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PEOPLES: A FRAMEWORK FOR EVALUATING RESILIENCE

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ABSTRACT

In recent years, the concept of resilience has been introduced to the engineering field in particular related to disaster mitigation and management. However, the built environment is only part of the elements that support community functions. Maintaining community functionality during and after a disaster, defined as resilience, is influenced by multiple components. The paper is proposing a framework for measuring community resilience at different spatial and temporal scales. Seven dimensions are identified for measuring the community resilience: *Population and Demographics, Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructures, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital*. They are summarized with the acronym PEOPLES. Each dimension is characterized by a corresponding performance metric that is combined with the other dimensions using a multi-layered approach. Therefore, once a hybrid model of the community is defined, the proposed framework can be applied to measure its performance against any type of extreme event during *emergency* and in *long term* post-disaster phases. A resilience index can be determined to reflect all, or part, of the dimensions influencing the events. Several applications of part of such framework can already be found in literature for different types of infrastructures, physical and organizational (e.g. gas network, water distribution networks, health care facilities etc.). The proposed framework can be used as decision support by stakeholders and managers and it can help planners in selecting the optimal restoration strategies that enhance the community resilience index.

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INTRODUCTION AND DEFINITION OF RESILIENCE

Recent disasters around the world have shown clearly that not all the threats can be averted. Modern societies are trying to enhance their resilience against extreme events after realizing that they cannot prevent every risk from being realized, but rather they must manage risks and adapt minimizing the impact on population and their support systems.

The concept of resilience has several definitions, because of its broad utilization in ecology, social science, economy and engineering fields, with different meanings and implications. As Klein *et al.* stated (2003), the term derives from the Latin word '*resilio'* that means '*to jump back*'. The term has been used first in psychology and psychiatry in 1940s, and it is mainly accredited to Norman Garmezy, Emmy Werner and Ruth Smith (Garmezy, 1974; Werner and Smith, 1989). Later the concept of resilience established in the field of ecology by Holling (1973) who stated that the resilience of an ecological system 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". An extended literature review about resilience has been assembled in the past (see Table -1) with each contribution adding new nuances. Primarily resilience has been defined in context to the speed of systems to go towards equilibrium (Adger, 2000) or capability to cope and bounce back, ability to adapt to new situations (Comfort, 1999), be inherently strong, flexible and adaptive (Tierney & Bruneau, 2007), or 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.

Engineering resilience is defined as the capability of a system to maintain its functionality and to degrade gracefully in the face of internal and external changes (Allenby and Fink, 2005). The main difference in defining resilience arises between the engineering approach where resilience occurs by recovering towards a previous or an improved stable state (Bruneau et al., 2003), and the ecological approach where resilience is achieved moving towards a different system state (Handmer & Dovers, 1996).

Social resilience is defined as the ability of groups or societies to cope with external stresses and disturbances because of social, political, and environmental change (Adger, 2000).

Economic resilience is defined as the inherent ability and adaptive response that enables individual business firms and entire regions to avoid maximum potential losses (Rose and Liao, 2005). It has mainly been studied in context to seismic response and recovery (Tierney, 1997), community behavior (Chang & Shinozuka, 2004) and disaster hazard analysis (Rose, 2004).

Research advancements have proven that resilience should be addressed at the large-scale level and not just locally. Bruneau et al. (2003) identified four types of resilience that should be adequately measured: *technical*; *organizational*; *social*; and *economical*, (TOSE). Technical and economical resilience, are mainly related to the physical systems, while organizational and social resilience, are related to the society and the non physical systems.

- *Technical resilience* describes the capability of a system to function and perform adequately.
- *Organizational resilience* describes 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 because of a disaster. For example, social resilience can become the most critical dimension of the global resilience, because of severe blackouts during a disaster.
- *Economic resilience* describes the capability to reduce both indirect and direct economic losses (Rose and Liao, 2005).

Following the initial resilience framework by Bruneau et al. (2003), other frameworks have been developed expanding and identifying different metrics to quantify resilience. For example, Chang and Shinozuka (2004) refined the method proposed by Bruneau (2003) by proposing a metric of system functionality *Q* that is evaluated comparing the extreme events scenario with the pre-event conditions and they applied the method to the case study of Memphis water system. Miles and Chang (2006) presented a comprehensive functionality restoration model that establishes the relationships between community's household, business and lifeline networks. The same year Cagnan et al. (2006) developed a discrete event simulation model for modeling the post-earthquake restoration process of an electric power system. The resilience concept as input to *decision support methodologies* has been applied to *hospitals* (Cimellaro et al., 2010b; Cimellaro and Pique`, 2014a), *lifeline structures* (Ouyang and Duenas-Osorio, 2011, Cimellaro et al., 2014b-c) and *cities* (Chang et al, 2014) using different optimization methods based on *economic* (Chang and Shinozuka, 2004), *downtime* (Cagnan et al., 2006) or *multi-criteria analysis* (Javanbarg et al., 2012).

Several methods for the quantification of infrastructures' resilience have been proposed that can be grouped in *probabilistic methods* (Miller-Hooks et al, 2012, Queiroz et al., 2013), *graph theory methods* (Berche et al, 2009; Dorbritz, 2011), *fuzzy logic methods* (Heaslip et al., 2010) and *analytical methods* (Cimellaro et al., 2010a; Tamvakis and Xenidis, 2013). For example, Tamvakis and Xenidis (2013) proposed a framework base on entropy theory concepts. Entropy describes the system's disorder at a given point in time and it is measurable in a single metric, analogous to resilience, which describes the system's potential of recovering to a desired system's condition.

It should be noted that the literature review presented above it is not exhaustive; however, most of the works cited herein summarize previous works to quantify resilience, therefore this review is adequate for the classification of the different trends in the quantification of resilience for infrastructures and communities in general. However, due to its complexity, a comprehensive model that quantifies resilience of local, metropolitan or disperses communities and considers all infrastructures and their interaction is still missing.

This paper suggests a novel framework to evaluate resilience of a community and to assess the performance of critical infrastructures and their interdependencies while taking into account the influence of the human behavior, societal, organizational, and economic issues. The framework is based on seven major groups of characteristics, defined here as dimensions, which can measure resilience at different scales. These are: ***P**opulation and Demographics,* ***E**nvironmental/Ecosystem,* ***O**rganized Governmental Services,* ***P**hysical Infrastructure,* ***L**ifestyle and Community Competence,* ***E**conomic Development, and* ***S**ocial-Cultural Capital* and are identified with the acronym **PEOPLES**: The framework can be used for resilience-based design (RBD) at different spatial (local, regional etc.) and temporal (emergency response, recovery and reconstruction phase, etc.) scales. It can also be used by decision makers for disaster and post-disaster management, minimizing all the possible consequences following an extreme event, both natural and man-made allowing the perturbed system to return to the initial conditions as quickly as possible.

Mathematical definition of Resilience

The definition of Resilience used in this paper is the one described also by Cimellaro et al., (2010a), where a resilience index *R* of a system is defined as the normalized area underneath the functionality-performance function *Q(t)* shown in Figure -1**Error! Reference source not found.**, while analytically is defined as

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

where $Q_{TOT}(t)$ is the global functionality-performance function of the area considered (local, regional, etc) which is described in the next paragraph; T_{LC} is a control time for the period of interest; t_{0E} is the time instant when the event happens; $\vec{r}$ is a spatial vector defining the position *P* in the region where the resilience index is evaluated (Cimellaro et al. 2010b). In general, the resilience index can be applied to different fields (e.g. engineering, economic, social science etc.) and it can be used at various *temporal and spatial* scales. The first step to quantify the resilience index (*R*) is to define the *spatial scale* (e.g. individual building, city, region, state, etc.) of the problem of interest, because large disasters tend to expand over interacting large spaces. The second step is to define the *temporal scale* (emergency response vs. long term reconstruction phase) of the problem of interest;

the selection of the control period T_{LC} affects the resilience index *R*, therefore it should be maintained fixed when comparing different scenarios.

THE SEVEN DIMENSIONS

The proposed framework expands the initial research at the Multidisciplinary Center of Earthquake Engineering Research (MCEER) and links with the previously identified resilience characteristics (*technical, organizational, societal,* and *economic*) and with the resilience attributes (r^4: *robustness, redundancy, resourcefulness,* and *rapidity*) (Bruneau et al. 2003; Bruneau and Reinhorn, 2007; Cimellaro et al. 2010b).

The new framework, identified by the acronym PEOPLES, incorporates the initial MCEER's definitions of service functionality of community components (assets, services, demographics) and parameters influencing resilience, all assembled into a layered approach. The seven dimension groups of the PEOPLES' framework (Renschler et al. 2010, 2011), listed below, are further explained in this section.

(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;

The specific dimensions represent groups of interwoven societal, technical, economic and organizational issues. Although other definitions of multiple dimensions were described by Rockefeller Foundation (Huq et al, 2007), United Nations (2013), the Institute for Social and Environmental Transition (ISET) (Tyler and Moench, 2012), Arup (da Silva and Morera, 2014), the aforementioned dimension groups were selected based on similar characteristics. A resilience index can be established for each of the above dimensions; however, the whole community resilience would be influenced by all, or only some dominant dimensions, as it is described in the following. Table -2 shows the extended list of components and sub-components of the "PEOPLES Framework", while the detailed description of each dimension is given in the next paragraphs. The description of the dimensions follows the order of the PEOPLES acronym, so it is not based on a specific hierarchy. Additional details can also be found in Renschler et al. (2010, 2011).

Population and demographics

The *Population and demographics* dimension describes and differentiate the communities using specific parameters (e.g. the *median income,* the *age distribution* etc.) which might be critical for understanding its economics, health, etc. These parameters help describing the *social vulnerability* which is defined as the *incapacity of societies, organizations and citizens to resist at the exposure of multiple undesirable events*. These events are generated by the interaction in the society, the institutions and the systems of different cultural values. Social vulnerability is a pre-existing state of the community that affects the society's capacity to get ready for and recover from an undesirable event.

This dimension can be measured using a social index that describes the socioeconomic status, the composition of the population (e.g. elderly and children), the population density, the rural agriculture, the race, the gender, the ethnicity, the infrastructure employment, and the county debt/revenue.

Following the general definition of Resilience given in Equation (1), a possible functionality-performance metric (Q_p) for the *Population and Demographic* dimension could be the *social vulnerability index* (SVI) (Barry et al., 2011). The domains that form the basis of the Social Vulnerability Index (SVI) are 1) socioeconomic status, 2) household composition and disability, 3) minority status and language, and 4) housing and transportation. The data can be collected from the European Census of Population and Housing at the census tract level. Each of the domains can be described as per following variables:

- *Socioeconomic status* comprising income, poverty, employment, and education variables;
- *Household Composition and Disability*, comprising age, single parenting, and disability variables;

- *Minority Status and Language*, comprising race, ethnicity, and language proficiency variables;
- *Housing and Transportation*, comprising housing structure, crowding, and vehicle access variables.

Each of the above census variables, except *per capita income*, could be ranked from highest to lowest across all census tracts, to construct the SVI. Per capita income should be ranked from lowest to highest because, unlike the other variables, a higher value indicates less vulnerability. A percentile rank is then calculated for each census tract over each of these variables. A percentile rank is defined as the proportion of scores in a distribution that a specific score is greater than or equal to. Percentile ranks are calculated by using the formula:

$$Percentile\ Rank = \left(Rank - 1\right) \ / \ \left(N - 1\right) \qquad (2)$$

where N is the total number of data points, and all sequences of ties are assigned the smallest of the corresponding ranks. In addition, a tract-level percentile rank is calculated for each of the four domains based on an across-the-board sum of the percentile ranks of the variables comprising that domain. Finally, an overall percentile rank for each tract could be calculated as the sum of the domain percentile rankings. This process of percentile ranking—for all variables, for each domain, and for an overall SVI— is then repeated for the individual communities.

Others *social vulnerability index* (SoVI) (Cutter, 1996; Cutter et al., 2000) can be used as well, such as the one proposed by Cutter that integrates exposure to hazards with the social conditions that make people vulnerable to them.

Environmental/Ecosystem

In the *PEOPLES Framework*, the environmental and ecosystem dimension measure the capability of the ecological system to go back to its pre-event condition defined as its basic functionality. This dimension measures the capability of an ecosystem to deal with disturbance, but also the amount of disturbance an ecosystem can absorb without considerably varying its processes and structures.

In order to measure the environmental/ecosystem dimension of functionality and resilience, key indicators should be integrated together such as air, water and soil quality, biodiversity, and other natural resources.

One possible functionality-performance metric for this dimension is the *Normalized Difference Vegetation Index* (NDVI), which is evaluated from satellite-derived remote sensing images that analyze the density of green vegetation across an area (Rouse et al., 1973). The NDVI index (≤1) is given by

$$NDVI = \left(NIR - \mathrm{Red}\right) / \left(NIR + \mathrm{Red}\right) \quad (3)$$

where *Red* are the visible (red) infrared absorption bands and *NIR* are the near infrared absorption bands. Indeed, the *NDVI* index is highly correlated with the *Aboveground Net Primary Productivity* index (ANPP) (Pettorelli, 2005; Olofsson et al., 2007), that is based on filed measurements of the biomass accumulation and therefore can be considered as an indicator of the ecosystem resilience. Several applications can be found in literature where the NDVI values obtained from Landsat images have been used to observe the restoration of the vegetation after a fire (Diaz-Delgado et al., 2002) and using time series analysis (Simoniello et al., 2008).

The NDVI index in Equation (3) can be used to quantify the Environmental/Ecosystem dimension by comparing the NDVI values before and after the event, to determine the variations of ecosystem productivity through the space and the time caused by natural disasters such as fire, flood, hurricanes, tsunami, etc. Instead, in other types of disasters such as blizzards, terrorist attacks etc., the variation of this index could be negligible, because the vegetation density might not be altered, while other indicators could be more relevant.

Organized governmental services

The dimension of *organized governmental services* includes legal and security services (e.g. Police, emergency departments, fire departments, the military etc.), and also the public health, the hygiene departments, the cultural heritage departments etc.. Each of the above mentioned organized government services play a key role in sustaining societies before and after an extreme event.

Key indicators for this dimension include the *number of available response units* and their *capacity*, if they are opportunely normalized with respect to the number of residents involved. This dimension can provide a measure on how much the various organized government services participate in emergency preparedness planning (e.g. survey, etc.) developing a memorandum of understanding (MOUs) and other mutual aid agreements (Tierney, 2009).

Other examples of performance metric for this dimension can be the patient waiting time (*WT*), that is the time the patient waits before receiving assistance (Cimellaro et al., 2011), in the case when the organized service is the Emergency Department (ED) of an hospital. This specific indicator measures the ability of the ED to provide service to all patients after a disaster. Analytically the functionality-performance metric (Q_o) is given by

$$Q_o = \frac{WT_0}{WT} \tag{3}$$

where WT_0 is the waiting time in normal operating conditions, while *WT* is the waiting time during the emergency.

The deficiencies associated with this resilience dimension have been observed during the 2010 Haiti Earthquake, where the *lack* of organized government services and orderly control together with a *perception* that the government could not deal with the disaster reduced the response and recovery processes. In contrast, this resilience's dimension dominated the post 2010 Darfield earthquake in New Zealand, because the local, territorial and national government services were well organized to provide a quick restoration process. The organizational response during an emergency is most likely to be effective and improve resilience when it blends discipline and agility (Harrald, 2006).

Discipline and proper reaction are guaranteed by emergency plans, training activities, exercises and mutual aid agreements that encourage action toward common goals (Weick, 1995; Weick et al., 2005). Agility, flexibility, adaptability, and improvisations are entities which enhance resilience of a society, through volunteers, spontaneous helping behavior, and emergency groups which infuse resources and creativity into disaster response activities (Stallings and Quarantelli, 1985; Drabek and McEntire, 2002). The emergency management system following a disaster involves different groups such as the emergency response teams, the volunteers, the mass media, the economic network etc. These groups, instead of transferring information in a hierarchic way in the top-down direction, use an upward flow of information, which is the most preferred direction of communication used during disasters. In fact, the experience in the field has shown that decentralized networks with flatter organizations and less hierarchical structure are quicker in responding to disasters because they promote a free flow of information (Simoniello and Quarantelli, 1985).

Physical infrastructure

The *physical infrastructure dimension* includes *facilities* (e.g. housing, commercial and industrial facilities, and cultural facilities) and *lifelines* (food supply, utilities, transportation, communication networks etc.) within a built environment (Cimellaro et al., 2014b). While *facilities* are traditional essential life support for its population, *lifelines* are essential utilities which serve communities across all jurisdictions such as: (a) energy utilities (e.g. power and natural gas networks (Bruneau et al, 2003, Cimellaro et al., 2014a)); (b) transportation systems (e.g. highways, railroads, airports, seaports etc.); (c) water, storm-water and sewerage pipelines; (d) communication systems; and (e) health care facilities (e.g. hospitals, etc) (Cimellaro et al., 2011), etc. Functionality of physical infrastructures has an important impact on the restoration process following a disaster; therefore, the organized government services work actively to restore their functionality. Such interactions are essential in resilient communities.

For example, following Hurricane Katrina in 2005, after the evacuation of New Orleans, attention has shifted towards the restoration of the physical infrastructures. The pictures of damages have been used to communicate to the media in the world the consequences of the hurricane and of the subsequent flood (e.g. collapse of critical facilities such as churches, schools, and hospitals). The critical facilities were not able to provide their services without water and electricity. The damaged schools affected the community's self confidence to overcome the disaster and restore the initial functionality. The roads full of debris created an obstacle to the supply chain, therefore the economy in the region could not restart, because even if shops and companies re-opened they could not be accessible and even if they relocated for a short term, the previous customers were having some difficulties in finding the new location.

After a disaster, the restoration of physical infrastructures remains a technical problem that is also related to the socio-political events and the economic situation. The resilience dimension of physical infrastructure should also take into account the interdependencies between the different types of infrastructures and sectors during the analysis (Cimellaro and Solari, 2014c). Different functionality-performance metrics for this dimension are available in literature (Cimellaro et al., 2014a-b-c) and vary for every type of infrastructure (e.g. gas, water, transportation, etc). However, a general definition of functionality-performance metric (Q_{ph}) for this dimension which applies to every type of infrastructure is given by

$$Q_{Ph}(t) = \frac{\sum_{t_{0E}}^{t} n(t)}{n_{TOT}} \tag{3}$$

where $n(t)$ is the number of households without service at a given instant t and n_{tot} is the total number of households with service before the emergency.

There are also other examples for *housing units* where a possible functionality-performance metric might be the proportion of housing stock not rated as substandard or hazardous and vacancy rates for rental housing (Tierney, 2009). Examples of functionality-performance metrics for the *communication networks* might be the (i) acceptable linkages between official and unofficial information sources, (ii) the number of ties between the mass media and the emergency management entities, (iii) the sufficiency of measures for communicating the public's need and information after the disaster (Tierney, 2009).

Lifestyle and Community Competence

Lifestyle Community competence dimension deals with flexibility, creativity and problem solving skills of a community through also political partnerships (Norris et al., 2008). Principal elements of this dimension include *collective actions and decision making, collective efficacy and empowerment and quality of life*. This dimension captures both the raw ***abilities*** of a community (e.g., skills to find multifaceted solutions to complex problems through the engagement in political networks) and the ***perceptions*** of a community (e.g. perception to have the ability to do a positive change through a common effort that relies on peoples' aptitude to resourcefully envision a new future and then move in that direction) (Brown and Kulig, 1996). In fact, the societies that believe that they can restore, renew and rebuild themselves are expected to be more determined when facing a disaster or in general, any type of changes.

Quality of life surveys can be used as indicators of this perception, because they reveal whether people inside the community are devoted to their community and willing to engage in the activities necessary to maintain the community alive, before or after the disaster strikes. Examples of performance metrics for the community competence in normal condition before the disaster might be the number of immigrants, the number of citizens involved in politics, etc.

Specific performance metrics for this dimension directly related to the disaster might be the extensiveness of community warning procedures and plans, measured using for example the number of citizens involved, the number of organizational disaster training programs, etc. (Tierney, 2009).

Economic development

The economic development dimension is composed of both a *static* and a *dynamic* assessment. The *static* assessment is the *market activity* of the current economy of a community, while the *dynamic* assessment corresponds to the *economic development* which is the community's ability to continuously sustaining the economic growth. Resilient communities are characterized by the community's capacity to replace goods, services, shift employment patterns when is needed. In other words, they are associated to the employment, the variety in production and services. The economic dimension consists of three sub-categories: (i) the production within the industry, (ii) the distribution of employments within the industry, and (iii) the financial services.

The key indicators of the economic development dimension can be: (i) the percentage of the inhabitants that are working in the diverse industries, and (ii) the variability of the distribution of employments in the different industries which are in the community (iii) the literacy rate, (iv) the life expectancy, (v) the poverty rates. Other examples of indicators for this dimension are related to the community performance following a disaster and are: (i) the adequacy of plans for inspecting damaged buildings following disasters, (ii) the extent of evacuation plans and drills for high-occupancy structures, (ii) the adequacy of plans for post-disaster commercial restoration, etc. (Tierney , 2009). Because of these indicators, this dimension is interdependent with the *Population and Demographics dimension*.

Analytically one possible functionality-performance metric (Q_E) for this dimension is given by

$$Q_E = \frac{per\_inco + med\_inco + emply + hsg\_value + buss + insurance}{6} \tag{3}$$

where *per_inco*= per capita income; *med_inco*= median household income; *employ* = employed civilian population; *hsg_value*= median value of owner occupied housing units; *buss* = business establishments; *insurance* = population with health insurance.

Social/cultural capital

The Social/cultural capital dimension includes numerous sub-categories such as: (i) education services, (ii) child and elderly services, (iii) cultural and heritage services, (iv) community participation etc. The key indicators in normal condition for this dimension are: (i) the number of members belonging to the diverse civil and community organizations, (ii) the surveys of leaders and their perception. The key indicators in emergency conditions are: (i) the existence of community plans targeting transportation-disadvantaged residents, (ii) the adequacy of post-disaster sheltering plans, (iii) the adequacy of plans for incorporating volunteers into official response activities, (iv) the adequacy of donations management plans, (v) the community's plans to manage various networks (Tierney, 2009).

In relation to disaster phases' activities, socio-cultural capital dimension can be measured using the following six components suggested in the literature (Mayunga, 2009):

1. *Participation in voluntary organizations (volunteerism)*: this component was measured using registered non-profit organizations;
2. *Involvement in social groups (association densities)*: the involvement in social groups was measured using recreational centers (bowling centers, and fitness centers), golf clubs, and sport organizations;
3. *Civic and political participation*: this social capital component was measured using three indicators including registered voters, civic and political organizations, and Census response rates for the decennial population and housing survey;
4. *Religious participation*: it was measured using religious organizations;
5. *Community attachment*: the community attachment component was measured using owner-occupied housing units;

6. *Connection to working places*: this element was measured using two indicators including professional organizations and business organizations;

Then a three-step procedure is employed in calculation of the socio-cultural capital dimension: (i) scale adjustment of indicators, (ii) standardization or normalization, and (iii) creation of the socio cultural community resilience index.

In addition, the *social support* underlies several services connected with the *social/cultural capital*, such as "helping behaviors within family and friendship networks" and the "relationships between individuals and their larger neighborhoods and communities" (Norris et al., 2008). In fact, the habitants of a community tend to manifest their sense of community and to bond with other members of the same group by providing social and cultural services. However, this emotional connection to the community is not necessary related only to the residents in those places (Manzo and Perkins, 2006). For example, several displaced residents of New Orleans after Hurricane Katrina expressed the desire to return home with a strong "place attachment", regardless the job they had and the people they knew. These residents are an important resource for the community, because if they will be provided with housing and employment after the disaster, they will act in order to restore the community to the initial condition before the disaster. The citizen participation in community organizations (e.g. religious congregations, school and resident associations, neighborhood watches, self-help groups etc.) is a way of demonstrating one's care for their community, one's care for meeting and understanding one's fellow citizens and it increases individuals' circle of influence and perception of control (Norris et al., 2008).

MATHEMATICAL FORMULATION OF THE PEOPLES FRAMEWORK

General description of the methodology and the community hybrid model

The main part of the methodology consists in developing a community hybrid model, coupling the *Network models* which will be used to model the *physical infrastructures networks* such as the power and the water, with the *Agent based models* which will be used to model the *socio-technical networks* such as the Emergency Medical Technicians and the fire brigade (Figure -2). Inside the ABM models, the emotions in the agents will be modeled using the extended version of Belief-Desire-Intention modeling framework proposed by Zoumpanaki (2010) that has been expanded and adapted to the proposed methodology (Figure 3).

Both types of models will be integrated in a hybrid framework and a matrix approach will be used to describe the interdependencies between the different layers. Each layer represents an infrastructure (Figure 3) and is described by an adjacency matrix **A**, while a **D** matrix will describe the interdependencies between the nodes of the different layers (e.g. $\mathbf{D}_{\mathbf{Water \rightarrow Power}}$) and it will be obtained using an *extended version of the Haimes' input-output inoperability matrix* (IIM) (Haimes et al., 2005). For example, in Figure -2, the hospital is a node of the EMT layer and it is interdependent with the power and the water network. Therefore, a **D** matrix describing the interdependencies between the EMT layer and the water and power layer will be determined using Haimes model.

The matrix **D** is composed of constant scalars terms if the system does not change though the time. In reality, the interdependent networks might change through the time their interconnectedness as shown in some applications (Fantini et al., 2014), however the proposed approach can also be applied in this case. The proposed approach will require substantial computational power if the spatial and temporal dimensions of the problem increase, therefore the use of parallel computing is recommended in these cases. Below is shown in simple terms how the agent base models and the network model interact in the proposed methodology. Once the hazard is determined (e.g. earthquake event), the corresponding damage in the infrastructure networks is determined using fragility analysis combined with graph theory in order to identify the nodes of the network that will not be functional following the extreme event. Because of physical infrastructure disservice, also the socio-technical networks operating in the community will be affected. For example the road transportation disservice, might limit the capacity of the emergency rescue teams to move and operate in the community. The water network disservice might limit the capacity of the fire brigade to extinguish fires etc. In order to study these interdependencies the network models and the agent-based model need to run simultaneously. So the output of the damage analysis in the network models should be used as input to modify the characteristics of the agent-based models, such as the extension of the environmental space (e.g. roads), the capacity to perform certain actions (e.g. extinguish fire) of the agents, etc.

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Resilience index and performance metrics

Once the *hybrid model* in Figure -2 is built, it is necessary to identify the performance metrics to estimate the resilience of each infrastructure. Several approaches exist in literature for hospitals (Cimellaro et al., 2011), lifeline structures (Ouyang et al., 2012, Cimellaro et al., 2014c) and cities (Chang et al, 2014). Once the proper performance metric is selected, the degree of interdependency between an infrastructure *x* and *y* is described using a matrix $\mathbf{D}_{\mathbf{x}\rightarrow\mathbf{y}}$ which is able to identify the exact location of the interdependency in the network (e.g. node or link). However, sometimes it is also useful to identify a global index *I* that measures the degree of interdependency between the different infrastructures, in order to have a global evaluation of the community performance and to assign an unbiased evaluation of the weight (or important factor) to each infrastructure. This index can be determined using time series analysis (Cimellaro et al., 2014c) or from linear algebra manipulation of the $\mathbf{D}_{\mathbf{x}\rightarrow\mathbf{y}}$ matrix etc. Then the indices *I* can be grouped into an infrastructure Interdependency Matrix (**IM**) (Figure 4). The infrastructures considered in the analysis of the community are listed in the rows and the columns, while in each cell is shown the degree of interdependency (from 0 to1) between them. The sum over the columns gives the *dependent factor* of the specific lifeline, while the sum over the rows gives the *importance factor* of a specific lifeline. Ideally, the target is to realize a community where all lifelines are independent, so **IM** will be an identity matrix. As mentioned above, the **IM** can also be used to have an unbiased estimation of the weight coefficients to assign to each infrastructure considered in the layered approach shown in Figure -2. Once the spatial and temporal boundaries of the problem at hand are defined, the performance metrics of all the resilience dimensions are aggregated following the procedure described in the paper of Cimellaro et al. (2014c). The global resilience indicator at the community level is evaluated using the following equation

$$R = \sum_{i} \left(R_i \times w_i \right) \tag{6}$$

where R_i is calculated using Equation (1). For example if it is considered the physical infrastructure dimension, R_i is the resilience indicator of a specific infrastructure, while w_i is the weight factor describing the interdependencies between the different indicators. The coefficient w_i are determined using a time series analysis approach borrowed by the economic field which is based on the analysis of the cross correlation function (CCF). The procedure can be applied to all the components and subcomponents of the PEOPLES framework in order to take into account the interdependencies between the different variables. Further details about the methodology can be found in Cimellaro et al. (2014c).

The selection of the proper performance metric for the critical infrastructures plays a key role in the analysis. Even if a realistic and predictive model is developed, the results might be affected by the selection of the final performance function adopted to evaluate the community resilience index using the methodology shown in Figure -2. Different innovative approaches to measure functionality are available in literature and they include agent-based modeling, input-output models, mathematical models and game theory (Pederson et al., 2006). Therefore, once the approach and the geographic scale is selected, the global performance indicator Q_{TOT} can be plotted over the region of interest using a contour plot at a given instant of time t, so the *time-dependent functionality maps* can be obtained. When also the control time T_{LC} is defined, the *resilience contour map* of the region of interest can also be plotted. The *Resilience contour maps* are obtained by integrating the functionality maps over time using Equation (1), therefore the resilience maps 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

$$R_{com} = \int_{A_C} R(\vec{r})/A_C dr = \int_{A_C} \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(\vec{r},t)/(A_C T_{LC}) dtdr \qquad (3)$$

where A_c is the area of the selected region. The contour plot of each dimension can be combined with the other plots using a layered approach. Then a radar graph is built (Figure -2) and the internal area will determine the final score of the resilience index that will be used to recognize the priority resilience actions to be taken in the community.

Resilience performance levels

The objective of Performance Based Seismic Engineering (PBSE) is to design, construct and maintain facilities with better damage control, coupling the expected or desired performance levels with the levels of seismic hazard. Generally the levels focus on the performances a structure can hold during the shaking and are related to engineering demand parameters such as deformations. More recently SPUR (Bonowitz, 2009), the San Francisco planning and Urban Research Association, introduced other definitions of performance levels for infrastructures based on recovery target states combining safety and recovery time. Five performance measures for buildings have been identified: (i) *Safe and Operational*; (ii) *Safe and usable during repair*; (iii) *Safe and usable after repair*; (iv) *Safe but not repairable*; (v) *Unsafe*.

The proposed Resilience Performance Levels (RPL) focus on building performance after the earthquake, recognizing the importance of the temporal dimension (Recovery time T_{RE}) in the assessment of the *RPLs* of structures and communities in general.

In this paper a 2-dimensional performance domain consisting of Performance Levels *PL(i, j)*, defined by the combination of *functionality* (index j) and *recovery time* (index i) is proposed. By accounting for the effect of the temporal dimension, a 3-dimensional performance matrix (Figure -5) can be visualized as a set of predefined joined performance domains (“masks”) for different seismic intensity level, IM and different RPLs.

The resilience performance levels can be defined using expert opinions as well as public interviews which will allow identifying the acceptable and desired performance levels by citizens for different type of infrastructures, for example.

Restoration models and recovery time

The *restoration phase* and the *recovery time* are key element for the quantification of the resilience index, but they are also the most uncertain and difficult to be computed. The first step for its evaluation consists in the definition of a performance index. In general, the community performance indices are function of time *t* and of other parameters that depend on the type of a community considered. Numerous models have been listed in Cimellaro et al. (2010a) to describe the restoration function. They can be either ***empirical*** or ***analytical*** depending on the type of analysis and data.

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

Analytical recovery models are developed using response data from numerical simulations (nonlinear time history analysis, response spectral analysis, etc) of system models. Few example of analytical recovery models (e.g. discrete event simulation models, metamodels, etc.) for critical facilities like hospitals can be found in Cimellaro et al., (2011, 2014d).

Step by step procedure for resilience evaluation

A schematic step-by-step procedure of the methodology described in is the following:

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

(9) Definition, calibration and validation of the hybrid model of the community;
(10) Run the analysis and evaluate the response of the model;
(11) Evaluate the performance metrics (e.g. losses, restoration time, performance index, resilience index) for different scenarios and compare with different performance levels;
(12) Recognize remedial mitigation actions (e.g. advanced technologies such as base isolation, passive dampers, etc.) and/or resilience actions (e.g. resourcefulness, redundancy, etc.);

The proposed design approach has analogies with the feedback loop taken from control theory and it can be applied both to communities and single structures (e.g. hospital, city hall, etc).
Several applications of this approach can be found in literature to hospitals (Cimellaro et al., 2011), natural gas distribution networks (Cimellaro et al., 2014a), water distribution network (Cimellaro et al., 2015), but they are not reported in this paper due to the lack of space.

CONCLUDING REMARKS

After the recent disasters, the general public became aware that Resilience is the solution to face natural and manmade threats. The paper presents a holistic framework to evaluate the resiliency of a community at various geographical and temporal scales and identifies the gaps in the definitions and quantification of resilience at the community level. The suggested framework summarized with the acronyms P.E.O.P.L.E.S. is combining different dimensions of resilience together using a layered approach. The main contribution in the field is the development of a *community hybrid model* combining *network models* to model the physical infrastructures (electric power, water, gas etc.) with *agent-based models* to model the socio technical networks (e.g. Emergency medical technicians, fire brigade, police, etc). Furthermore, special attention is given to the human behavior and its emotions which plays a key role during the emergency and they have been modeled using the extended version of *Belief-Desire-Intention* (BDI) modeling framework proposed by Zoumpanaki in 2010.

Each *dimension* of the framework is made of *components* and *sub-components* with their respective performance indicators. These indicators can be grouped according to their difficulty in evaluating them, their complexity as well as spatial and temporal scales. Some of them might be valid on a multi hazard approach, while others might be valid only for certain type of hazard. In the paper are shown some examples of indicators, while is made reference to the several applications already available in literature of the PEOPLES methodology because the framework has been the result of a NIST project developed in 2009.

In the long term, the proposed framework can be used as decision support software by decision makers and by planners/engineers to help implementing Resilience-Based Design (RBD) techniques. The goal is to make individual structures and communities safe and resilient with both *advanced technologies* (e.g. base isolation, passive dampers etc.) and *resilience actions* that allow each system to recover its functionality in a short time by selecting the optimal restoration strategy and enhancing the community resilience index by comparing it with the resilience levels targets.

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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 Empowerment	c) Quality of Life
i) Conflict Resolution	ii) Self-Organization		
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	

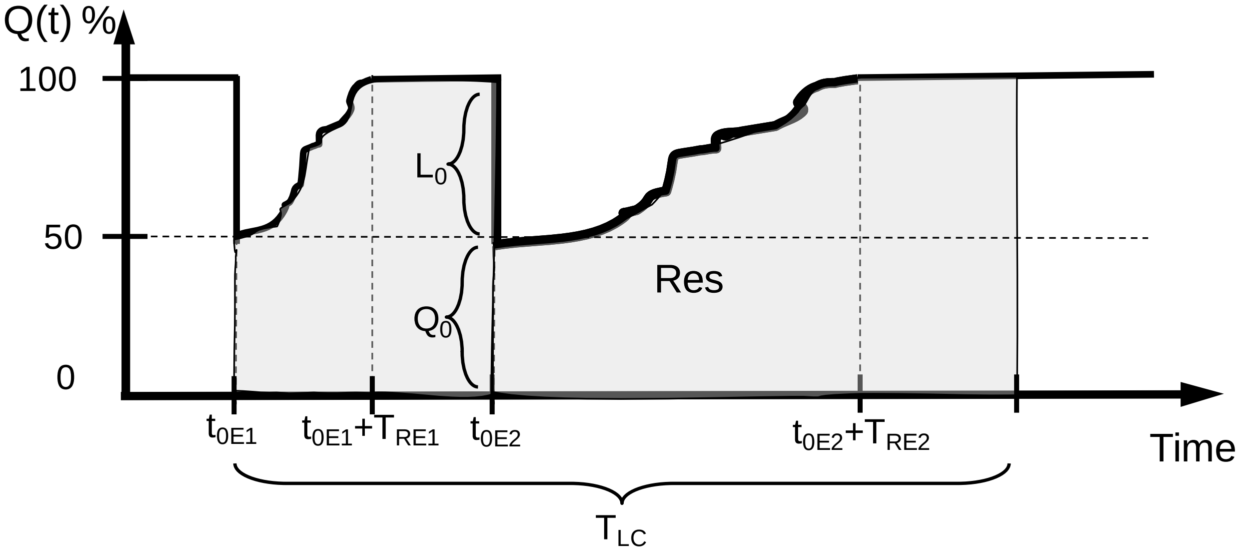


Figure -1 Resilience (adapted from Cimellaro et al., 2010a)

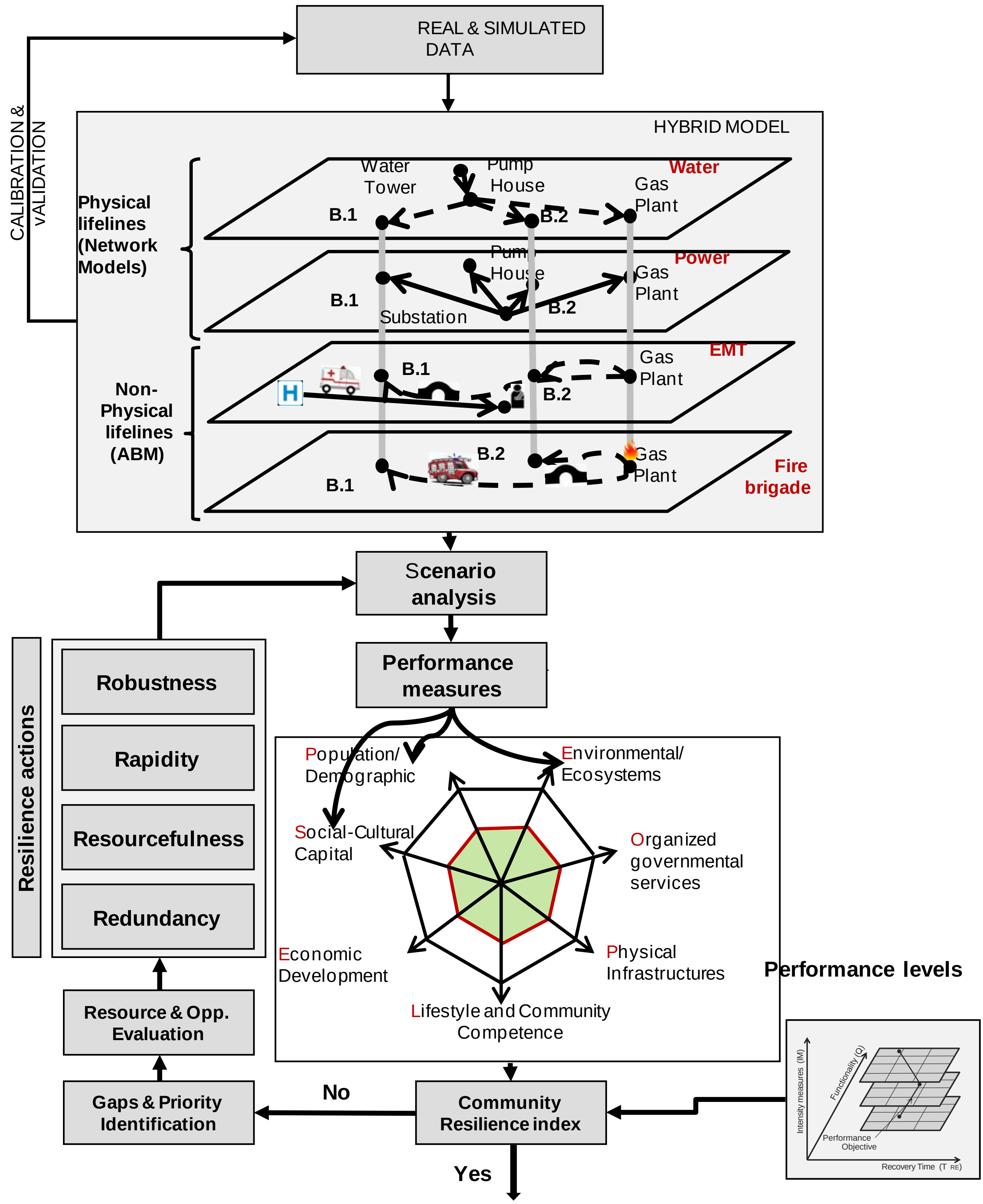


Figure -2 Methodology for Resilience-based design (RBD) based on control (feedback loop) approach and hybrid layered model

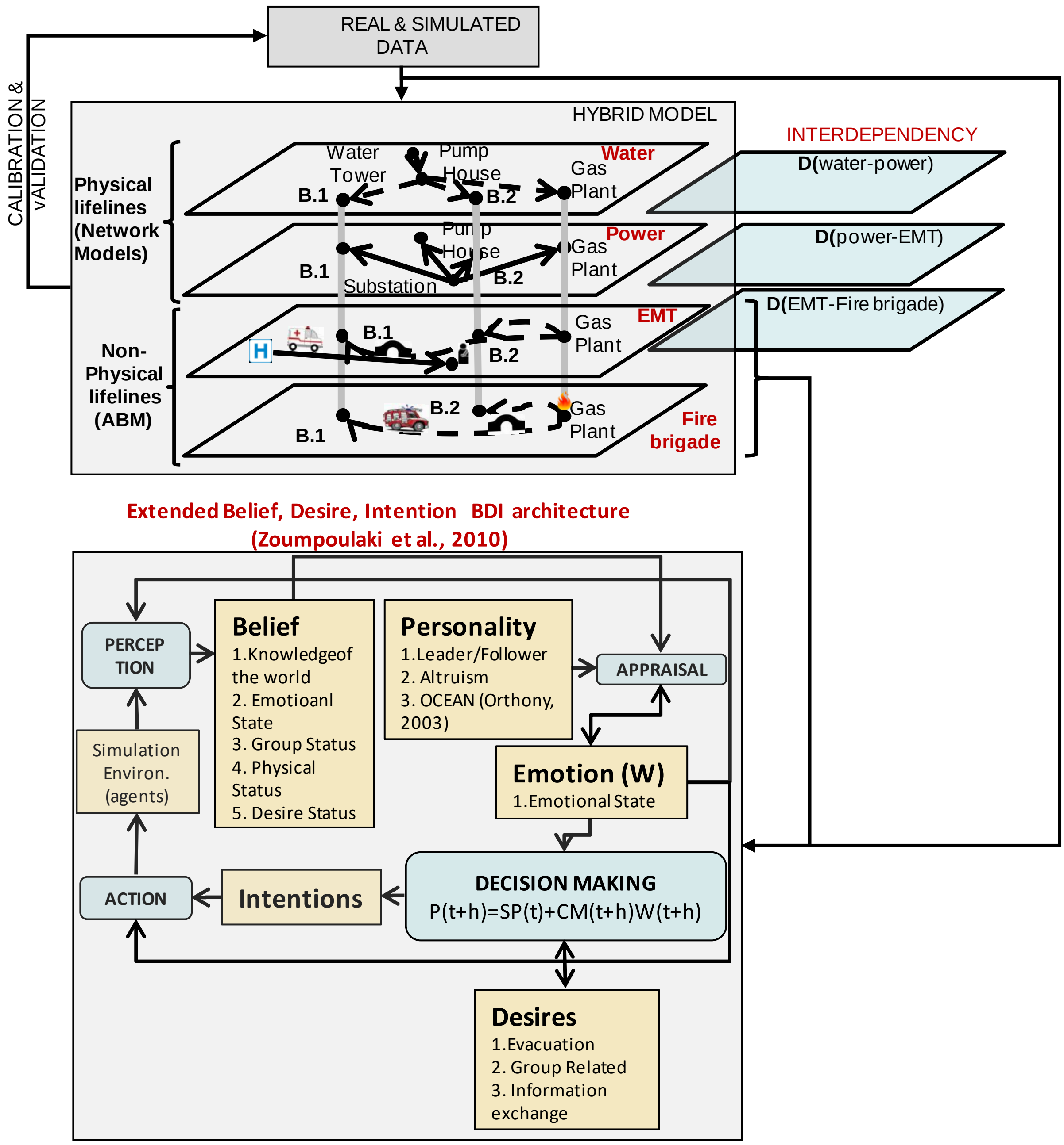
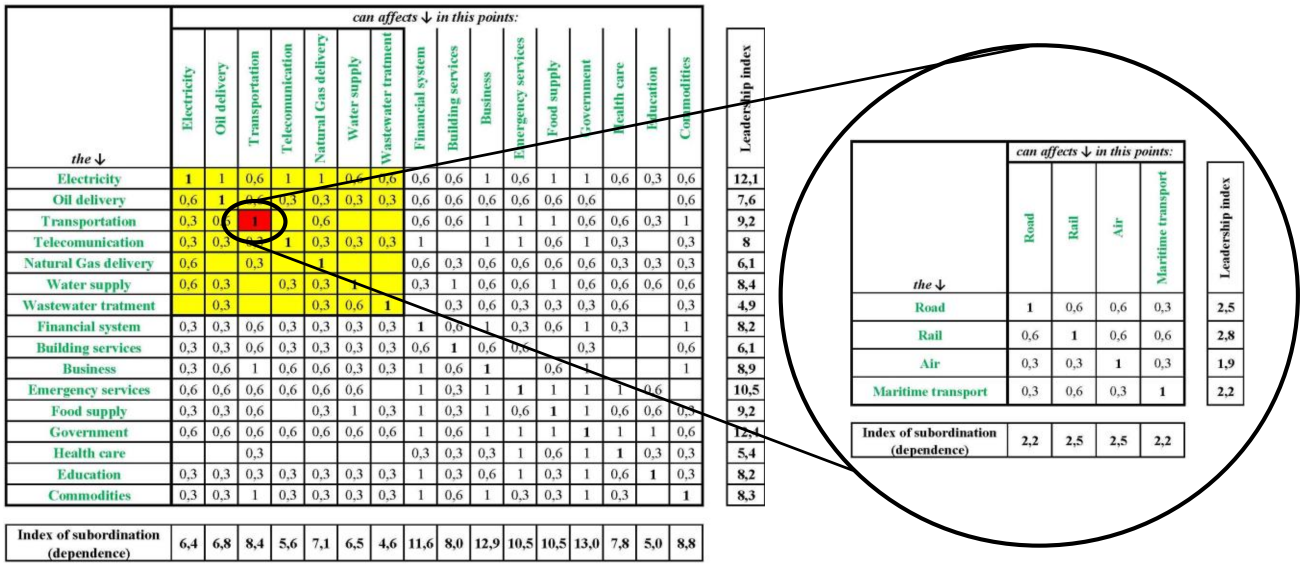


Figure 3 Methodology to model the interdependency and the human behavior within the community hybrid model



the ↓ / can affects ↓ in this points:	Electricity	Oil delivery	Transportation	Telecomunication	Natural Gas delivery	Water supply	Wastewater tratment	Financial system	Building services	Business	Emergency services	Food supply	Government	Health care	Education	Commodities	Leadership index
Electricity	**1**	1	0,6	1	1	0,6	0,6	0,6	0,6	1	0,6	1	1	0,6	0,3	0,6	**12,1**
Oil delivery	0,6	**1**	0,6	0,3	0,3	0,3	0,3	0,6	0,6	0,6	0,6	0,6	0,6			0,6	**7,6**
Transportation	0,3	0,6	**1**		0,6			0,6	0,6	1	1	1	0,6	0,6	0,3	1	**9,2**
Telecomunication	0,3	0,3	0,3	**1**	0,3	0,3	0,3	1		1	1	0,6	1	0,3		0,3	**8**
Natural Gas delivery	0,6		0,3		**1**			0,6	0,3	0,6	0,6	0,6	0,6	0,3	0,3	0,3	**6,1**
Water supply	0,6	0,3		0,3	0,3	**1**		0,3	1	0,6	0,6	1	0,6	0,6	0,6	0,6	**8,4**
Wastewater tratment		0,3			0,3	0,6	**1**		0,3	0,6	0,3	0,3	0,3	0,6		0,3	**4,9**
Financial system	0,3	0,3	0,6	0,3	0,3	0,3	0,3	**1**	0,6	1	0,3	0,6	1	0,3		1	**8,2**
Building services	0,3	0,3	0,6	0,3	0,3	0,3	0,3	0,6	**1**	0,6	0,6		0,3			0,6	**6,1**
Business	0,3	0,6	1	0,6	0,6	0,3	0,3	1	0,6	**1**		0,6	1			1	**8,9**
Emergency services	0,6	0,6	0,6	0,6	0,6	0,6		1	0,3	1	**1**	1	1	1	0,6		**10,5**
Food supply	0,3	0,3	0,6		0,3	1	0,3	1	0,3	1	0,6	**1**	1	0,6	0,6	0,3	**9,2**
Government	0,6	0,6	0,6	0,6	0,6	0,6	0,6	1	0,6	1	1	1	**1**	1	1	0,6	**12,4**
Health care			0,3					0,3	0,3	0,3	1	0,6	1	**1**	0,3	0,3	**5,4**
Education	0,3	0,3	0,3	0,3	0,3	0,3	0,3	1	0,3	0,6	1	0,3	1	0,6	**1**	0,3	**8,2**
Commodities	0,3	0,3	1	0,3	0,3	0,3	0,3	1	0,6	1	0,3	0,3	1	0,3		**1**	**8,3**
Index of subordination (dependence)	**6,4**	**6,8**	**8,4**	**5,6**	**7,1**	**6,5**	**4,6**	**11,6**	**8,0**	**12,9**	**10,5**	**10,5**	**13,0**	**7,8**	**5,0**	**8,8**	

the ↓ / can affects ↓ in this points:	Road	Rail	Air	Maritime transport	Leadership index
Road	**1**	0,6	0,6	0,3	**2,5**
Rail	0,6	**1**	0,6	0,6	**2,8**
Air	0,3	0,3	**1**	0,3	**1,9**
Maritime transport	0,3	0,6	0,3	**1**	**2,2**
Index of subordination (dependence)	**2,2**	**2,5**	**2,5**	**2,2**	

Figure 4 Sketch of a typical **IM** matrix.

		Recovery Time		
		Short term (Emergency)	Midterm	Long term (Reconstruction)
Functionality Performance Levels	Fully Operational (Q1)	Basic Objective	Unacceptable	Unacceptable
	Operational (Q2)	Essential Objective	Basic Objective	Unacceptable
	Partially Operational (Q3)	Critical Objective	Essential Objective	Basic Objective
	Near not Operational (Q4)	Not feasible	Critical Objective	Basic Objective

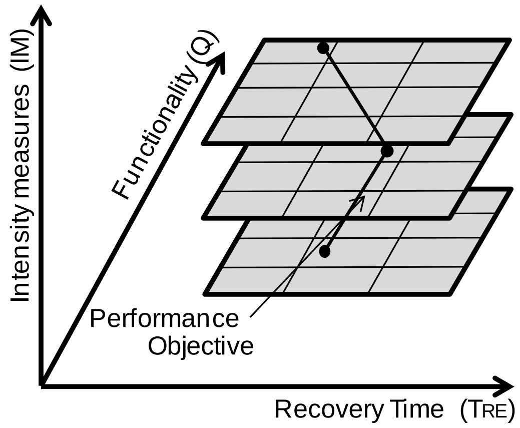


Figure -5 Tridimensional Resilience Performance levels matrix for structures, communities, systems etc.