The State of Art of Community Resilience of Physical Infrastructures

G. P. Cimellaro, A. M. ASCE[1], Chris S. Renschler, A. M. ASCE[2], Amy Frazier[2], Lucy A. Arendt[3], A.M. Reinhorn, F. ASCE[4], Michel Bruneau, M. ASCE[4]

[1] Department of Structural & Geotechnical Engineering (DISTR), Politecnico di Torino, room 7, Corso Duca degli Abruzzi 24, 10129 Turin, Italy PH +39 (011) 090 4801 FAX +39 (011) 090 4899, email: gianpaolo.cimellaro@polito.it
[2] Department of Geography, University at Buffalo, The State University of New York, 135 Ketter Hall, Buffalo NY, email: rensch@buffalo.edu
[3] Department of Management | Professional Programs in Business, University of Wisconsin, Green Bay, email: arendtl@uwgb.edu
[4] Department of Civil, Structural & Environmental Engineering, University at Buffalo, The State University of New York, 135 Ketter Hall, Buffalo NY, email: reinhorn@buffalo.edu

ABSTRACT

The concept of Disaster Resilience has received considerable attention in recent years and it is increasingly used as an approach for understanding the dynamics of natural disaster systems. The goal of this paper has two distinct tasks: (i) conduct a literature survey analyzing asset-based approaches for defining and measuring disaster resilience for physical infrastructures that is one of the seven dimensions of the PEOPLES Resilience Framework; (ii) identify the gaps between asset-based approaches and community-scale approaches. It is offered an overview of the models developed in literature to quantify resilience and performances of electric power, water, wastewater and natural gas utilities; communication companies and transportation networks as well as health care facilities. Discussion will be added related to strengths and weakness on how these approaches could facilitate the comparison of alternative resilience options/strategies and measure the speed with which disruptions can be overcome and community functions restored.
A new geographic approach will be introduced to measure community resilience, focusing on spatial, temporal scale of resilience.

INTRODUCTION

Resilience is clearly becoming increasingly important for modern societies as states come to accept that they cannot prevent every risk from being realized, but rather must learn to adapt and manage risks in a way that minimizes impact on human and other systems.
While studies on the disaster resilience of technical systems have been undertaken for quite some time, the societal aspects and the inclusion of various and multiple types of extreme events are new developments. In this regard, countries and states around the world are increasingly debating ways to enhance community resilience. At this time, there is no explicit set of procedures in the existing literature that suggests how to quantify resilience in the context of multiple hazards, how to compare communities with one another in terms of their resilience, or how to determine whether individual communities are moving in the direction of becoming more resilient in the face of various hazards. Considerable research has been accomplished to assess

direct and indirect losses attributable to earthquakes, and to estimate the reduction of these losses as a result of specific actions, policies, or scenarios. However, the notion of resilience suggests a much broader framework than the reduction of monetary losses alone. Equally important, in addition to focusing on the losses produced by multiple hazards, research must also address the ways in which specific pre- and post-event measures and strategies can prevent and contain losses (Bruneau et al, 2003). Resilience (R) is defined as a function indicating the capability to sustain a level of functionality or performance for a given building, bridge, lifeline networks, or community, over a period defined as the control time T_{LC} that is usually decided by owners, or society (usually is the life cycle, life span of the system etc.). Resilience is defined graphically as the normalized shaded area underneath the functionality function of a system, defined as $Q(t)$. $Q(t)$ is a non stationary stochastic process and each ensemble is a piecewise continuous function as the one shown in Figure 1 (Cimellaro et al. 2010):

$$R = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q(t)/T_{LC}\, dt$$
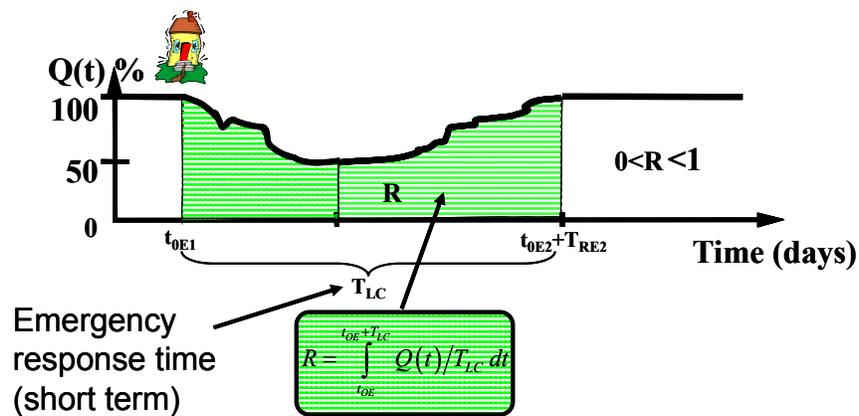
Figure 1 Schematic Representation of Community Resilience

Disaster resilience is often divided between technological units and social systems. On a small scale, when considering critical infrastructures, the focus is mainly on technological aspects. On a greater scale, when considering an entire community, the focus is broadened to include the interplay of multiple systems – human, environmental, and others – which together add up to ensure the functioning of a society. At the community level, the human component is central, because in the case of a major disruptive event, resilience depends first on the actions of people operating at the individual and neighborhood scale. Community resilience also depends heavily on the actions of different levels of government and its agencies at the local and regional scales when a disruptive extreme event occurs.

In order to emphasize the primary role of the human system in community sustainability, the acronym "PEOPLES" have been used This nomenclature highlights both the physical and environmental assets as well as the socio-economic-political/organizational aspects of a particular community. The PEOPLES Resilience Framework is built on and expands previous research at MCEER linking several previously identified resilience dimensions (technical, organizational, societal, and economic) and resilience properties (r4: robustness, redundancy, resourcefulness, and rapidity). PEOPLES incorporates MCEER's widely accepted definitions of service functionality, its components (assets, services, demographics) and the parameters influencing their integrity and resilience.

The PEOPLES Resilience Framework defines components of functionality shown in Figure 2 using a geospatial-temporal distribution within its influence boundaries. Interdependencies

between and among these components are key for determining the resilience of communities. PEOPLES enables the use of various community resilience indices that integrate over space and time the system functionality and services of a community in a landscape setting. In this particular dimension, historical and continuously gathered information through remote sensing and Geographic Information Systems (GIS) will play a major role in assessing the resilience of all integrated systems and feed a predictive resilience model. 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 infrastructures, and it can use various geographic scales. To be able to expand the assessment of resilience to a community and landscape perspective, the PEOPLES Resilience Framework is based on basic community organizational units at a local (neighborhoods, villages, towns or cities) and regional scale (counties/parishes, regions, or states) (see Figure 2).
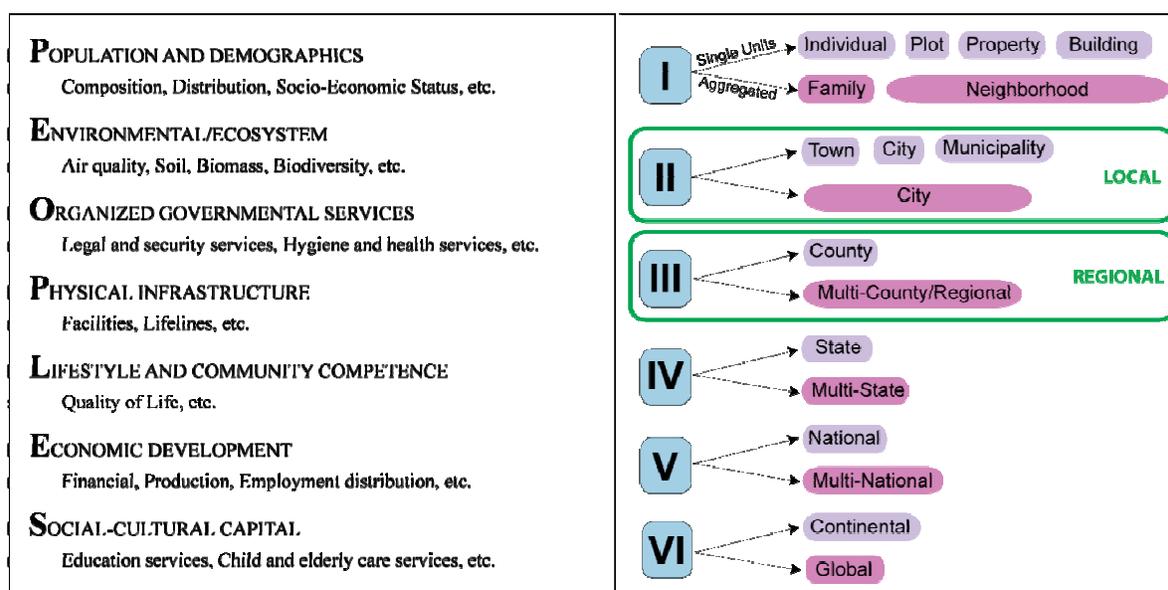
Figure 2 The PEOPLES Resilience Framework and their Geographic Scales

The goal of this paper is to focus only on the physical infrastructure dimension of the PEOPLES framework identifying the different performance measures of the different components.

PHYSICAL INFRASTRUCTURE DIMENSION

The physical infrastructure dimension incorporates both facilities and lifelines. 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, and communication networks (Figure 3).

a) **Facilities**	ii) Health Care
i) Residential	(1) Acute Care
(1) Housing Units	(2) Long-Term Acute Care
(2) Shelters	(3) Primary Care
ii) Commercial	(4) Psychiatric

(1) Distribution Facilities	(5) Specialty
(2) Hotels - Accommodations	iii) Food Supply
(3) Manufacturing Facilities	iv) Utilities
(4) Office Buildings	(1) Electrical
iii) Cultural	(2) Fuel/Gas/Energy
(1) Entertainment Venues	(3) Waste
(2) Museums	(4) Water
(3) Religious Institutions	v) Transportation
(4) Schools	(1) Aviation
(5) Sports/Recreation Venues	(2) Bridges
b) Lifelines	(3) Highways
i) Communications	(4) Railways
(1) Internet	(5) Transit
(2) Phones	(6) Vehicles
(3) TV	(7) Waterways
(4) Radio	
(5) Postal	

Figure 3 List of subcomponents of the PHYSICAL INFRASTRUCTURE dimension of the PEOPLES framework

Eulerian indicators for facilities and lifelines

For residential, commercial and cultural facilities it is possible to use point location indicators such as physical damage indicators and using the analogy with fluid mechanics, these indicators can also be called Eulerian indicators, because they describe the performance of each component at a given location. Some facilities due to their malfunction can also cause indirect damage such as commercial distribution facilities, religious institutions, schools etc. Therefore for these facilities their influence area needs to be considered evaluating the number of users that will not receive service over the total number of users that received service before the extreme event.

When considering residential housing units (1) a good indicator of resilience to extreme events is also the ratio between the vacancy rates for rental housing and the housing stock not rated as substandard or hazardous (Tierney 2009). This indicator is however affected by the damage state of the housing units, so it is representative if all housing units are opportunely retrofitted.

Point location indicators can also be used when considering the other group of physical infrastructures, the lifelines for communication, food supply and utilities lifelines (electric, water, gas etc.). In this case the indicators are defined as percentage of households receiving service at a given location.

Indicators for communication networks

In terms of communication networks, key indicators may include the 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).

Indicators for health care facilities

In term of health care facilities, a key indicator is the waiting time (WT) that is the time that the patient needs to wait in the hospital before receiving service (Cimellaro et al, 2010b,c). Other models are also available in literature and are summarized in the following table. Further details about key indicators for this dimension can be found in the MCEER report (Cimellaro et al. 2009).

KEY INDICATORS OF THE TRANSPORTATION SYSTEM

Among physical infrastructures special attention should be given to the transportation system. When considering road network in the past, lot of attention has been given to the damage of individual bridge structures, while indicators measuring the performance of the overall transportation system should be considered.

Lagrangian Indicators

Eulerian indicators can be used for lifelines such as water, electric power, natural gas, and telecommunications, where performance can be readily measured by the percentage of households in the study area that have lost lifeline service. However this approach cannot be used for transportation systems, because transportation service is consumed by an individual user across the network, rather than at a point location, therefore using the analogy of fluid mechanics the indices that better describe the performance are the so called lagrangian indicators that describe the performance of a user that move across the network. For example they belong to this group indicators based on the original destination (OD) nodes (e.g. Bocchini and Frangopol, 2011) and on the network connectivity analysis (CA) (Chang and Nojima, 2001).

In term of transportation system there are many key indicators available in literature, therefore it is necessary to distinguish between normal and critical operating conditions. Many indicators can be found describing the performance of the road network in normal operating conditions, while a few can be found to evaluate performances after extreme events as shown in Table 1.

Normal operating condition indicators	Extreme event indicators
Average road user costs	Total length of highway open L (Chang and Nojima, 2001);
Travel time as measure of level of satisfaction	Total distance-based accessibility D (Chang and Nojima, 2001);
Number of fatalities as measure of user risk	Bocchini and Frangopol (2011)
Overhead percentage (fixed costs/total costs) as indicator of road administration's cost-effectiveness	REDARS (Werner et al. 2006)
Roughness (IRI is widely used indicator) related to pavement quality, travel cost and user satisfaction	
States of bridges	
Satisfaction with the road system as indicator of road users overall satisfaction	
…	

Table 1 Key indicators divided by normal and critical operating conditions (not exhaustive)

Each of these extreme events indexes is estimated as the ratio of post-earthquake to pre-earthquake conditions and ranges from 0 (system non-functional) to 1 (system fully functional).

Among all it is worthed to focus on the extreme event indicators that are of interest for the PEOPLES framework therefore some of the most relevant and simple to understand are summarized below.

The indicator L (Chang and Nojima, 2001) reflects the length x of highway in the network that is open to traffic at any point in time t, and is defined as a ratio to the pre-earthquake length open $\bar{x}$:

$$L(t) = \frac{x(t)}{\bar{x}} \tag{1}$$

The limit of this indicator is that it is basd only on the extend of damage. A second indicator D is based on minimum network travel distances and thus takes into account both the extent and the location of damage. It attempts to measure changes in accessibility at all nodes on the network:

$$D(t) = \frac{f - A(t)}{f - 1} \tag{2}$$

where

$$A(t) = \frac{\sum_i \sum_j d_{i,j}(t)}{\sum_i \sum_j \bar{d}_{i,j}} \qquad\qquad 1 \le A \le f \tag{3}$$

with f=effective distance multiplier for link closure; A=total network accessibility ratio; $d_{i,j}$=minimum travel distance between nodes i and j on damaged network; $\bar{d}_{i,j}$=minimum travel distance between nodes i and j on intact network.

Recently Bocchin and Frangopol (2011) developed an index for the functionality of a bridge network. The index is based on the assumption that the time to cover the length of a highway segment is assumed to be the sum of two parts: (i) the time spent on the highway; (ii) the time spent on detour routes. These hypotheses are consequential to the assumption that for every (partially) closed bridge there is at least one possible detour route to bypass the damaged bridge. These detours cause a delay due to the necessity to change the path and to the limited capacity of local routes.

$$Q(t) = 100 \cdot \frac{\Gamma(t) - \Gamma^0}{\Gamma^{100} - \Gamma^0} \tag{4}$$

where

$$\Gamma(t) = \frac{1}{\gamma_t \cdot TTT(t) + \gamma_D \cdot TTD(t)} \tag{5}$$

$TTT(t) = \sum_{i \in I} \sum_{j \in J} f_{ij}(t) \cdot c_{ij}$ is the Total Travel Time; $TTD(t) = \sum_{i \in I} \sum_{j \in J} f_{ij}(t) \cdot d_{ij}$ is the total travel distance; γ_T=is a balancing factor (cost) associated with the time spent by the network users, γ_D=is a similar factor related to length. f_{ij} = is the traffic transiting over the highway segment between nodes i and j; i is the set of nodes of the network and j is the subset of nodes connected to node i; c_{ij}=is the time required to cover segment i–j with traffic flow f (t); d_{ij} =is the length of highway segment i–j.

Seismic Risk Analysis for transportation system (REDARS)

Another interesting methodology for measuring the global road network performance after earthquakes is implemented in REDARS (Risks from Earthquake DAmage to Roadway Systems) that is a multi-disciplinary tool for seismic risk analysis (SRA) of highway systems (Werner et al., 2006). Once defined the region of interest the seismic hazard is evaluated and the resulting damage states for each component of the system considering damage extend, type and location. How each component's damage will be repaired, including its repair costs, downtimes, and time-dependent traffic states (i.e., its ability to carry traffic as the repairs proceed over time after the earthquake). Next, REDARS incorporates these traffic states into a highway-network link-node model, in order to form a set of system-states that reflect the extent and spatial distribution of link closures at various times after the earthquake. It applies network analysis procedures to each system-state, in order to estimate how these closures affect system-wide travel times and traffic flows. Finally, REDARS estimates corresponding economic losses and increases in travel times to/from key locations or along key lifeline routes. These steps can be applied for a single earthquake and no uncertainties (deterministic analysis) or for multiple earthquakes and simulations in which uncertainties in earthquake occurrence and in estimates of seismic hazards and component damage are considered (probabilistic analysis).

INTEGRATING FUNCTIONALITIES OF PEOPLES FRAMEWORK

Within the *PEOPLES Resilience Framework,* each dimension and/or service and its indicators or terms of functionality will be represented with a GIS layer of the area of interest (Figure 4). Each dimension of the framework can be represented by a combination of sub-dimensions (or layers), each having spatial-temporal dependent functionalities, each representing a subcomponent. For example the physical infrastructure layer shown in Figure 4 can be subdivided into layers representing the housing, transportation, electric power, water, sewage, communications, etc.
In Figure 4, Q_{HOU} = functionality of the housing units in the community; Q_{TRA} = functionality of the transportation network; Q_{ELE} = functionality of electric power system; Q_{H2O} = functionality of the water system; Q_{COM} = functionality of the communication network; Q_{SEW} = functionality of the sewage system; all terms are function of the location (**r**) and of the time (**t**). This list of functionality terms that is inserted within the physical infrastructure is not exhaustive. Additional terms can be added, such as functionality of schools, dams, fire stations, oil and natural gas systems, emergency centers, etc. For each layer, is possible to define a *resilience index contour map* after integrating the functionality for the control time (T_{LC}) period.
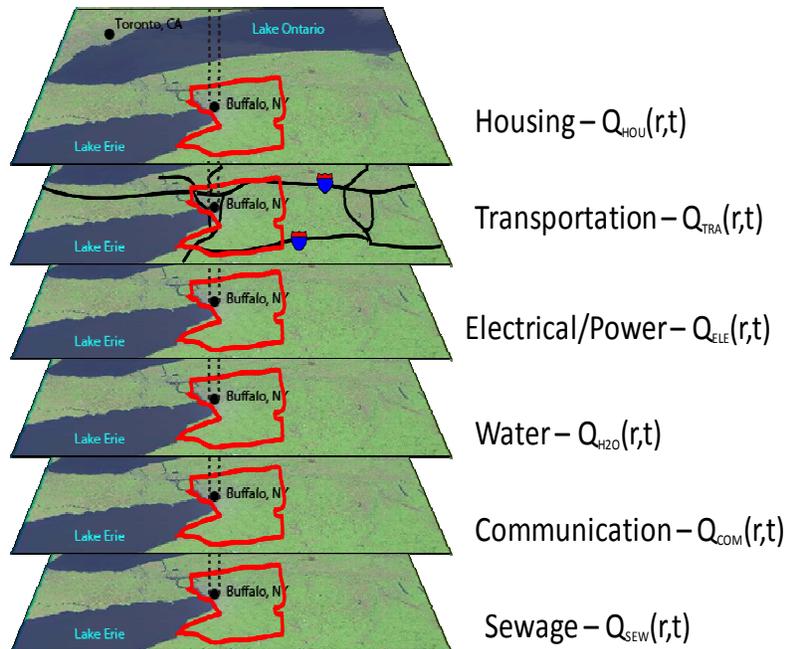
Figure 4 Schematic representation of Physical Infrastructure Functionality Maps

Region of interest

The spatial distribution of functionalities in each dimensional layer is also specific to the area of influence of the network of lifelines that it represents. For example the highway network and the electric grid have different boundaries as well as the areas served by the water system and by the communication system. These areas of influence are not the same for each layer and they can be national, regional or local, dependent on the service provided. Multiple community resilience indices, *Ri*, for each component, i, or a single combined index, R, would be dependent on a defined temporal and geographic size or scale defined by community boundaries. The community will include in its boundaries an entire network, or several networks, but most likely will include only parts of the larger national or regional networks. Therefore in determining resilience, first, the boundaries of the region of interest should be defined. Geographic Information Systems (GIS) are increasingly being used to map vulnerability, and to better understand how various phenomena (hydrological, meteorological, geophysical, social, political and economic) effect human populations. The region of interest is further divided in grid cells and inside each cell, r, a definition of functionality Qi(r,t) at a given time instant, t, is given for each dimension (Figure 5). For example, if the community resilience index of the electric power network has to be calculated for a given region, first the definition of functionality Q_{ELE} needs to be defined, for example as

$$Q_{ELE}\left(\mathbf{r},t\right)=\frac{N_{CP}\left(\mathbf{r},t\right)}{N_{C}\left(\mathbf{r},t\right)} \tag{1}$$

where N_{CP}=number of households receiving power in the grid cell and N_C= total number of households in the grid cell.
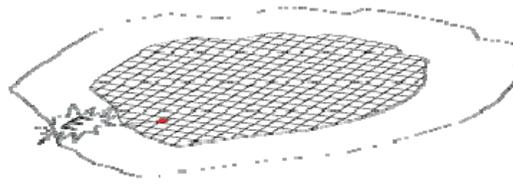
Figure 5 Example of region of interest divided in grid cells

Then, after evaluating the functionality $Q_{ELE}(\mathbf{r},t)$ in each grid cell for the entire period of control, T_{LC}, different ways of representing the data are available.

Resilience maps

At every instant t_0 a given functionality maps $Q_{ELE}(\mathbf{r},t_0)$ (or contour plots) can be plotted over the region of interest. These maps can be used during the entire recovery process, especially in the days immediately after the extreme events and they can be updated on regular basis for example. They can be used to direct resources and personnel toward the zones more affected by the extreme event in the region. At different time periods defined also by the control time, T_{LC}, it is possible integrate the functionality for the given control time and calculate the resilience at each location $\mathbf{r}$.

$$R_{ELE}(\mathbf{r}) = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{ELE}(\mathbf{r},t)/T_{LC}\, dt \tag{2}$$

Then the resilience indices can be used to develop the resilience maps in the form of contour plots. These maps can be used as information during the entire recovery process, or during any given control period. At the end of the emergency period they give you a status on the level of achieved resiliency of the component/dimension in the aftermath of the extreme event.

Finaly, a global **community resilience index for the specific dimension** (*electric power system in the example below*) can be provided by double integrating over the entire region, r_{LC}, and the control period, T_{LC}..

$$R_{ELE} = \int_{\mathbf{r}_{LC}(t)} R_{ELE}(\mathbf{r})\, dr = \int_{\mathbf{r}_{LC}(t)} \int_{T_{LC}(t)} Q_{ELE}(\mathbf{r},t)/T_{LC}\, dt dr \tag{3}$$

All equations above are presented for the functionality of the electric power network, only, but formulation can be easily extended to all components/dimensions.

Community Resilience indices

When a global resilience index is required to assess the entire community, as a result of all components and dimensions, this index can be obtained using the total functionality $Q_{TOT}(r,t)$, that combines the different dimensions, so the final community resilience index is given by:

$$R = \int_{\mathbf{r}_{LC}(t)} R(\mathbf{r}) \, dr = \int_{\mathbf{r}_{LC}(t)} \int_{T_{LC}(t)} Q_{TOT}(\mathbf{r},t)/T_{LC} dt dr \tag{4}$$

where $Q_{TOT}(r,t)$ is the global functionality that is a function of time and space and combines all functionality terms considered; r_{LC} is the region of interest that can change with time; t is the time parameter; $T_{LC}=$ control time that can change through the time.

Interdependencies

All resilience dimensions and their respective indices to measure their performances are interdependent (Figure 6).
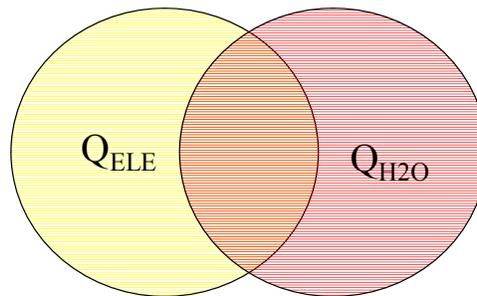
Figure 6 Interdependencies among different functionalities

A simple way of combining different functionalities is using the analogy with the probability axiom of arbitrary events therefore the global definition of functionality is given by

$$Q_{TOT} = \sum_{j=1}^{n} Q_j - \sum_{i=1}^{n}\sum_{j=2}^{n} Q_i Q_J + \sum_{i=1}^{n}\sum_{j=2}^{n}\sum_{k=3}^{n}(Q_i Q_j Q_k) - \ldots + (-1)^{n-1}\sum_{i=1}^{n}\sum_{j=2}^{n}\sum_{k=3}^{n}\ldots\sum_{l=n-1}^{n}(Q_i Q_j Q_k \ldots Q_l Q_n) \tag{5}$$

It is obvious that not all functionalities might have the same weight; therefore the global functionality can be determined using the mathematical expectation denoted by $E\{Q(\mathbf{r},t)\}$ that is defined by

$$Q_{TOT} = E\{Q(\mathbf{r},t)\} = \sum_{i=1}^{n} p_i(\mathbf{r},t) Q_i(\mathbf{r},t) \tag{6}$$

where n is the number of dimensions considered relevant in the functionality, $p_i(r,t)$=priority (probability) factors; Q_i=functionality associated to a given dimension of PEOPLE framework. Notable, for the total system functionality, the number of dimensions can be maximum seven (n=7) as indicated in the PEOPLES framework. However, the same formulation (recurrence formula), with suitable adjustment of the meaning of the indices, applies to the total functionality of a single component/dimension such as the physical infrastructure, or the organizational system, thus allowing to determine the resilience index of just that component/dimension.
The formulation suggested above provides the base for further development of the resilience indices for various locations using a probability framework while considering inherent uncertainties in the systems.

REMARKS AND CONCLUSIONS

The paper conducts a literature survey analyzing asset-based approaches for defining and measuring disaster resilience for physical infrastructures that is one of the seven dimensions of the PEOPLES Resilience Framework. It is offered an overview of the most relevant models developed in literature to quantify resilience and performances of electric power, water, wastewater and natural gas utilities; communication companies and transportation networks as well as health care facilities. A new geographic approach is introduced to measure community resilience, focusing on spatial, temporal scale of resilience. System community resilience measures can provide a very useful tool for mitigation of multiple hazards such as earthquakes and are important for several reasons:

1. They enable comparisons of system conditions across disaster events in different regions.
2. They allow comparisons across scenario disaster events for a single study region, and with a rapid development can be used for pre-event mitigation planning.
3. They may also facilitate discussions of what levels of risk and potential loss are acceptable or unacceptable.
4. They can be used in efficient post-disaster restoration strategies by prioritizing damage repair optimizing system performance.
5. They be implemented for estimating economic impacts for emergency response and recovery planning.

ACKNOWLEDGEMENTS

REFERENCES

Arcidiacono, V., Cimellaro, G. P., and Reinhorn, A. M. "A software for measuring disaster community resilience according to the PEOPLES methodology." *Proceedings of COMPDYN 2011 - 3rd International Conference in Computational Methods in Structural Dynamics and Earthquake Engineering*, Corfu`, Greece, May 26-28, 2011.

Bocchini, P., and Frangopol, D. (2011). "A stochastic computational framework for the joint transportation network fragility analysis and traffic flow distribution under extreme events " *Probabilistic Engineering Mechanics*, 26(2), 182-193.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., M., R. A., Masanobu, S., Kathleen, T., Wallace, W. A., and Winterfeldt, D. v. (2003). "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities." *Earthquake Spectra*, 19(4), 733-752.

Chang, S. E., and Nojima, N. (2001). "Measuring Post-Disaster Transportation System Performance: The 1995 Kobe Earthquake in Comparative Perspective." *Transportation Research Part A: Policy and Practice*, 35(6), 475-494

Chang, S. E., and Shinozuka, M. (2004). "Measuring Improvements in the Disaster Resilience of Communities." *Earthquake Spectra*, 20(3), 739-755.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010a). "Framework for analytical quantification of disaster resilience." *Engineering Structures*, 32(2010), 3639–3649.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010b). "Seismic resilience of a hospital system." *Structure and Infrastructure Engineering*, 6(1-2), 127-144.

Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010c). "Performance-based metamodel for health care facilities." *Earthquake Engineering & Structural Dynamics*, article first published online: 16 DEC 2010, DOI: 10.1002/eqe.1084.

Cimellaro, G. P., Fumo, C., Reinhorn, A. M., and Bruneau, M. (2009). "Quantification of Seismic Resilience of Health care facilities " *MCEER Technical Report-MCEER-09-0009*, Multidisciplinary Center for Earthquake Engineering Research, Buffalo, NY.

Renschler, C., Frazier, A., Arendt, L., Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010). "Framework for Defining and Measuring Resilience at the Community Scale: The PEOPLES Resilience Framework." *MCEER Technical Report –MCEER-10-006, pp. 91*, University at Buffalo (SUNY), The State University of New York, Buffalo, New York.

Miles, S., and Chang, S. (2003). "Urban Disaster Recovery: A Framework and Simulation Model." *MCEER-03-0005*, State University of New York, University at Buffalo, Buffalo, NY.

Miles, S., and Chang, S. (2006). "Modeling Community Recovery from Earthquakes." *Earthquake Spectra*, 22(2), 439-458.

Tierney, K. (2009). Disaster response: Research findings and their implications for resilience measures. CARRI Research Report 6. Oak Ridge, TN: Community and Regional Resilience Initiative (CARRI). URL: www.resilientUS.org

Werner, S. D., Taylor, C. E., Cho, S., Lavoie, J.-P., Huyck, C., Eitzel, C., Chung, H., and Eguchi, R. (2006). "REDARS 2 Metholodgy and Software for Seismic Risk analysis of highway systems." *Technical Report MCEER-06-SP08*, MCEER Multidisciplinary Center Earthquake Engineering Research, Buffalo, NY.