**POLITECNICO DI TORINO**

FINAL PROJECT

# MEASURING RESILIENCE AT THE COMMUNITY SCALE: THE PEOPLES FRAMEWORK

Author: Joan Puigdellivol Goday

Tutor: Gian Paolo Cimellaro

Academic year: 2012-2013

# MEASURING RESILIENCE AT THE COMMUNITY SCALE: THE PEOPLES FRAMEWORK

Gian Paolo Cimellaro[1], Chris Renschler[2], Andrei M. Reinhorn[3]

## ABSTRACT

The paper is proposing a holistic framework for defining and measuring disaster resilience for a community at various scales. Seven dimensions characterizing community functionality have been identified and are represented by the acronym PEOPLES: Population and Demographics, Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital. The proposed framework provides the basis for development of quantitative and qualitative models that measure continuously the functionality and resilience of communities against extreme events or disasters in any or a combination of the above-mentioned dimensions. Over the longer term, this framework will enable the development of geospatial and temporal decision-support software tools that help planners and other key decision makers and stakeholders to assess and enhance the resilience of their communities.

Keywords: Community functionality; disaster resilience; population and demographics; environment/ecosystem; organized governmental services; physical infrastructure; lifestyle, community competence; social and cultural services.

---

[1] *Assistant Professor, Department of Structural, Building & Geotechnical Engineering (DISEG), Politecnico di Torino, 10129 Torino, Italy, E-mail: gianpaolo.cimellaro@polito.it*
[2] *Associate Professor, Department of Geography, University at Buffalo, SUNY, 116 Wilkeson Quad, Buffalo, NY 14261, U.S.A. E-mail: rensch@buffalo.edu.*
[3] *Professor Emeritus, Department of Civil, Structural & Environmental Engineering, University at Buffalo (SUNY), 135 Ketter Hall, North Campus, 14260-4300, Buffalo, NY, U.S.A. reinhorn@buffalo.edu*

## 1.1 Introduction

Over the past years, the concept of resilience has gained attention recognizing the fact that not all threats or disasters can be averted. In fact, communities around the world are turning their attention to efforts and ways that can enhance their resilience against extreme events of any kind. Resilience is becoming increasingly important for modern societies as States start accepting the fact that they cannot prevent every risk from being realized, but rather they must learn to adapt and manage risks in a way that minimizes impact on human and other systems.

This paper intends to provide a framework which is able to manage risks in a community at different scales (local, regional etc.), minimizing all the possible consequences and reaching as soon as possible the initial conditions again. The framework represents a new step in risk prevention and resilience management. It is based on seven dimensions which encompass all the key parameters of a modern society.

## 1.2 Defining Resilience

The concept of resilience does not have a unique definition, because of its broad utilization in the field of ecology, social science, economy, and engineering with different meanings and implications.

As Klein *et al.* stated (2003), the root of the term has to be found in the Latin word '*resilio'* that literary means 'to jump back'. The field, in which it was originally used, first, is still contested, however, it has been claimed that the study of resilience evolved from the disciplines of psychology and psychiatry in the 1940s, and it is mainly accredited to Norman Garmezy, Emmy Werner and Ruth Smith.

The concept of resilience was originally established in the field of ecology by Holling (1973) who stated that for ecological systems resilience is “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables. Stability represents the ability of a system to return to an equilibrium state after a temporary disturbance; the more rapidly it returns to equilibrium and the less it fluctuates, the more stable it would be”.

The researches in resilience have forced to study it deeper and in a wider way. An extended literature review has been elaborated about resilience for years (Table -1), each contribution has added new nuances. Primarily resilience has been defined in context to the speed of systems to go towards equilibrium (Adger, 2000), capability to cope and bounce back (Wildavsky, 1988), ability to adapt to new situations (Comfort, 1999), be inherently strong and flexible and adaptive (Tierney & Bruneau, 2007), ability to withstand external impacts and recover with least outside interferences (Mileti, 1999).

After the original definition of resilience in ecological systems, the word expanded its meaning to *engineering*, *social* and *economical* fields.

In *engineering,* resilience is defined as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must (Allenby and Fink, 2005). The main difference in defining and understanding resilience arises between the engineering approach that resilient recovery occurs by moving towards the previous stable state (Bruneau et al., 2003), and the ecological approach that resilience is developed to move towards a different system state (Handmer & Dovers, 1996).

*Social resilience*, explained by Adger (2000), is the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change.

*Economic resilience* was first defined by Rose and Liao (2005) as the inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses. It has mainly been studied in context to seismic response and recovery (Tierney, 1997; Bruneau et al., 2003), community behavior (Chang & Shinozuka, 2004) and disaster hazard analysis (Rose, 2004b), among others (Rose,2009a). From the literature described above it appears that even though there are different opinions in defining resilience, there is some consensus in the measurement of system resilience. Generally resilience is measured in terms of the amount by which a system is able to avoid maximum impact (static resilience (Rose, 2004a)/robustness (McDaniels et al., 2008)) and the speed at which the system recovers from a disruption (dynamic resilience (Rose, 2004a)/ rapidity (Zobel, 2010)).

As the research advances, one realizes that resilience must be studied on a global level and not individually. Bruneau et al. (2003) consider four types of resilience: *technical*; *organizational*; *social*; and *economical*, (TOSE). They note that different measures of resilience are needed to adequately address these different dimensions. Technical and economic, are related to the resilience of physical systems, and organizational and social, are more related to the community affected by the physical systems. *Technical resilience* concerns the ability of a system to function. Some measures of technical resilience for electric power systems are the percentage of demand met, the ratio of supply to demand, time to restoration, time to full recovery, etc. *Organizational resilience* concerns the ability of the organization(s) to manage the system. For example, measures of organizational resilience could include how well emergency units function, how quickly spare parts are replaced, how quickly repair crews are able to reach the affected components of a system, etc. *Social resilience* concerns how well society copes with the loss of services as a result of a blackout. For severe blackouts, social resilience can be the most critical dimension of resilience. Finally, e*conomic resilience* concerns the ability to reduce direct and indirect economic losses. Rose and Liao (2005) note that direct costs manifest themselves in four ways: lost sales; equipment damage/restart costs; spoilage of variable inputs; and idle labor costs (in addition to the costs of measures to reduce potential losses, such as backup generators and capacity expansion). Indirect costs are multipliers that ripple through the economy, such as impacts on the customers and suppliers of a disrupted firm, decreased consumer spending, decreased investments in the disrupted firm, public-health problems (such as dysfunctional sewage treatment), and economic disorder (looting, etc.)

After the 4 dimension framework provided by Bruneau *et al.* (2003) various studies have been carried out, with the goal of practically evaluate the concept of resilience and identify the main units of measurement of it (Miles and Chang, 2011). In this paper, is intended to expand the holistic resilience approach with a seven dimension framework known by the acronym PEOPLES: *Population and Demographics, Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructure, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital*. The seven dimensions are used to characterize the community functionality for defining and measuring disaster resilience at various scales.

### 1.3 Mathematical definition of Resilience

The resilience index is illustrated graphically in Figure -1 as the normalized shaded area underneath the functionality function of a system *Q(t).* Analytically, *Resilience* is defined as

$$R(\vec{r}) = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(t)/T_{LC} \, dt \qquad (1)$$

where $Q_{TOT}(t)$ is the global functionality of the region considered which will be described in the next paragraph; $T_{LC}$ is the control time of the period of interest; $\vec{r}$ is a position vector defining the position *P* in the selected region where the resilience index is evaluated (Cimellaro et al. 2009, 2010). The community functionality is the combination of all functionalities related to different facilities, lifelines, etc.

### 1.4 Spatial vs. temporal scale of Community Resilience

Resilience can be considered as a dynamic quantity that changes over time and across space. It can be applied to engineering, economic, social, and institutional infrastructure, and it can be used for various geographic scales.

The first step to quantify the resilience index (*R*) is to define the *spatial scale* (e.g. building, structure, community, city, region, etc.) of the problem of interest (Figure -2). It is important to mention that the entire recovery process is affected by the *spatial scale* of the disaster. Huge disasters will take longer recovery process. The *spatial scale* will also be used to define the performance measures for the global functionality of the system. The second step is to define the *temporal scale* (short term emergency response, long term reconstruction phase, midterm reconstruction phase, etc.) of the problem of interest. The selection of the control period $T_{LC}$ will affect the *R* index, therefore when comparing different scenarios the same control period should be considered.

## 1.5 The seven dimensions of Community Resilience

In order to emphasize the primary role of the human system in community sustainability, the acronym “PEOPLES” (Renschler et al. 2010, 2011) has been adopted to describe a framework that is built on and expands previous research at the Multidisciplinary Center of Earthquake Engineering Research (MCEER). This framework linked several previously identified resilience characteristics (technical, organizational, societal, and economic) and resilience attributes (r4: *robustness, redundancy, resourcefulness, and rapidity*) (Bruneau et al. 2003; Bruneau and Reinhorn, 2007; Cimellaro et al. 2010b). These are the four attributes along which resilience can be improved. Further details about the description of these attributes can be found in Cimellaro et al. (2010b).

PEOPLES incorporates MCEER’s definitions of service functionality, and its components (assets, services, demographics) and parameters influencing resilience.

The seven dimensions of the PEOPLES framework are the following:

(1) **P**opulation and demographics;

(2) **E**nvironment/ecosystem;

(3) **O**rganized government services;

(4) **P**hysical infrastructure;

(5) **L**ifestyle and community competence;

(6) **E**conomic development;

(7) **S**ocial-cultural capital

In Table -2 is shown the complete list of components and sub-components of the "PEOPLES Framework". The dimensions will be explained in the next points but further details about the description of each one can be found in Renschler et al. (Renschler et al., 2010, 2011).

### 1.6 Population and demographics

The first dimension *Population and demographics* is used to describe and differentiate communities using for example the *median income* and *age distribution* which might be critical for understanding its economic, health and potential resilience. One measure of the functionality of this dimension ($Q_p$) can be quantified for example by using the social vulnerability index (SoVI) proposed by Cutter (1996). Social vulnerability is defined as the inability of people, organizations, and societies to withstand adverse impacts from multiple stressors to which they are exposed. These impacts are due in part to characteristics inherent in social interactions, institutions, and systems of cultural values. Social vulnerability is a pre-existing condition of the community that affects the society's ability to prepare for and recover from a disruptive event.

*Resilience* focuses on the quality of life of the people at risk and develops opportunities to enhance a better outcome, while *vulnerability* places stress on the production of nature to resist the natural hazard. Manyena (2006) evaluates all the possible definitions provided from the 90's up until the present, and compares the concept of *resilience* as the opposite of *vulnerability*.

This dimension of vulnerability can be measured using a social index that describes the socioeconomic status, the composition of the population (elderly and children), development density, rural agriculture, race, gender, ethnicity, infrastructure employment, and county debt/revenue. The social index described is based on Cutter's Hazards-of-Place Model of Vulnerability framework that integrates exposure to hazards with the social conditions that make people vulnerable to them (Cutter, 1996; Cutter et al., 2000). High SoVI indicates high vulnerability, and conversely, low SoVI indicates low vulnerability. Analytically, functionality of population can be given as follow:

$$Q_P(\mathbf{r},t) = 1/\left(f1 + f2 + f3 + f4 + f5 + f6 + f7 + f8 + f9 + f10 + f11\right) \quad (2)$$

where $f_1$, $f_2$, .., $f_n$ are the 11 independent factors considered. Among the 11 independent factors are *socioeconomic status*, *elderly and children*, *development density*, *rural agriculture, race, gender, ethnicity, infrastructure employment, and county debt/revenue*. Additionally, qualitative and quantitative measures about population and demographics from the US Census database are an essential component for this dimension of the PEOPLES Resilience Framework. Key indicators include educational attainment, marital status, annual income, age, gender, race/ethnicity distribution, and other data that describe and differentiate the focal population.

### 1.7 Enviromental/Ecosystem

The *Environmental/Ecosystem* dimension is typically measured by the amount of disturbance an ecosystem can absorb without drastically altering its functions, processes, and structures, or by the ability of an ecosystem to cope with disturbance.

In the context of the *PEOPLES Resilience Framework*, environmental and ecosystem resources serve as indicators for measuring the ability of the ecological system to return to or near its pre-event state. One such indicator is the Normalized Difference

Vegetation Index (NDVI), which is calculated from satellite-derived remote sensing imagery that analyzes the density of green vegetation across a region. NDVI can be used in the framework as a proxy for ecosystem productivity and is calculated using the red (Red) and near infrared (NIR) absorption bands:

$$NDVI = (NIR - Red)/(NIR + Red) \tag{3}$$

NDVI correlates strongly with above-ground net primary productivity (NPP) (Pettorelli, 2005; Olofsson et al., 2007, Prince, 1991), which measures biomass accumulation and can be an indicator of ecosystem resilience. Simoniello et al., (2008) characterized the resilience of Italian landscapes using a time series to calculate NDVI trends, and Diaz-Delgado et al. (2002) used NDVI values derived from Landsat imagery to monitor vegetation recovery after fire disturbance.

Building on previous research, the *PEOPLES Resilience Framework* quantifies a portion of ecological resilience through a comparison of stable-state NDVI trends to post-disturbance NDVI trends to determine differences in ecosystem productivity across spatial-temporal scales. NDVI is applicable for quantifying ecosystem structure following disturbances such as fire, flooding, and hurricanes. In other types of disasters such as terrorist attacks or blizzards, vegetation density and ecosystem structure may not be altered. In these instances, ecological resilience quantification through NDVI would be negligible and other indicators would be more relevant. As with the other dimensions, ecological resilience is the integration of all key indicators that include air, water and soil quality, biodiversity, and other natural resources.

## 1.8 Organized governmental services

*Organized governmental services* dimension include traditional legal and security services such as police, emergency, and fire departments and increasingly, the military. In this dimension, are also included the services provided by public health and hygiene departments as well as cultural heritage departments. Each of these organized government services plays a key role in sustaining communities both before and after extreme events. A good example of the necessity of a well-functioning government may be seen in the devastating January 12, 2010 earthquake in Haiti. In the aftermath, the news media reported a lack of government services and orderly control, and a general perception that the government is not in a position to help its people (Schwartz, 2010). In contrast, the Darfield earthquake in New Zealand was followed by quick response on the part of local, territorial, and national government services.

Spontaneous helping behavior, convergence, mass volunteering, and emergent groups are sources of resilience, in that they infuse resources and creativity into disaster response activities (Stallings and Quarantelli, 1985; Drabek and McEntire, 2002). At the level of organizations and networks, organizational responses during crisis are most likely to be effective—and resilient—when they successfully blend discipline and agility (Harrald, 2006). Pre-existing plans, training, exercises, mutual aid agreements, and other concepts of operations help ensure disciplined and appropriate responses, but they do so not because they encourage the playing out of pre-determined scripts but rather because they facilitate collective sense-making and inspire action toward shared goals (Weick, 1995; Weick et al., 2005). Flexibility, adaptability, and improvisation among responding entities make their own distinctive contributions to resilience.

Organizational expansion, extension, and emergence are key bases of resilient disaster responses (Sutton and Tierney, 2006).

The concept of collaborative emergency management seeks to engage all critical community sectors in preparing for and responding to disasters, including local elected and appointed officials; subject matter experts; community-based, faith based and other non-governmental organizations, the general public, including both community members that belong to groups such as community emergency response teams and volunteers; the private sector and business networks; and the mass media (Patton, 2007). Collaborative management, as opposed to top-down direction, is another characteristic of resilient systems. Hierarchies tend to stand in the way of upward information flow, the form of communication that is most essential during disasters. Less hierarchical forms of organization work best in all types of turbulent environments, including disasters, in part because they encourage a free flow of ideas, but also because flatter organizations and decentralized networks are more nimble in responding to those environments (Burns and Stalker, 1961; Waugh and Streib, 2006).

Key indicators for this dimension include the number of available response units and their capacity. Population and demographic numbers would be used to normalize the number and capacity of these services. In addition to assessing the availability of government services in terms of personnel and equipment, this dimension also includes an evaluation of emergency preparedness planning. For example, surveys may reveal the extent to which organized government services have developed memoranda of understanding (MOUs) and other types of mutual aid agreements, and the extent to which various organized government services participate in emergency and evacuation drills and table-top exercises (Tierney, 2009).

## 1.9 Physical infrastructure

The *physical infrastructure dimension* focuses on a community's built environment. It incorporates both facilities and lifelines while different performance indicators are available in literature.

Within the category of facilities, we include housing, commercial facilities, and cultural facilities. Within the category of lifelines, we include food supply, health care, utilities, transportation (Arcidiacono et. al., 2012), and communication networks (Scura et al., 2013). Lifelines are those essential utility and transportation systems that serve communities across all jurisdictions and locales. Lifelines are thus components of the nation's critical infrastructure, which also includes medical (Cimellaro et al., 2010), financial, and other infrastructure systems that create the fabric of modern society. For clarity, lifeline infrastructures are simply called in short *lifelines* in this report. Lifelines include: (a) energy utilities and companies (electric power and natural gas (Cimellaro et al., 2013) and liquid fuel pipelines); (b) transportation systems (roads and highways, railroads, airports, and seaports); (c) water, storm-water, and sewerage; (d) communication systems; and (e) health care facilities (Cimellaro et al., 2011) (hospitals, emergency facilities, etc), most distributed in well linked networks.

Next to impacts on people, the physical infrastructure is often the most compelling "story" in the immediate aftermath of a disaster, as organized government services work to restore needed utilities and clear roadways of structural and other debris. After people had been evacuated from New Orleans after Hurricane Katrina in 2005, people focused on the physical infrastructure. Everywhere one looked, one saw destroyed houses, commercial buildings, and cultural and other critical facilities such as churches, schools, and hospitals. Photographs of destruction are used to communicate the devastating effects of the hurricane and subsequent flooding to the world outside New Orleans.

Without water and electricity, critical facilities such as hospitals cannot perform effectively their primary functions. Inaccessible roads make surface transportation impossible, creating an obstacle for supply chain management and efficient movement. When streets and buildings are cordoned off because of damage, businesses may be open, but will not be “in business.” Even when businesses relocate for the short-term due to damage to facilities, customers may not find the businesses. Damaged schools shake a community’s confidence in itself to overcome disasters and recover.

In terms of housing, key indicators may include proportion of housing stock not rated as substandard or hazardous and vacancy rates for rental housing (Tierney, 2009). In terms of communication networks, key indicators may include adequacy (or sufficiency) of procedures for communicating with the public and addressing the public’s need for accurate information following disasters, adequacy of linkages between official and unofficial information sources, and adequacy of ties between emergency management entities and mass media serving diverse populations (Tierney, 2009).

In the aftermath of a disaster, the restoration and recovery of physical infrastructure remain by-and-large technical issues; however those are tightly related and often driven by organizations, economics and socio-political events. Resilience must consider these interactive dimensions in order to be relevant to the system; therefore interdependencies among different lifelines should be taken in account during the analysis (Cimellaro and Solari, 2013).

## 1.10 Lifestyle and Community Competence

*Lifestyle Community competence dimension* deals with community action, critical reflection and problem solving skills, flexibility and creativity, collective efficacy, empowerment, and political partnerships (Norris et al., 2008).

This dimension reflects the reality that community resilience is not simply a passive “bouncing back” to pre-disaster conditions (Brown and Kulig, 1996/97) but rather a concerted and active effort that relies on peoples’ ability to creatively imagine a new future and then take the requisite steps to achieve that desired future. It captures both the raw *abilities* of the community (e.g., ability to develop multifaceted solutions to complex problems, ability to engage in meaningful political networks) and the community’s *perceptions* of its ability to effect positive change. Communities that collectively believe that they can rebuild, restructure, and revive themselves are more likely to be persistent in the face of environmental, governmental, and other obstacles.

Quality of life surveys often reveal whether members of a given community are committed to that community and willing to engage in the activities necessary to sustain the community, regardless of whether a disaster strikes. Less soft general indicators of community competence may include measures of migration, measures of citizen involvement in politics, and others. Disaster-specific indicators may include the comprehensiveness of community warning plans and procedures, and the extensiveness of citizen and organizational disaster training programs (Tierney, 2009).

## 1.11 Economic development

*Economic development dimension* includes both the static assessment of a community's current economy (economic activity) and the dynamic assessment of a community's ability to continuously sustain economic growth (economic development).

As described in the RICSA Poverty Project (2010), economic *activity* takes into account the supply of labor for the production of economic goods and services, which includes:

> "All production and processing of primary products whether for market, for barter or for own consumption, the production of all other goods for the market and, in the case of households which produce such goods and services for the market, the corresponding production for own consumption."

Economic *development* addresses the future and growth. It addresses a community's efforts to increase its:

> "productive capacities ..., in terms of technologies (more efficient tools and machines), technical cultures (knowledge of nature, research and capacity to develop improved technologies), and the physical, technical and organizational capacities and skills of those engaged in production."

Resilient communities are characterized by their involvement in a diverse array of products and services that are both produced in and available to the community. Diversity in production and employment is linked to a community's ability to substitute goods and services and shift employment patterns as the situation demands. The *PEOPLES Resilience Framework* incorporates three illustrative subcategories within this dimension: Industry – Production, Industry – Employment Distribution, and Financial Services. Primary indicators of this dimension include the proportion of the population that is employed within the various industries, and the variability that might characterize a community's industrial employment distribution.

This dimension is closely interconnected with the Population and Demographics dimension. For example, key indicators of economic development beyond employment and industry distribution include literacy rates, life expectancy, and poverty rates. Disaster-specific indicators related to economic development include extent of evacuation plans and drills for high-occupancy structures, adequacy of plans for inspecting damaged buildings following disasters, and adequacy of plans for post-disaster commercial reconstruction (Tierney, 2009).

### 1.12 Social/cultural capital

*Social/cultural capital dimension* incorporates several subcategories, including education services, child and elderly services, cultural and heritage services, and community participation. Measuring social/cultural capital requires acquisition of tallies, such as the number of members belonging to various civil and community organizations. It also requires surveys of community leaders and their perceptions (e.g., quality of life surveys).

For example, social support underlies many of the services associated with social/cultural capital. It includes both the "helping behaviors within family and friendship networks" and the "relationships between individuals and their larger neighborhoods and communities" (Norris et al., 2008, p. 139). People choose to provide social and cultural services that manifest and extend their sense of community, defined as an attitude of bonding with other members of one's group Norris et al., 2008). They may feel an emotional connection to their neighborhood or city, which may or may not relate to the people who inhabit those places (Manzo and Perkins, 2006). For example, after Hurricane Katrina, many displaced residents of New Orleans expressed a strong desire to return home, irrespective of the people they knew or the jobs they once had. It seems likely that people with a strong "place attachment" would be more willing to act in order to help their community bounce back after a disaster, assuming that other essential factors such as employment and housing were available. Citizen participation takes into account the "engagement of community members in formal organizations, including religious congregations, school and resident associations, neighborhood watches, and self-help groups" (Norris et al., 2008, p. 139). Participation in community organizations is a means of demonstrating one's care for one's community. Pragmatically, participation in community organizations is a means for meeting and understanding one's fellow citizens. It increases individuals' circle of influence and perception of control.

Measuring social/cultural capital requires acquisition of tallies, such as the number of members belonging to various civil and community organizations. It also requires surveys of community leaders and their perceptions (e.g., quality of life surveys). Disaster-specific indicators include existence of community plans targeting transportation-disadvantaged populations, adequacy of post-disaster sheltering plans, adequacy of plans for incorporating volunteers and others into official response activities, adequacy of donations management plans, and the community's plans to coordinate across diverse community networks (Tierney, 2009).

## 1.13 General framework at community level

The general framework at the community level is described by the equations below, where for each dimension a performance indicator and /or functionality is defined by combining different functionality dimensions:

$$Q_{TOT}(t) = Q_{TOT}(Q_P, Q_{Env}, Q_O, Q_{Ph}, Q_L, Q_{Eco}, Q_S) \qquad (4)$$

where $Q_{TOT}$=global functionality; and $Q_x$=functionality of each of the seven dimensions defined above. Within each dimension, functionality is defined as a combination of functionalities of their respective subsystems. For example, the functionality of the physical infrastructure $Q_{ph}$ is defined as follows:

$$Q_{Ph}(t) = Q_{Ph}(Q_{Hosp}, Q_{Ele}, Q_{Road}, Q_{Water}, \ldots) \qquad (5)$$

where $Q_{hosp}$=functionality of health care facilities; $Q_{Ele}$=functionality of the electric network; $Q_{Road}$=functionality of the road network; $Q_{Water}$=functionality of the water network; etc. Once the geographic scale is defined, it is possible to plot the global functionality $Q_{TOT}$ over the region of interest in a contour plot at a given instant of time t, so *time-dependent functionality maps* of the region can be obtained. When also the temporal scale is defined through the control time $T_{LC}$, then the *resilience contour map* of the region of interest can be plotted (e.g Figure -6). The *Resilience contour map* is obtained by integrating functionality maps over time using Equation (2), therefore they will be *time independent*, but they will vary in space from point to point in the selected region. Finally, the community resilience index $R_{com}$ is given by the double integral over time and space as follows:

$$R_{com} = \int_{A_C} R(\vec{r})/A_C dr = \int_{A_C} \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(t)/(A_C T_{LC}) dt dr \qquad (6)$$

where $A_c$ is the total area of the selected region. For each dimension, a contour plot can be determined and combined using a layered approach as shown in Figure -3. Then a radar graph can be plotted and the area will determine the final value of the resilience score for the region of interest. This will identify gaps as well as priority actions, which will enter in the decision process.

In summary a schematic step-by-step procedure of the MCEER methodology described in Figure -4 is the following:

(1) Define extreme event scenarios (e.g. PSHA and ground motion selection);

(2) Define the system model;

(3) Evaluate the response of the model;

(4) Compute performance measures (e.g. losses, recovery time, functionality, resilience);

(5) Identify remedial mitigation actions (e.g. advanced technologies) and/or resilience actions (e.g. resourcefulness, redundancy, etc.);

This design approach has analogies with the feedback loop taken from control theory. The same framework can be used for a region as well as a single structure (e.g. hospital). In this case, functionality reduces the functionality of a single hospital $Q_{hosp}$ which can be evaluated for example with the procedure described in Cimellaro et al. (2011), where the waiting time of a patient before receiving assistance is the main parameter of response to measure resilience. The hospital performance is described using a double exponential function, called metamodel which is able to estimate the hospital capacity and the dynamic response in real time incorporating the influence of damage of structural and non-structural components.

## 1.14 Recovery models

In general, the performance measure of a community and a system during transient analysis is a function of time *t* and other parameters that depend on the type of a community considered. Therefore at time *t* after the crisis, functionality is given by

$$Q(t) = f\left(t, x_1, \ldots, x_n\right) \tag{7}$$

where $x_1, \ldots, x_n$ are the parameters involved in describing the recovery model. Several models have been presented in Cimellaro et al. (2010a) to describe the recovery function which can be either ***empirical*** or ***analytical*** depending on the source of data and the type of analysis.

**Empirical recovery functions** are based on test or field data interpretation and engineering judgment. They can be built using the maximum likelihood method based on data reported from past extreme events as well as Monte Carlo simulations of specified community models. Since the complexity of the problem changes case by case, no specific model is presented in this part.

**Analytical recovery functions** are developed from community response data obtained through analysis of the system using numerical simulations. For example, for the case of earthquake events, they can be obtained from nonlinear time history analysis, response spectral analysis, etc.

Since the recovery process is characterized by uncertainties, the parameters considered in the model are modeled as random variables in order to quantify the uncertainties in the system. These uncertainties can be divided in aleatoric and epistemic uncertainties (Ang and Tang, 2007).

Several models can be fitted to the observed data, and subsequently, model selection can be carried out using as goodness of fit measure, such as the $r^2$ value. The essential requirement of the analytical recovery models is the simplicity, therefore the model should be selected so that it is easy to fit to real or numerical observation data and the number of parameters involved should be as low as possible. Below are reported five different recovery models which are grouped according to the two control periods (*short term* vs. *long term*). *Long term recovery models* are used when the reconstruction phase needs to be modeled, while *short term recovery models* are used when the emergency phase after the extreme event needs to be focused upon.

Several *long term recovery models* are proposed in Cimellaro et al. (2010). They can be grouped according to the number of parameters (one, two, or three parameters). Complex recovery models with more parameters can be proposed, but simpler mathematical models have benefits over more complex ones. They have fewer unknown parameters, and thus it is easier to fit to data (fewer experiments are needed). There is also less chance of “overfitting”. With more free parameters, a model can be made to fit any data; however, at best the exercise is little more than curve fitting (with little meaningful understanding gained), while at worst the model may give an overconfidence in its predictive ability.

The simplest recovery model is the *uniform cumulative distribution* (cdf) recovery function (also known as the *linear model*). This model is usually adopted when there is no information regarding the preparedness, resources available, societal response, etc.

$$Q(t) = Q_0 + F\left(t/t_0, t_0 + T_{RE}\right)\cdot\left[Q_R - \left(Q_0 - L_0\right)\right] \qquad (8)$$

where $Q_0$ is the initial functionality after the drop; $L_0$ is the initial total loss of functionality after the drop; $Q_R$ is the residual functionality after the recovery process ends; and $F\left(t/t_0, t_0+T_{RE}\right)$ is the uniform cumulative distribution function which is given by

$$F\left(t/t_0, t_0+T_{RE}\right)=\frac{\left(t-t_0\right)}{T_{RE}} I\left(t_0, t_0+T_{RE}\right) \tag{9}$$

where $I(t_0, t_0+T_{RE})$ is the interval step function. The model is characterized by only one parameter (Figure -5a) which defines the slope of the curve and it represents *rapidity* (Cimellaro et al., 2010). The model can also be generalized by dividing the recovery process in several time intervals using a *multilinear model* that is given by

$$Q\left(t\right)=Q_i+\sum_i H\left(t-t_i\right)\frac{\left(t-t_i\right)}{\left(t_{i+1}-t_i\right)}\left(Q_{i+1}-Q_i\right) \tag{10}$$

where $Q_i$ is the residual functionality at the step $i$ and $Q_{i+1}$ is the residual functionality at the step $i+1$; $H(\ )$ is the Heaviside step function.

Alternatively, *lognormal cumulative distribution* (cdf) recovery function, can be adopted, having three parameters ($L_0$, $\theta$, $\beta$), and it is given by

$$Q\left(t\right)=Q_0+F\left(t/\theta,\beta\right)\cdot\left[Q_R-\left(Q_0-L_0\right)\right] \tag{11}$$

where

$$F\left(t/\theta,\beta\right)=\frac{1}{\beta\sqrt{2\pi}}\int_{-\infty}^{t}\frac{e^{-\frac{\left(\log\left(x\right)-\theta\right)^2}{2\beta^2}}}{x}dx \tag{12}$$

This model combines both the exponential recovery model proposed by Kafali and Grigoriu (2005) and the trigonometric recovery model proposed by Chang and Shinozuka (2004). The parameter $L_0$ in Equation (11) can be used to define the initial total loss of functionality after the drop (Figure -5d). The parameter $\theta$ can be used to define the time frame (Figure -5e) when the societal response and recovery are driven by lack or limited organization and/or resources. The parameter $\beta$ defines the rapidity of the recovery process (Figure -5f).

The second group of recovery models is called *short term recovery models* and instead of using *cdf* shape models such as in the long term recovery models, they use the probability density functions (*pdf*) shape models. The simplest recovery model after the linear model proposed in Equation (8) is the Rayleigh probability density function recovery model, and it is defined as

$$Q(t) = 1 - L_0 \frac{f(t|b)}{\max\left(\left|f(t|b)\right|\right)} \tag{13}$$

where

$$f(t|b) = \frac{t}{b^2} e^{\left(\frac{-t^2}{2b^2}\right)} \tag{14}$$

The model is calibrated using two parameters: $L_0$ is related to the robustness dimension (Figure -5b), while $b$ is related to the rapidity and the delay in the recovery process (Figure -5c).

Another model is the *lognormal probability density recovery function* which is given by

$$Q(t) = 1 - L_0 \frac{f(t|\theta,\beta)}{\max\left(\left|f(t|\theta,\beta)\right|\right)} \tag{15}$$

where

$$f(t|\theta,\beta) = \frac{1}{x\beta\sqrt{2\pi}} e^{-\frac{(\log(x)-\theta)^2}{2\beta^2}} \tag{16}$$

The sensitivity of the three parameters on the recovery process is shown in Figure -5g-h-i. In the short term emergency response, more complex analytical recovery models are available such as the *metamodel* for describing the organizational performance of a hospital facility (Cimellaro et al., 2010). The model is based on a *double exponential function* and its parameters are calibrated based on simulated data obtained by a discrete event simulation model. The *metamodel* is capable of estimating the hospital capacity and dynamic response in real-time incorporating the influence of structural and non-structural damaged components on the entire organizational model. It is important to mention that the constants in all the models presented can be continuously updated as soon as more data are available using a Bayesian approach.

### 1.15 Uncertainties in Resilience-Based Design

Either a deterministic or probabilistic approach can be used within the PEOPLES framework methodology with preference to the latter approach when a particular level of confidence of achieving performance objective is of interest. Five random variables are involved in the probabilistic description of the resilience index when uncertainties are included and variables are dependent. The joint probability density function of resilience, intensity, response, performance, and recovery is given by the following expressions

$$f_{R,T_{RE},Q,X,I}\left(r,t_{RE},q,x,i\right)=f_{R,T_{RE},Q,X,I}\left(r\middle|t_{RE},q,x,i\right)\cdot f_{T_{RE},Q,X,I}\left(t_{RE}\middle|q,x,i\right)\cdot f_{Q,X,I}\left(q\middle|x,i\right)\cdot f_{X,I}\left(x\middle|i\right)\cdot f_{I}\left(i\right)$$

(17)

where *I*=intensity measures; *X*=response measures; *Q*=performance measures; $T_{RE}$=recovery time measures; *R*=resilience index; $m_r$=mean resilience index. The marginal PDF of the resilience index is given by

$$f_R\left(r\right)=\int_{t_{RE}}\int_{q}\int_{x}\int_{i} f_{R,T_{RE},Q,X,I}\left(r,t_{RE},q,x,i\right)dt_{RE}\cdot dq\cdot dx\cdot di \qquad (18)$$

Therefore the expected value of the resilience index is given by

$$m_r = E\left\{R\right\} = \int_{-\infty}^{\infty} r\cdot f_{R,T_{RE},Q,X,I}\left(r,t_{RE},q,x,i\right)\cdot dr \qquad (19)$$

## 1.16 Numerical example

The PEOPLES Resilience Framework methodology has been implemented in a software with a user friendly graphical interface in Google earth environment (Arcidiacono et al, 2011). The software is divided in five parts:

1-Input data collection;

2-Damage State Probability Analysis;

2-Resilience analysis;

4-Output data;

5-Decision making;

Further details about the software development can be found in the paper Arcidiacono et al. (2011).

In order to show the implementation issues the old medieval center of L'Aquila historical center, in Central Italy, that was subjected to 2009 L'Aquila earthquake, has been selected for the study. Ten buildings in Piazza del Duomo have been chosen as shown in Figure -6. First the selected buildings have been classified according to the building typology and occupancy level. These features are represented in Table -3. Four different recovery plans are considered having the same limit state characteristics but different site availability - i.e. number of construction sites that might fall within the considered area. The first and fourth scenarios have, respectively, the maximum and minimum availability, that consists having respectively a maximum of 10 and 0 building construction sites per day inside the selected area. The second scenario has the maximum limit of five construction building sites per day and of four simultaneous starts of construction building sites. The third scenario has the limit of one building site per day. In all cases there is no-limit on economic budget. It was found the following results are summarized in Table -4 assuming a return period for the earthquake of 2475 years and a control period of 2 years.

From Figure -6 it is possible to see how are distributed the damage states in all buildings presented in the selected area. In particular, the buildings that have the higher damages are the buildings 1, 2 and 9. Table -5 shows the administrative time, the resilience over the control period and the rank in recovery plan for each building.

From Figure -7, that shows the four functionality functions for each case, it is possible to observe that case I is the most resilient, while case IV has the smallest values of resilience. Case III is like a cumulative sum of all functionality functions of the buildings, because the works follow each other sequentially. The resilience index in Table -6 is defined as the value of community resilience from the disaster time $T_{Dis}$ to the time of completion of the works $T_{CW}$ (at this time the functionality will be equal to 100% or highest value). This index decreases with decreasing of the velocity of recovery, so it is a good parameter to evaluate the performance of the community and of the chosen recovery plan.

## 1.17 Concluding Remarks

The purpose of this study is to identify gaps in the definitions and quantification of resilience at the community scale with the goal of developing a consistent framework that can address simultaneously the assets of the community and their functionality at various geographic and temporal scales. The suggested framework is including an attempt to mix multiple dimensions contributing to the functionality of the community. Moreover, each component is described also as a system with its functionality contributing to the overall community system functionality. As such, a "system of systems" was created. The elements of the new framework were defined and justified based on available information. However, much of the quantification is still in its infancy and requires aggregation of widely used methods in systems analysis and management.

The framework presented in this paper uses as a central part in the definition and quantification of resilience, the basic functionality of various components contributing to community resilience. These functionalities are complex functions of various parameters, which need to be yet defined and quantified, even though several applications of the framework are already available in literature as shown in the reference list. However, there is still much to be done before the implementation of this concept is feasible and efficient. However, the initial framework defined in this paper, can serve as guide for definitions of functionalities, parameters identifications, data collection, computational evaluations, etc.

## 1.18 Acknowledgements

The research leading to these results has also received funding from the European Community's Seventh Framework Programme - Marie Curie International Reintegration Actions - FP7/2007-2013 under the Grant Agreement n° PIRG06-GA-2009-256316 of the project ICRED - Integrated European Disaster Community Resilience.

**References**


Adger, W. N. (2000) Social and ecological resilience: are they related? Progress in Human Geography 24(3): 347-64

Allenby, B. and J. Fink (2005) Toward inherently secure and resilient societies. Science 309(5737): 1034-36.

Arcidiacono, V., G. P. Cimellaro, et al. (2012) Road network resilience assignment methodology. In: *6th International Conference on Bridge Maintenance, Safety and Management (IABMAS2012).* F. B. D. Frangopol. CRC Press Taylor & Francis Group, Stresa, Lake Maggiore, July 8-12, 2012.

Brown, D. and J.Kulig (1996) The conceptof resiliency: Theoretical lessons from community research. Health and Canadian Society 4: 29-52.

Bruneau, M. and A. M. Reinhorn (2007) Exploring the Concept of Seismic Resilience for Acute Care Facilities. Earthquake Spectra 23(1): 41-62.

Bruneau, M., S. E. Chang, et al. (2003) A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities. Earthquake Spectra 19(4): 733-52.

Chang, S. and M. Shinozuka (2004) Measuring Improvements in the Disaster Resilience of Communities. Earthquake Spectra 20(3): 739-55.

Cimellaro, G. P., I. P. Christovasilis, et al. (2010) L`Aquila Earthquake of April 6, 2009 in Italy: Rebuilding a resilient city to withstand multiple hazards. In: *MCEER Technical Report –MCEER-10-0010*. MCEER, State University of New York at Buffalo (SUNY), Buffalo, New York.

Cimellaro, G. P., C. Fumo, et al. (2009) Quantification of Seismic Resilience of Health care facilities In: *MCEER Technical Report-MCEER-09-0009*. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.

Cimellaro, G. P., A. M. Reinhorn, et al. (2010) Framework for analytical quantification of disaster resilience. Engineering Structures 32(11): 3639–49.

Cimellaro, G. P., A. M. Reinhorn, et al. (2010) Seismic resilience of a hospital system. Structure and Infrastructure Engineering 6(1-2): 127-44.

Cimellaro, G. P., A. M. Reinhorn, et al. (2011) Performance-based metamodel for health care facilities. Earthquake Engineering & Structural Dynamics 40 1197–217.

Cimellaro, G. P., O. Villa, et al. (2013) Resilience-Based Design of Natural gas distribution networks. Journal of Infrastructure Systems, ASCE in review.

Cimellaro, G. P., D. Solari, et al. (2013) Interdependency and regional resilience index after 2011 Tohoku earthquake in Japan. Earthquake Engineering & Structural Dynamics in review.

Comfort, L. K. (1999) Shared Risk: Complex Systems in Seismic Response. Pergamon, New York.

Cutter, S. L. and J. T. Mitchell (2000) Revealing the vulnerability of people and places: A case study of Georgetown County, South Carolina. Annals of American Geographers 90(4): 713-37.

Cutter, S. (1996) Vulnerability to Environmental Hazards. Progress in Human Geography 20(4): 529-39.

Department of Homeland Security (DHS) (2008). DHS Risk Lexicon, Risk Steering Committee, U.S. Department of Homeland Security, Washington, D.C.

Díaz-Delgado, R., F. Lloret, et al. (2002) Satellite Evidence of Decreasing Resilience in Mediterranean Plant Communities After Recurrent Wildfires. Ecology 83(8): 2293-303.
Drabek, T. E. and D. A. McEntire (2002) Emergent Phenomena and Multiorganizational Coordination in Disasters: Lessons from the Research Literature. International Journal of Mass Emergencies and Disasters 20: 197-224.
FEMA (2000) FEMA 356 Prestandard and Commentary for the seismic rehabilitation of buildings. In. Federal Emergency management Agency Washington DC.
Fiksel, J. (2003) Designing resilient, sustainable systems. Environmental Science and Technology 37(23): 5330-39.
Gunderson, L. H., C. S. Holling, et al. (2002) Resilience of large-scale resource systems, Washington, D.C.
Haimes, Y. Y. (2009) On the definition of resilience in systems. Risk Analysis 29(4): 498-501.
Haimes, Y. Y., N.C.Matalas, et al. (1998) Reducing vulnerability of water supply systems to attack. Reducing vulnerability of water supply systems to attack 4(4): 164-77.
Handmer, J. and S. Dovers (1996) A typology of resilience: Rethinking institutions for sustainable development. Organization & Environment 9: 482-511.
Harrald, J. (2006) Agility and Discipline: Critical Success Factors for Disaster Response. Annals of the American Academy of Political and Social Science 604: 256–72.
Holling, C. S. (1973) Resilience and Stability of Ecological Systems. Annual Review of Ecology and Systematics 4: 1-23.
Hollnagel, E. (2006) Resilience - the challenge of the unstable, Hampshire.
Holmgren, A. (2007) A framework for vulnerability assessment of electric power systems., New York, NY.
Horne, J. F. and J. E. Orr (1998) Assessing behaviors that create resilient organizations. Employment Relations Today 24(4): 29-39.
Kafali, C. and M. Grigoriu (2005) Rehabilitation decision analysis. In: *ICOSSAR'05: Proceedings of the Ninth International Conference on Structural Safety and Reliability*, Buffalo.
Klein, R. J. T., R. J. Nicholls, et al. (2003) Resilience to natural hazards: How useful is this concept? . Global Environmental Change Part B: Environmental Hazards 5(1-2): 35-45.
Manyena, S. B. (2006) The concept of resilience revisited. Disasters 30: 434.
Manzo, L. and D. Perkins (2006) Finding common ground: The importance of place attachment to community participation and planning. Journal of Planning Literature 20: 335-50.
McDaniels, T., S. Chang, et al. (2008) Fostering resilience to extreme events within infrastructure systems: Characterizing decision contexts for mitigation and adaptation. Global Environmental Change-Human and Policy Dimensions 18(2): 310-18.
Miles, S. B. and S. E. Chang (2011) ResilUS: A community based disaster resilience model. Journal of Cartography and GIS (CAGIS) 38(1): 36-51.
Milleti, D. S. (1999) Disasters by Design: A Reassessment of Natural Hazards in the United States, Washington, D.C.
Norris, F. H., S. P. Stevens, et al. (2008) Community Resilience as a Metaphor, Theory, Set of Capacities, and Strategy for Disaster Readiness. Am J Community Psychol 41: 127-50.

Olofsson, P., L. Eklundh, et al. (2007) Estimating net primary production for Scandinavian forests using data from Terra/MODIS. Space Res 39: 125-30.
Pettorelli, N., J. Vik, et al. (2005) Using the satellite-derived NDVI to assess ecological responses to environmental change. TRENDS in Ecology and Evolution 20(9): 503-10.
Prince, S. (1991) A model of regional primary production for use with coarse resolution satellite data. International Journal of Remote Sensing 12: 1313-30.
Renschler, C., A. Frazier, et al. (2010) Framework for Defining and Measuring Resilience at the Community Scale: The PEOPLES Resilience Framework. In: *MCEER Technical Report –MCEER-10-006, pp. 91*. University at Buffalo (SUNY), The State University of New York, Buffalo, New York.
Renschler, C., A. M. Reinhorn, et al. (2011) The PEOPLES Resilience Framework: A conceptual approach to quantify community resilience. In: *Proceedings of the 3rd International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2011).* M. F. a. V. P. M. Papadrakakis. National Technical University of Athens, Corfu`, Greece,
RICSA (2010) RISCA Poverty Project. URL: http://web.uct.ac.za/depts/ricsa/projects/publicli/poverty.
Rose, A. (2004) Defining and measuring economic resilience to disasters. Disaster Prevention and Management 13: 307-14.
Rose, A. (2004) Economic principles, issues, and research priorities in hazard loss estimation, Springer Verlag.
Rose, A. (2009) Economic resilience to disasters. In. Center for Risk and Economic Analysis of Terrorism Events University of Southern California.
Rose, A. and S. Y. Liao (2005) Modeling regional economic resilience to disasters: A computable general equilibrium analysis of water service disruptions. Journal of Regional Science 45(1): 75-112.
Scura, G., V. Arcidiacono, et al. (2013) Integrated Damage Assessment Communication system using smartphone network during 2012 Emilia earthquake. In: *Vienna Congress on Recent Advances in Earthquake Engineering and Structural Dynamics & 13. D-A-CH Tagung (VEESD2013)*, Vienna, Austria, August 28-30, 2013.
Simoniello, T., Lanfredi, M., Liberti, M., Coppola, R., and Macchiato, M. (2008). Estimation of vegetation cover resilience from satellite time series. Hydrol. Earth Syst. Sci., 12, 1053-1064.
Simoniello, R. A. and E. L. Quarantelli (1985) Emergent Citizen Groups and Emergency Management. Public Administration Review 45: 93-100.
Sutton, J. and K. Tierney (2006) Disaster Preparedness: Concepts, Guidance, and Research, San Francisco, CA.
Tierney, K. (1997) Business impacts of the northridge earthquake. Journal of Contingencies and Crisis Management 5: 87-97.
Tierney, K. and M. Bruneau (2007) Conceptualizing and Measuring Resilience. TR News 250: 14-17.
Tierney, K. (2009) Disaster Responce: Research Findings and their implications for Resilience Measures. In. CARRI Research Report 6, Community & Regional Resilience Institute, Colorado Boulder.
Vugrin, E. D., D. E. Warren, et al. (2010) A Framework for assessing the resilience of infrastructure and economic systems, Springer, Berlin, Germany.
Weick, K. E. (1995) Sensemaking in Organizations, CA: Sage.
Weick, K. E., K. Sutcliffe, et al. (2005) Organizing and the Process of Sensemaking. Organization Science 16: 409-21.

Wildavsky, A. (1991) Searching for Safety, New Brunswick.
Woods, D. D. (2006) Essential characteristics of resilience, Aldershot, UK.
Zobel, C. (2010) Comparative visualization of predicted disaster resilience. In: *7th International ISCRAM Conference*.

Table -1 Literature review about resilience definitions

| Author | Definition |
|---|---|
| Holling (1973) | Ecological systems resilience is a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables. |
| Wildavsky (1991) | Resilience is the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back. |
| Horne and Orr (1998) | Resilience is the ability of a system to withstand stresses of ‘environmental loading’... [it is] a fundamental quality found in individuals, groups, organizations, and systems as a whole. |
| Haimes et al. (1998) | Resilience is the ability of system to return to its optimal condition in a short period of time. Considering resilience one of four strategies for hardening a system, together with security, redundancy and robustness. |
| Mileti (1999) | Local resiliency with regard to disasters means that a locale is able to withstand an extreme natural event without suffering devastating losses, damage, diminished productivity, or quality of life and without a large amount of assistance from outside the community. |
| Comfort (1999) | Resilience is the capacity to adapt existing resources and skills to new situations and operating conditions. |
| Adger (2000) | Social resilience is the ability of groups or communities to cope with external stresses and disturbances as a result of social, political, and environmental change. |
| Gunderson et al. (2002) | Engineering resilience […] is the speed of return to the steady state following a perturbation […] ecological resilience […] is measured by the magnitude of disturbance that can be absorbed before the system is restructured…. |
| Fiksel (2003) | Resilience is the essence of sustainability […] the ability to resist disorder. |
| Bruneau et al. (2003) | Resilience is defined in terms of three stages: the ability of a system to reduce the probability of an adverse event, to absorb the shock if the adverse event occurs, and to quickly re-establish normal operating conditions. So resilience thus encompasses the four characteristics of robustness, redundancy, resourcefulness, and rapidity. Are considered four types of resilience: technical; organizational; economic; and social. |
| Allenby and Fink (2005) | Resiliency is defined as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must. |
| Rose and Liao (2005) | Regional economic resilience is the inherent ability and adaptive response that enables firms and regions to avoid maximum potential losses. |
| Hollnagel (2006) | Resilience is defined as the intrinsic ability of an organization (system) to maintain or regain a dynamically stable state, which allows it to continue operations after a major mishap and/or in the presence of a continuous stress. |
| Manyena (2006) | Evaluating all the possible definitions provided from the 90’s to nowadays, resilience could be viewed as the intrinsic capacity of a system, community or society predisposed to a shock or stress to adapt and survive by changing its non essential attributes and rebuilding itself. |
| Woods (2006) | Evaluating all the possible definitions provided from the 90’s to nowadays, resilience could be viewed as the intrinsic capacity of a system, community or society predisposed to a shock or stress to adapt and survive by changing its non essential attributes and rebuilding itself. |
| Holmgren (2007) | Resilience is the ability of the system to return to a stable condition after a disruption. Distinguishing robustness and resilience, using robustness to imply that the system will remain (nearly) unchanged even in the face of disruption. |

| | |
|---|---|
| Tierney and Bruneau (2007) | Resilience is both the inherent strength and ability to be flexible and adaptable after environmental shocks and disruptive events. |
| DHS (2008) | Resilience is the ability of systems, infrastructures, government, business, and citizenry to resist, absorb, recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national significance. |
| Haimes (2009) | Resilience is defined as the ability of the system to withstand a major disruption within acceptable degradation parameters and to recover within an acceptable time and composite costs and risk. |
| Vugrin et al. (2010) | Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation from targeted system performance levels. |

Table -2 Complete list of components and subcomponents of PEOPLES framework

| | | | |
|---|---|---|---|
| **1) POPULATION AND DEMOGRAPHICS** | | | |
| a) Distribution/Density | b) Composition | c) Socio-Economic Status | |
| i) Urban | i) Age | i) Educational Attainment | iv) Home Ownership |
| ii) Suburban | ii) Gender | ii) Income | v) Housing Vacancies |
| iii) Rural | iii) Immigrant Status | iii) Poverty | vi) Occupation |
| iv) Wildland | iv) Race/Ethnicity | | |
| **2) ENVIRONMENTAL/ECOSYSTEM** | | | |
| a) Water Quality/Quantity | b) Air Quality | c) Soil Quality | d) Biodiversity |
| e) Biomass (Vegetation) | f) Other Natural Resources | | |
| **3) ORGANIZED GOVERNMENTAL SERVICES** | | | |
| a) Executive/Administrative | | b) Judicial | c) Legal/Security |
| i) Emergency Response and | ii) Health and Hygiene | | |
| **4) PHYSICAL INFRASTRUCTURE** | | | |
| a) Facilities | | b) Lifelines | |
| i) Residential | | i) Communications | |
| (1) Housing Units | | (1) Internet (2) Phones (3) TV (4) Radio (5) Postal | |
| (2) Shelters | | ii) Health Care | |
| ii) Commercial | | (1) Acute Care (2) Long-Term Acute Care (4) Psychiatric | |
| (1) Distribution Facilities | (3) Manufacturing Facilities | (3) Primary Care (5) Specialty | |
| (2) Hotels - Accommodations | (4) Office Buildings | iii) Food Supply | |
| iii) Cultural | | iv) Utilities | |
| (1) Entertainment Venues | (4) Schools | (1) Electrical (2) Fuel/Gas/Energy (3) Waste | |
| (2) Museums | (5) Sports/Recreation Venues | v) Transportation | |
| (3) Religious Institutions | | (1) Aviation (2) Bridges (3) Highways | |
| | | (4) Railways (5) Transit (6) Vehicles (7) Waterways | |
| **5) LIFESTYLE AND COMMUNITY COMPETENCE** | | | |
| a) Collective Action and Decision Making | | b) Collective Efficacy and | c) Quality of Life |
| i) Conflict Resolution | ii) Self-Organization | Empowerment | |
| **6) ECONOMIC DEVELOPMENT** | | | |
| a) Financial Services | b) Industry – Employment - Services | | c) Industry – Production |
| i) Asset Base of Financial Institutions | i) Agriculture | x) Number of Corporate Headquarters | i) Food Supply |
| ii) Checking Account Balances (Personal and Commercial) | ii) Construction | xi) Other Business Services | ii) Manufacturing |
| iii) Consumer Price Index | iii) Education and Health Services | xii) Professional and Business Services | |
| iv) Insurance | iv) Finance, Insurance and Real Estate | (1) Employment Services | |
| v) Number and Average Amount of Loans | v) Fortune 1000 | (a) Flexibilities | |
| vi) Number of Bank and Credit Union Members | vi) Fortune 500 | (b) Opportunities | |
| vii) Number of Banks and Credit Unions | vii) Information, Professional Business, Other | (c) Placement | |
| viii) Savings Account Balances (Personal and Commercial) | viii) Leisure and Hospitality | (2) Transport and Utilities | |
| ix) Stock Market | ix) Manufacturing | (3) Wholesale and Retail | |
| **7) SOCIAL/CULTURAL CAPITAL** | | | |
| a) Child and Elderly Services | b) Commercial Centers | c) Community Participation | d) Cultural and Heritage Services |
| e) Education Services | f) Non-Profit Organizations | g) Place Attachment | |

| NAME | | TYPE OF INFRASTRUCTURE | | |
|---|---|---|---|---|
| N° | Name | | | |
| 1 | Building 1 | Facilities | Residential | Housing Units |
| 2 | Building 2 | | | |
| 3 | Building 3 | | | |
| 4 | Building 4 | | Commercial | Office Buildings |
| 5 | Building 5 | | | |
| 6 | Building 6 | | | |
| 7 | Building 7 | | Residential | Housing Units |
| 8 | Building 8 | | | |
| 9 | Building 9 | | Commercial | Hotels – Accommodations |
| 10 | Building 10 | | Residential | Housing Units |

Table -3 Type of infrastructure for each building

| GLOBAL RESILIENCE OUTPUT DATA | | | | |
|---|---|---|---|---|
| Case: | I | II | III | IV |
| Community Resilience (Ta; Tb) [%]: | 98,3 | 95,0 | 74,8 | 58,2 |
| Community Functionality (Tb) [%]: | 100,0 | 100,0 | 88,6 | 58,2 |

Table -4 Global resilience output data for the four scenarios

RESILIENCE OUTPUT DATA FOR EACH BUILDING

| Case: | I | II | III | IV | I | II | III | IV |
|---|---|---|---|---|---|---|---|---|
| Building N° | AT [days] | | | | RES [%] | | | |
| 1 | 0 | 133 | 152 | inf. | 95,6 | 82,1 | 80,2 | 45,2 |
| 2 | 0 | 91 | 336 | inf. | 96,0 | 87,2 | 63,8 | 48,1 |
| 3 | 0 | 0 | 0 | inf. | 99,6 | 99,6 | 99,6 | 84,9 |
| 4 | 0 | 0 | 51 | inf. | 99,4 | 99,4 | 97,5 | 82,5 |
| 5 | 0 | 34 | 843 | inf. | 98,7 | 96,9 | 61,3 | 74,3 |
| 6 | 0 | 51 | 744 | inf. | 98,7 | 96,0 | 61,3 | 74,3 |
| 7 | 0 | 34 | 643 | inf. | 98,6 | 96,6 | 61,7 | 74,1 |
| 8 | 0 | 0 | 942 | inf. | 98,9 | 98,9 | 64,3 | 77,8 |
| 9 | 0 | 66 | 511 | inf. | 97,7 | 93,0 | 61,4 | 67,4 |
| 10 | 0 | 0 | 118 | inf. | 99,8 | 99,8 | 97,2 | 89,2 |

Table -5 Output data of Resilience features for each building and each case.

Table Legend:
AT: Administrative time [days];
RES: Resilience over the control period [%].

RESILIENCE INDEX

| Case: | I | II | III | IV |
|---|---|---|---|---|
| Community Resilience index [%]: | 92,0 | 87,6 | 80,6 | 58,2 |
| Time of completion of work, $T_{CW}$ [days]: | 183,9 | 316,8 | 1033,0 | inf. |

Table -6 Output data of Global Resilience for each case.

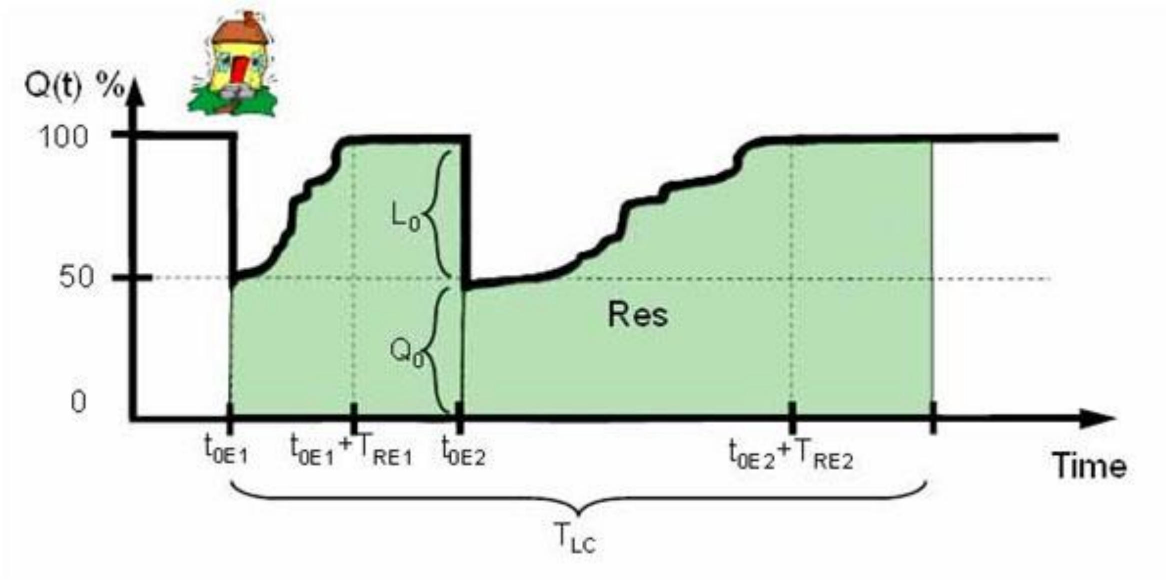



Figure -1 Resilience (Cimellaro et al., 2010a)

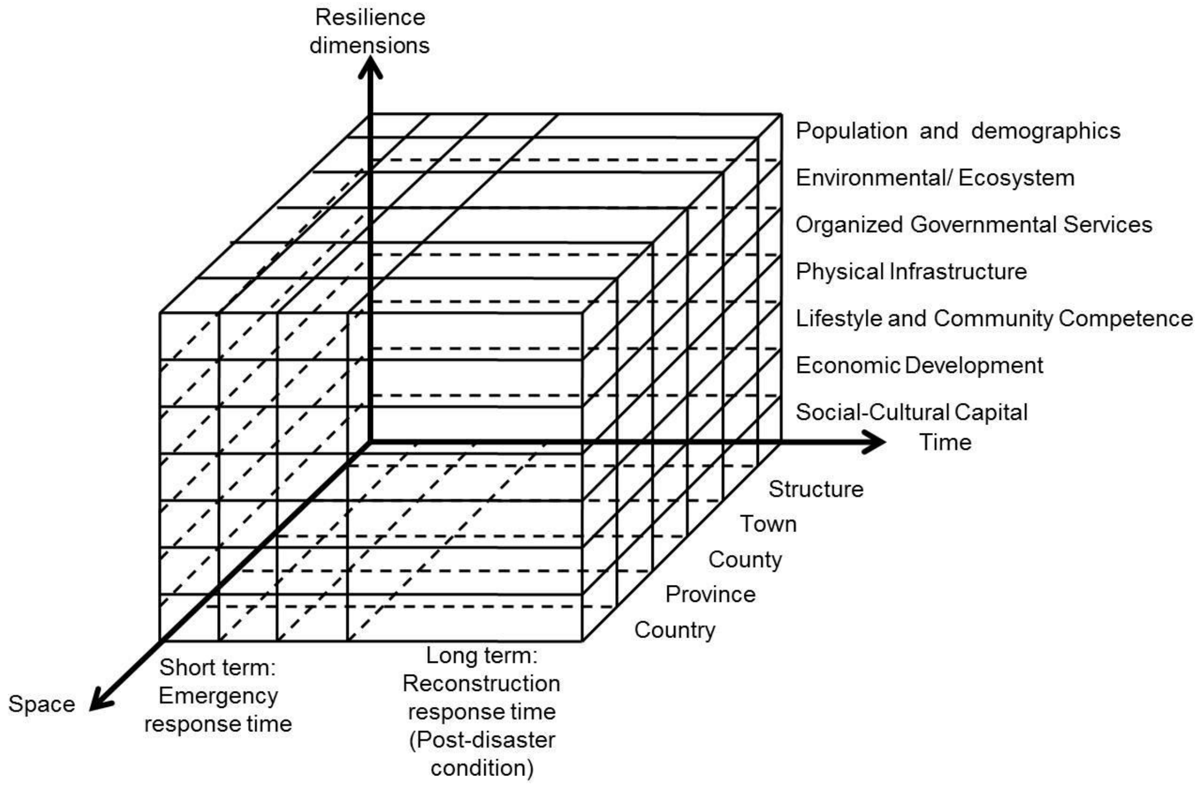



Figure -2 Spatial and temporal dimension of Resilience-Based design (RBD) using PEOPLES approach

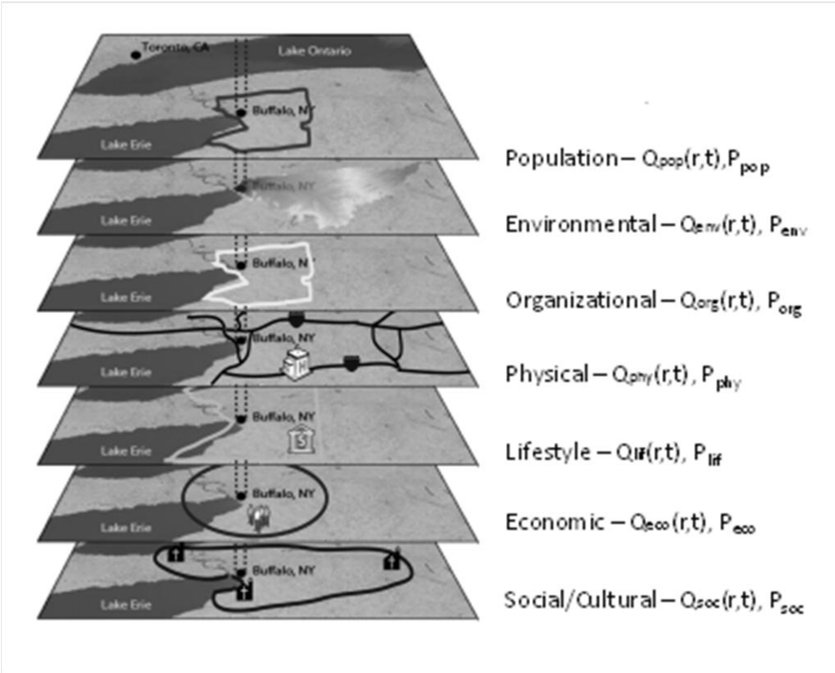



Figure -3 Layer model of PEOPLES

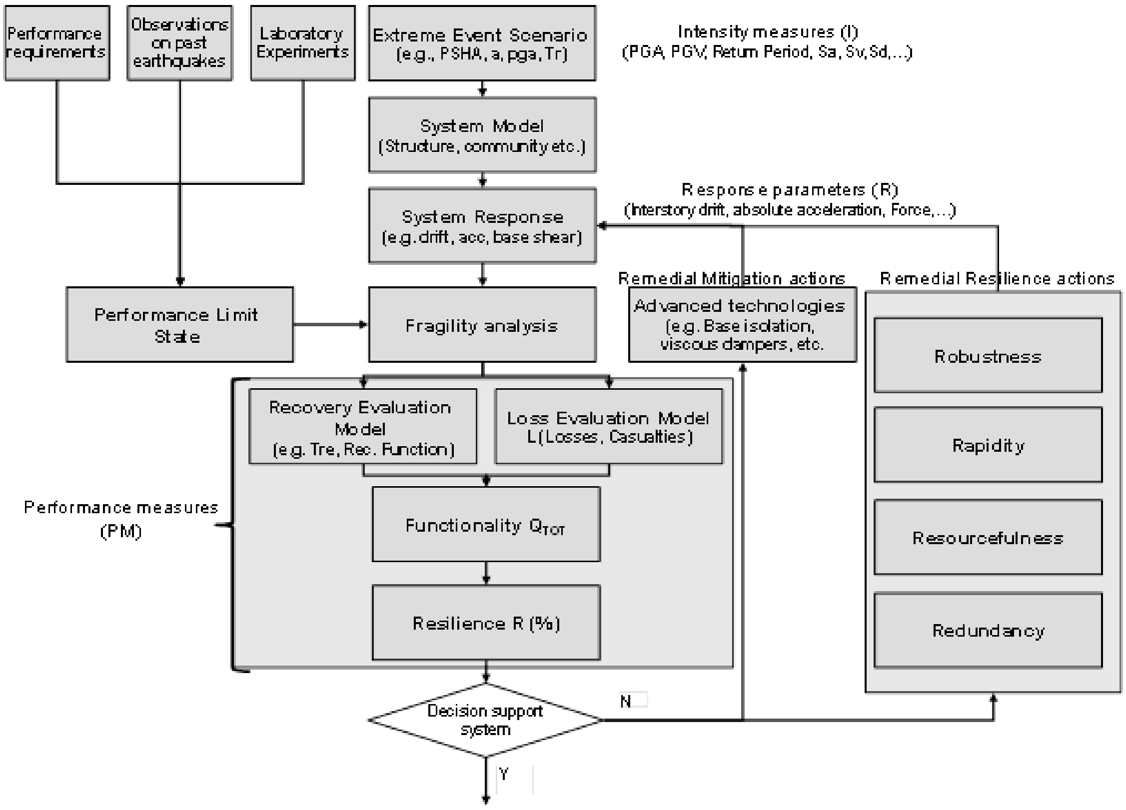



Figure -4 MCEER center methodology for Resilience-based design (RBD) based on control (feedback loop) approach

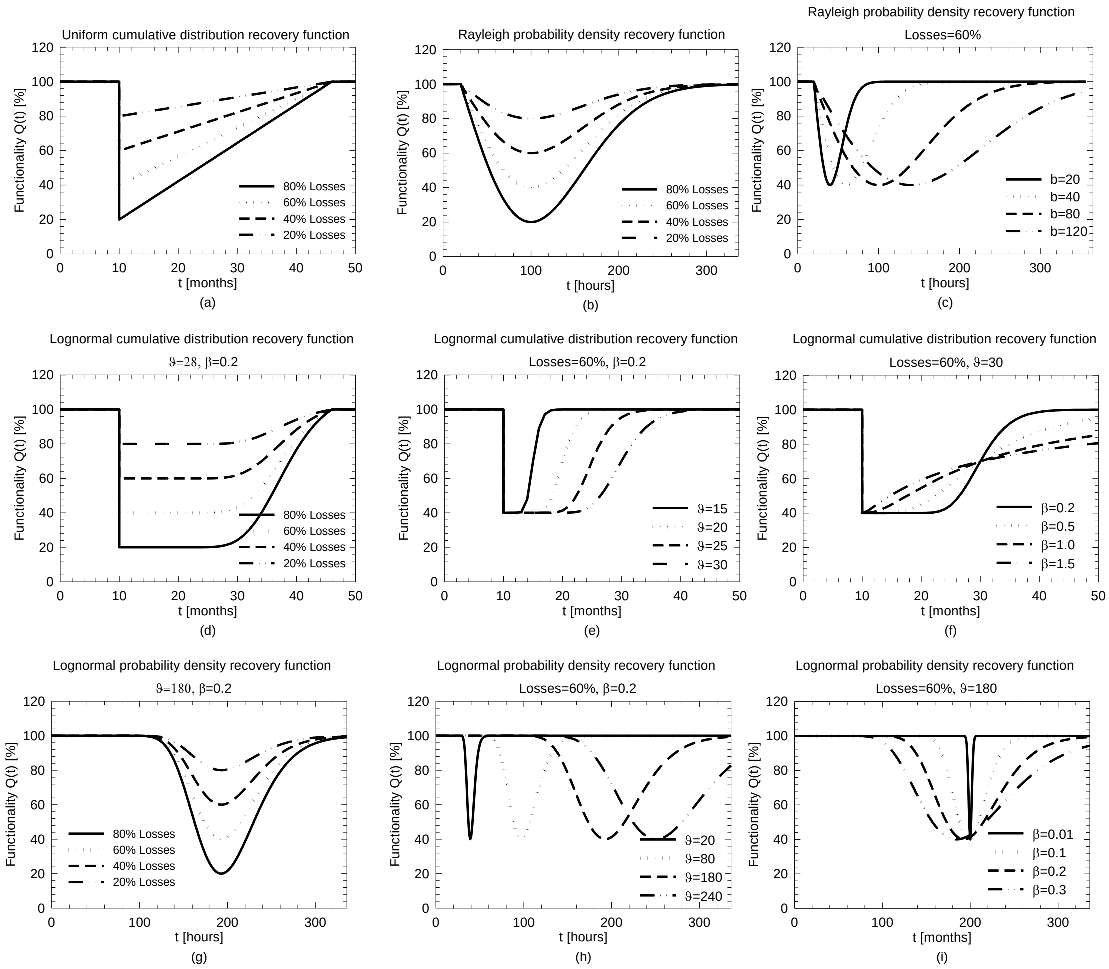
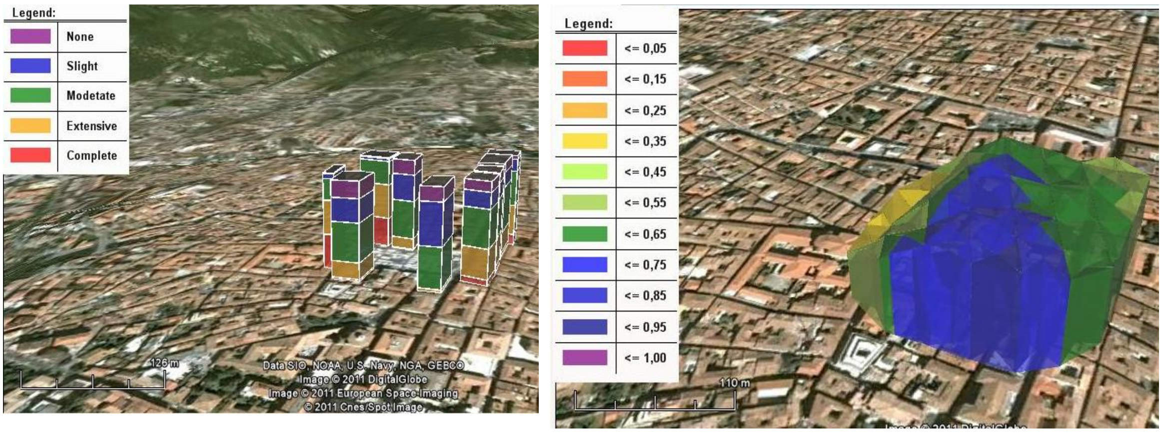



Figure -5 Long term and short term recovery function




(a) (b)

Figure -6 (a) Histogram of discrete probability of damage states; (b) Contour plot of functionality.

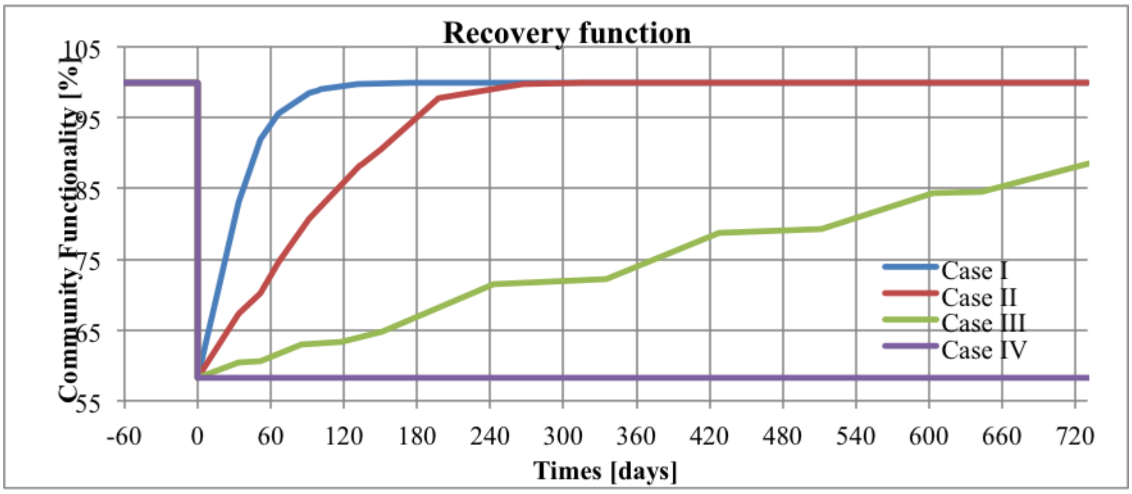



Figure -7 Recovery function for each case.