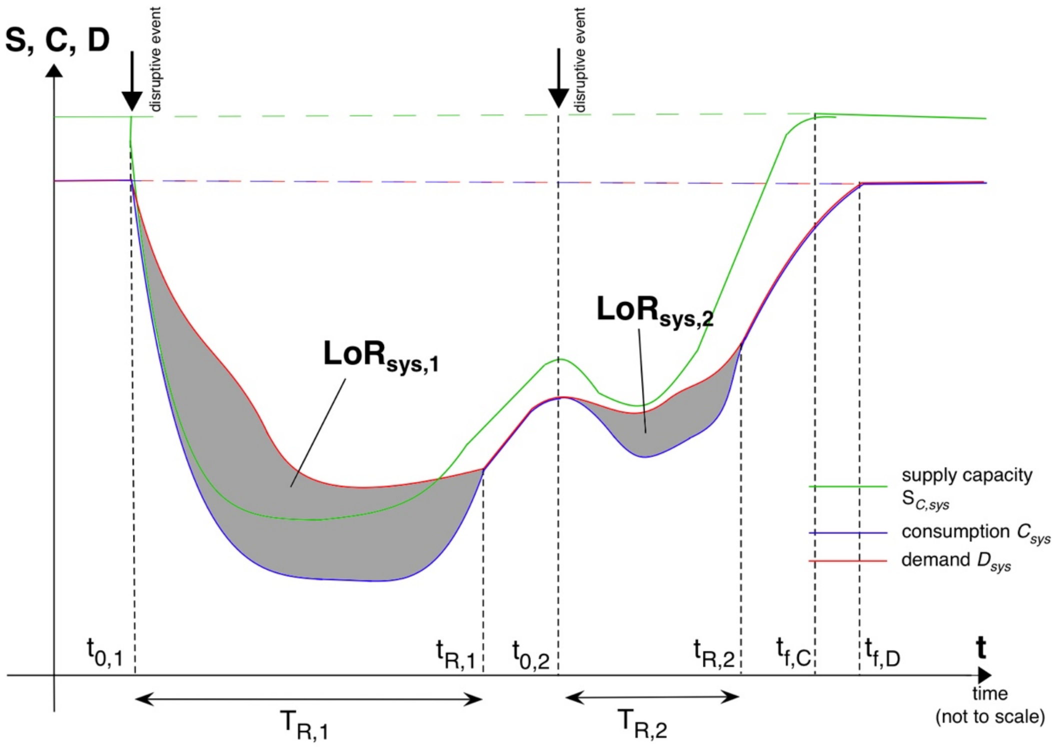


Fig. 4.4 Resilience time T_R in the case of two consecutive disastrous events

4.3 APPLICATIONS OF THE COMPOSITIONAL SUPPLY/DEMAND RESILIENCE QUANTIFICATION FRAMEWORK

The proposed compositional demand/supply resilience quantification framework allows to deal with some limitations of the existing resilience models based purely on the functional performance of the evaluated system. The focus of the resilience assessment using the proposed framework is not on the lost functionality over time, but on the resilience in terms of the ability of the assessed system to supply the time-varying demand of a community.

When a disaster hits a community, changes in both the demand of the community and in the supply provided by the CISs can be expected. The drop in supply depends on the vulnerability of the components forming the assessed CIS. Non-redundant CISs composed of vulnerable components tend to have a more prominent drop in performance then robust and redundant ones. Similarly, demand for services drops more and remains low for a longer period of time in more vulnerable and less prepared communities. The proposed framework accounts for changes in the demand quantity and distribution into account. This important property of the proposed framework is illustrated using three special cases:

a. *The demand decreases or completely disappears*

The most prominent examples for this case are Pompeii, Italy (after the 62 AD Pompeii earthquake and the volcano eruption in 72 AD) and the Fukushima region, Japan (after the Fukushima Daiichi nuclear disaster in 2011). Entire regions might be destroyed or become uninhabitable after major disasters. In these cases, the focus on the recovery of full functionality of lifelines is misleading. Valuable resources and time might be used more efficiently, as there is no need for a recovery of the CISs if no community exists anymore to provide the supply to. The proposed compositional demand/supply resilience framework covers those cases, as shown in Fig. 4.5.

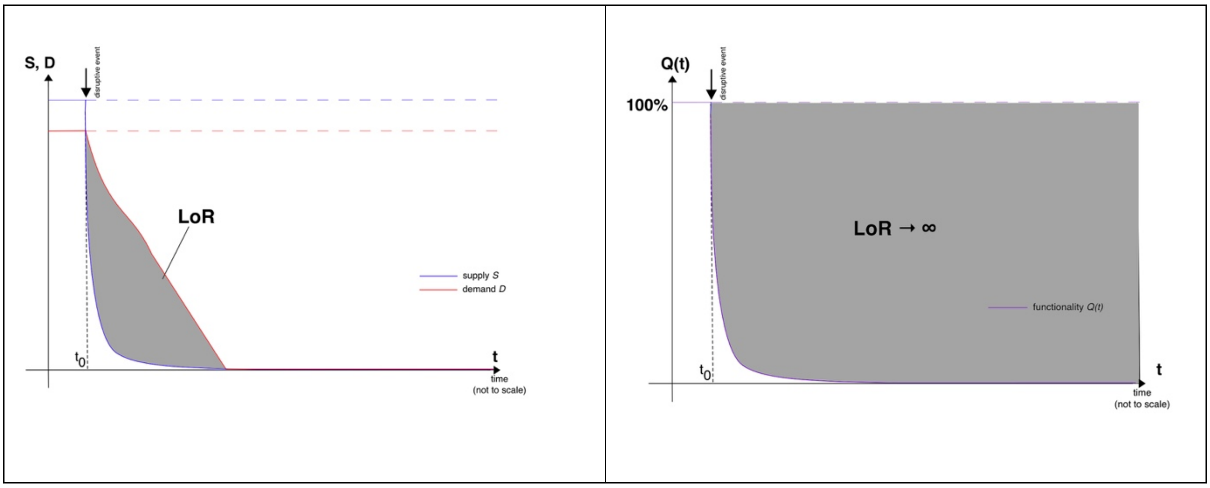


Fig. 4.5 Lack of Resilience in the compositional framework (left) and in a functionality-based resilience framework (right), in a Pompeii-like scenario.

b. The demand switches to other geographic locations

During major disasters, a huge part of the population might be displaced or economic activities might switch to other geographic locations. An example for this case is the port of Kobe after the 1995 earthquake. Precious resources have been allocated for the rebuilding of the port, however, until now, it has never reached its past activity again. For example, container transshipments cargo traffic in 2014 87.6% of the pre-disaster levels as it has switched to other ports (City of Kobe 2014). Such situations are not covered by functionality-based, supply side, resilience frameworks, but can be quantified using the proposed framework by taking changes in demand into account as shown in Fig. 4.6. The same is true if large parts of the population are reallocated to other regions. In such cases there is also no need to recover CIS services to the initial, pre-event levels. Instead, the CISs in the newly populated areas might need to be upgraded. Such considerations may help to better plan the post-disaster recovery process.

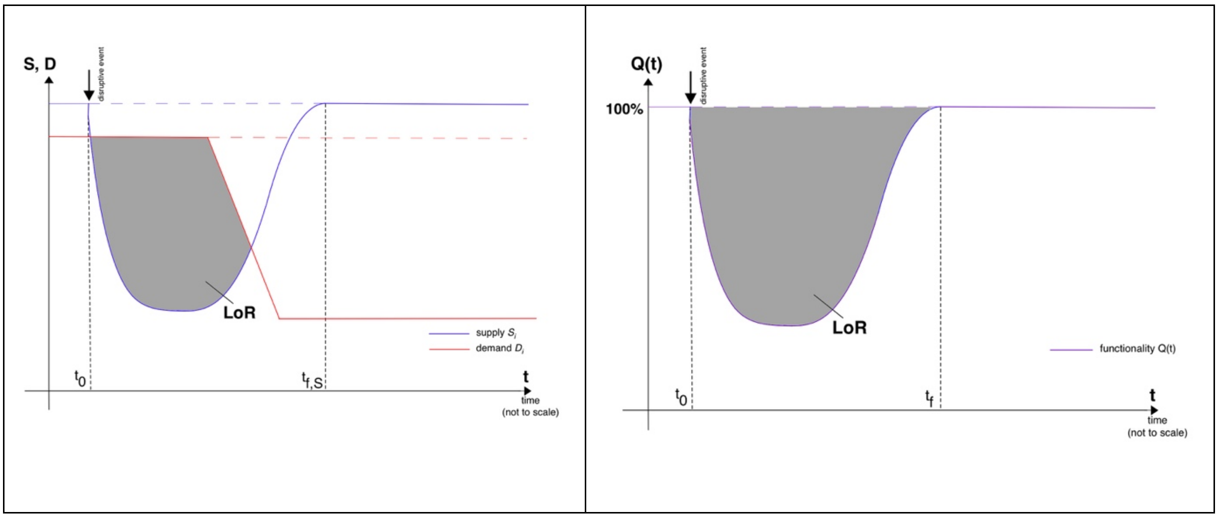


Fig. 4.6 Lack of Resilience in the compositional framework (left) and in a functionality-based resilience framework (right), in a Port-of-Kobe-like scenario.

c. The demand increases in the aftermath of an event

The communication network and hospitals in particular, and, at least locally, the transportation systems, are expected to be confronted by a significant increase in demand after a major catastrophe (the emergency phase). Even if those CISs stay fully functional (i.e. there is no loss of resilience in a functionality-based resilience framework), it might be possible that the CISs are not able to cover the post-disaster demand. In the aftermath of the 2011 Japan earthquake, demand to the telecommunication system is indicated to have increased up to 8 or 10 times the normal demand. The proposed compositional demand/supply resilience quantification framework correctly identifies such demand-induced *Lack of Resilience*, as shown in Fig. 4.7.

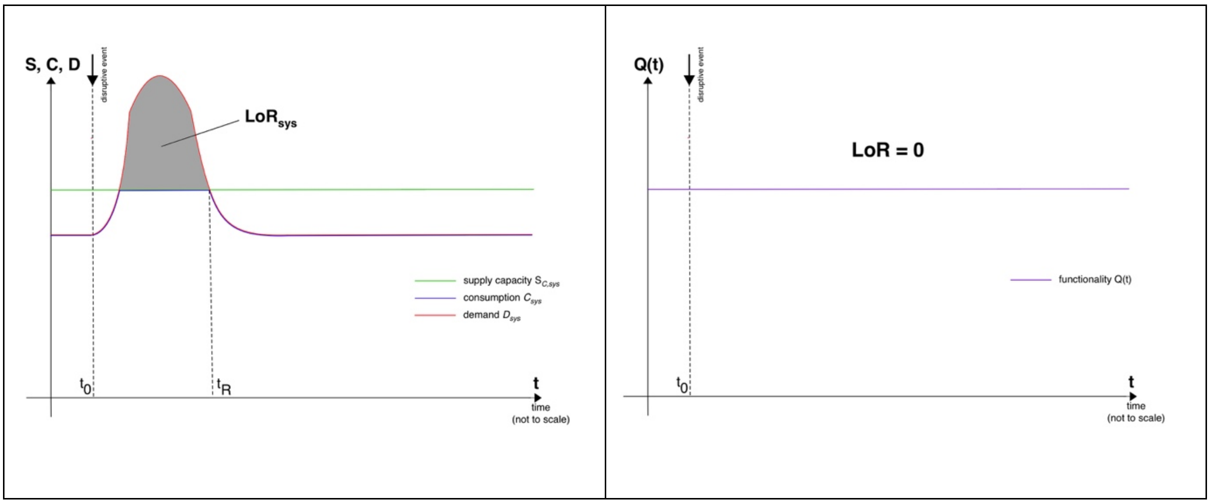


Fig. 4.7 Lack of Resilience in the compositional framework (left) and in a functionality-based resilience framework (right) for an intact cellular network facing an increase of post-disaster demand.

Instead of imposing a recovery back to the past, pre-disaster state (considered as optimal state in a functionality-based framework), the proposed compositional supply/demand resilience quantification framework allows for a flexible adaptation to the actual post-disaster situation. It is able to account for different recovery priorities and different rates of recovery of different community systems (e.g. the electrical power supply systems may recover in a few days, while the built inventory may require significantly more time). Ability to identify and quantify such situations using the proposed framework makes it possible to optimally allocate the sparse resources and financial means in the aftermath of a disaster, with a focus not only on the immediate emergency but also on the long-term recovery and rebuilding of the affected community, accounting for the future evolution of both the demand and the supply side. For example, during the 2009 L'Aquila earthquake the gas pipe network was modified in response to a new set of needs: inaccessible zones were bypassed, the gas network in L'Aquila downtown was completely replaced, missing links added, and temporary or new urbanized areas connected (Esposito et al. 2013). The topology and operation of the L'Aquila gas networks changed significantly in the aftermath of the 2009 earthquake. Therefore, it is difficult to compare its functionality to the pre-disaster level.

5 Conclusions

5.1 STRESS-TESTING COMMUNITY RESILIENCE

Natural hazards such as earthquakes (and tsunami), hurricanes, and floods can damage a community's built environment, which in turn can disrupt the security, economy, safety, health, and welfare of the society. In response, many communities have developed and implemented regulatory frameworks to ensure minimum levels of performance for individual parts of the built environment.

A regulatory framework provides the legal and technical basis for allowing a system to operate through all phases of its lifecycle. It comprises three basic elements: regulations, mechanisms for enforcing the regulations, and guidance for satisfying the regulations. The following paragraphs discuss each element in further detail.

Regulations include codes, standards, and other documents that specify the rules, requirements, and provisions for a system. Regulations typically exist in the public domain and carry the weight of law. If a system does not comply with regulations, it can potentially face a variety of penalties, ranging from fines and lawsuits to temporary or permanent shutdown of the system. Regulations typically arise in response to societal problems. For example, in the United States, building codes were developed to protect the public from unsafe living and working conditions brought about by poorly designed, constructed, and maintained buildings.

Enforcement mechanisms include the agencies and organizations charged with interpreting and enforcing the regulations. These agencies and organizations are commonly referred to as regulators. Enforcement is a crucial component in any framework. Without it, system operators and designers might ignore certain regulations if they impose significant cost or burden.

Guidance includes anything that aids in satisfying the regulations. It can range from written documents developed by technical societies (and later adopted by regulators) to electronic communications with regulators. Guidance is typically optional, providing one of many possible ways to satisfy the regulations. Often, however, guidance becomes the de facto means to satisfying the regulations and thus plays a crucial role in a regulatory framework.

A regulatory framework is ideal when it produces systems that are also ideal. An ideal system is safe, serviceable, compatible, durable, and analysable (adapted from Bea 2007 and Bea 2008) Again, the word ideal refers to an abstract or hypothetical optimum. Therefore, an ideal regulatory may not be realistic; however, it represents a desirable end point that, to the extent practical, should be aspired to. In general, an ideal regulatory framework is expansionist (top-down), risk-informed, comprehensive, performance-based, probabilistic, technology-neutral, transparent, acceptable, feasible, consistent, and enforceable (adapted from ONRR 2007, USNRC 1998).

Notably, researchers have only recently started to develop elements of the regulatory framework to formally regulate the resilience of the community built environment as a system of systems, including CISs (e.g. Miles and Chang 2006, Mieler et al. 2015). Communities are eager to implement the outcomes of such research, and some have already undertaken this task (Poland et al. 2009). Development of a framework that regulates the resilience of communities (societal resilience) is a key step to enable structured evaluation of societal resilience, establishment of community resilience performance objectives, engineering of systemic community resilience, and, thus, design of resilient communities. Given the complexity of community systems (Fig. 2.2) and CIS (Fig. 2.1), this effort is necessarily multidisciplinary, involving hazard sciences, engineering disciplines and systems engineering, urban planning, economy, sociology, and public policy.

The stress test methodology and framework, ST@STREST (Fig. 5.1 Fig. 5.1), developed in Work Package 5 of this project addresses the regulation, enforcement and guidance aspects of a regulatory framework for evaluation and design of resilient CIS. The methodology is expansionist and acceptable, as it mandates a top-down view of the CIS and a clear statement of the acceptance criteria for the CIS assessment in the pre-assessment phase; risk-informed, comprehensive and technology-neutral, as it addresses the hazard and the consequences of the hazard (the risk) on the components of the systems and the system itself without referring to specific component or system technologies in the in the assessment phase; probabilistic, performance-based, transparent and consistent, as it addresses the outcome of the assessment, points to the critical components and systems, and offers guidance on how to proceed with assessment improvement in the decision phase; and enforceable, providing a graded outcome on a common scale that allow comparison of different infrastructure systems in different natural and social settings in the decision phase. The ST@STREST framework supports the methodology in that it provides for the hazard assessment (results of Work Package 3) and vulnerability assessment (results of Work Package 4) at both the component and the system levels. The feasibility of the ST@STREST methodology and framework has been demonstrated through its application to stress test six different CISs: a high dam, a port, a refinery, an industrial zone, an oil pipeline, and a natural gas network (results of Work Package 6).

The ST@STREST methodology is, in this stage, focused on the assessment of CIS vulnerability, i.e. on the loss accumulation phase of the CIS resilience process (Fig.1.2). However, the methodology can be expanded to evaluate not only the vulnerability but also the planning (loss absorption) and the recovery phases of the CIS resilience process. To do this, the ST@STREST framework needs to be expanded to include the recovery functions for CIS components (the counterparts of vulnerability functions), models of the recovery process including the estimates of the needed resources (material, equipment, workforce, money), and operation models of the CISs in both normal and emergency conditions. Feasibility studies of CIS resilience evaluation have already been conducted (Didier et al. 2015, Sun et al. 2015). More important, communities, regulators, CIS operators and researchers need to work together to formulate the performance objectives that define the desired levels of community resilience and define the community resilience, and therefore by derivation the system and component, acceptance criteria. Only then, with such acceptance criteria in place, will it be possible to use a stress test, as one of the regulatory tools, to examine and regulate the CIS, community and societal resilience.

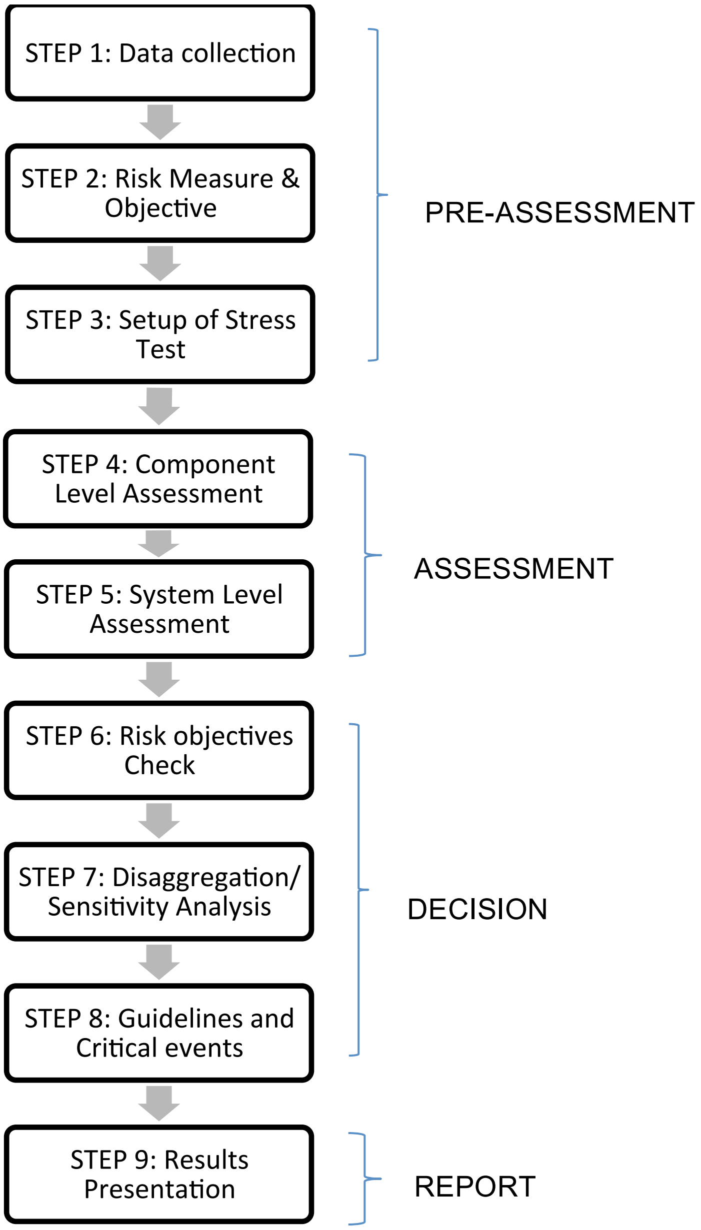


Fig. 5.1 Workflow of the ST@STREST methodology (Report WP5.1, Esposito et al., 2016).

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