POLITECNICO DI TORINO Repository ISTITUZIONALE

PEOPLES: A Framework for Evaluating Resilience

Original

PEOPLES: A Framework for Evaluating Resilience / Cimellaro, GIAN PAOLO; Renschler, Chris; Reinhorn, Andrei M.; Arendt, Lucy. - In: JOURNAL OF STRUCTURAL ENGINEERING. - ISSN 0733-9445. - ELETTRONICO. - 142:10(2016), p. 04016063. [10.1061/(ASCE)ST.1943-541X.0001514]

Availability: This version is available at: 11583/2652922 since: 2019-10-18T12:50:35Z

Publisher: American Society of Civil Engineers (ASCE)

Published DOI:10.1061/(ASCE)ST.1943-541X.0001514

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

1 2

3

4

PEOPLES: A FRAMEWORK FOR EVALUATING RESILIENCE

Gian Paolo Cimellaro¹, Chris Renschler², Andrei M. Reinhorn³, Lucy Arendt⁴,

ABSTRACT

5 In recent years, the concept of resilience has been introduced to the engineering field in particular 6 related to disaster mitigation and management. However, the built environment is only part of the 7 elements that support community functions. Maintaining community functionality during and after a 8 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 9 10 dimensions are identified for measuring the community resilience: Population and Demographics, 11 Environmental/Ecosystem, Organized Governmental Services, Physical Infrastructures, Lifestyle and Community Competence, Economic Development, and Social-Cultural Capital. They are 12 13 summarized with the acronym PEOPLES. Each dimension is characterized by a corresponding 14 performance metric that is combined with the other dimensions using a multi-layered approach. 15 Therefore, once a hybrid model of the community is defined, the proposed framework can be applied 16 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 17 Several applications of part of such framework can already be found in 18 influencing the events. literature for different types of infrastructures, physical and organizational (e.g. gas network, water 19 distribution networks, health care facilities etc.). The proposed framework can be used as decision 20 21 support by stakeholders and managers and it can help planners in selecting the optimal restoration 22 strategies that enhance the community resilience index.

¹Visiting Professor, Department of Structural & Environmental Engineering, University of California, Berkeley, Berkeley, USA, Email: <u>gianpaolo.cimellaro@polito.it</u>

² Associate Professor, Department of Geography, University at Buffalo, SUNY, 116 Wilkeson Quad, Buffalo, NY 14261, U.S.A. Email: <u>rensch@buffalo.edu</u>.

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. <u>reinhorn@buffalo.edu</u>

⁴ Associate Professor of Management, Associate Dean, College of Professional Studies, Director, Austin E. Cofrin School of Business, University of Wisconsin-Green Bay, 2420 Nicolet Dr, Green Bay, WI 54311, USA, <u>arendtl@uwgb.edu</u>

Keywords: Resilience; disaster resilience; infrastructures, performance metric; community resilience;
 environment/ecosystem; organized governmental services; physical infrastructure.

- 25
- 26

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.

31 The concept of resilience has several definitions, because of its broad utilization in ecology, social 32 science, economy and engineering fields, with different meanings and implications. As Klein et al. 33 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 34 35 Garmezy, Emmy Werner and Ruth Smith (Garmezy, 1974; Werner and Smith, 1989). Later the 36 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 37 38 absorb change and disturbance and still maintain the same relationships between populations or state 39 variables. Stability represents the ability of a system to return to an equilibrium state after a 40 temporary disturbance; the more rapidly it returns to equilibrium and the less it fluctuates, the more 41 stable it would be". An extended literature review about resilience has been assembled in the past 42 (see Table -1) with each contribution adding new nuances. Primarily resilience has been defined in 43 context to the speed of systems to go towards equilibrium (Adger, 2000) or capability to cope and 44 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 45 46 outside interferences (Mileti, 1999). After the original definition of resilience in ecological systems, 47 the word expanded its meaning to *engineering*, social and economical fields.

48 *Engineering resilience* is defined as the capability of a system to maintain its functionality and to 49 degrade gracefully in the face of internal and external changes (Allenby and Fink, 2005). The main 50 difference in defining resilience arises between the engineering approach where resilience occurs by 51 recovering towards a previous or an improved stable state (Bruneau et al., 2003), and the ecological 52 approach where resilience is achieved moving towards a different system state (Handmer & Dovers, 53 1996).

54 *Social resilience* is defined as the ability of groups or societies to cope with external stresses and 55 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 78 system functionality Q that is evaluated comparing the extreme events scenario with the pre-event 79 conditions and they applied the method to the case study of Memphis water system. Miles and 80 Chang (2006) presented a comprehensive functionality restoration model that establishes the 81 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 82 83 restoration process of an electric power system. The resilience concept as input to decision support 84 methodologies has been applied to hospitals (Cimellaro et al., 2010b; Cimellaro and Pique`, 2014a), 85 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), 86 87 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.

95 It should be noted that the literature review presented above it is not exhaustive; however, most of 96 the works cited herein summarize previous works to quantify resilience, therefore this review is 97 adequate for the classification of the different trends in the quantification of resilience for 98 infrastructures and communities in general. However, due to its complexity, a comprehensive model 99 that quantifies resilience of local, metropolitan or disperses communities and considers all 100 infrastructures and their interaction is still missing.

101 This paper suggests a novel framework to evaluate resilience of a community and to assess the 102 performance of critical infrastructures and their interdependencies while taking into account the 103 influence of the human behavior, societal, organizational, and economic issues. The framework is 104 based on seven major groups of characteristics, defined here as dimensions, which can measure 105 resilience at different scales. These are: *Population and Demographics*, *Environmental/Ecosystem*, 106 **O**rganized Governmental Services, **P**hysical Infrastructure, Lifestyle and Community Competence, 107 Economic Development, and Social-Cultural Capital and are identified with the acronym The framework can be used for resilience-based design (RBD) at different spatial 108 **PEOPLES**: 109 (local, regional etc.) and temporal (emergency response, recovery and reconstruction phase, etc.) 110 It can also be used by decision makers for disaster and post-disaster management, scales. 111 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. 112

113 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 -1Error! Reference source not found., while analytically is defined as

118
$$R(\vec{r}) = \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(\vec{r},t) / T_{LC} dt$$
(1)

where $Q_{TOT}(t)$ is the global functionality-performance function of the area considered (local, 119 120 regional, etc) which is described in the next paragraph; T_{LC} is a control time for the period of interest; 121 t_{0E} is the time instant when the event happens; \vec{r} is a spatial vector defining the position P in the 122 region where the resilience index is evaluated (Cimellaro et al. 2010b). In general, the resilience 123 index can be applied to different fields (e.g. engineering, economic, social science etc.) and it can be 124 used at various temporal and spatial scales. The first step to quantify the resilience index (R) is to 125 define the spatial scale (e.g. individual building, city, region, state, etc.) of the problem of interest, 126 because large disasters tend to expand over interacting large spaces. The second step is to define the 127 temporal scale (emergency response vs. long term reconstruction phase) of the problem of interest; 128 the selection of the control period T_{LC} affects the resilience index *R*, therefore it should be maintained 129 fixed when comparing different scenarios.

130

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 (r⁴: *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.

- 141 (1) **P**opulation and demographics;
- 142 (2) Environment/ecosystem;
- 143 (3) Organized government services;
- 144 (4) **P**hysical infrastructure;
- 145 (5) Lifestyle and community competence;
- 146 (6) Economic development;
- 147 (7) Social-cultural capital;

148 The specific dimensions represent groups of interwoven societal, technical, economic and 149 organizational issues. Although other definitions of multiple dimensions were described by 150 Rockefeller Foundation (Huq et al, 2007), United Nations (2013), the Institute for Social and 151 Environmental Transition (ISET) (Tyler and Moench, 2012), Arup (da Silva and Morera, 2014), the 152 aforementioned dimension groups were selected based on similar characteristics. A resilience index 153 can be established for each of the above dimensions; however, the whole community resilience 154 would be influenced by all, or only some dominant dimensions, as it is described in the following. 155 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).

159 **Population and demographics**

160 The Population and demographics dimension describes and differentiate the communities using 161 specific parameters (e.g. the *median income*, the *age distribution* etc.) which might be critical for 162 understanding its economics, health, etc. These parameters help describing the social vulnerability 163 which is defined as the incapacity of societies, organizations and citizens to resist at the exposure of 164 multiple undesirable events. These events are generated by the interaction in the society, the 165 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 166 167 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 functionalityperformance 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 182 183 variables;
- 184 185

Housing and Transportation, comprising housing structure, crowding, and vehicle access variables.

186

187 Each of the above census variables, except per capita income, could be ranked from highest to 188 lowest across all census tracts, to construct the SVI. Per capita income should be ranked from lowest 189 to highest because, unlike the other variables, a higher value indicates less vulnerability. A percentile 190 rank is then calculated for each census tract over each of these variables. A percentile rank is defined 191 as the proportion of scores in a distribution that a specific score is greater than or equal to. Percentile 192 ranks are calculated by using the formula:

$$Percentile Rank = (Rank-1) / (N-1)$$
(2)

194 where N is the total number of data points, and all sequences of ties are assigned the smallest of the 195 corresponding ranks. In addition, a tract-level percentile rank is calculated for each of the four 196 domains based on an across-the-board sum of the percentile ranks of the variables comprising that 197 domain. Finally, an overall percentile rank for each tract could be calculated as the sum of the 198 domain percentile rankings. This process of percentile ranking-for all variables, for each domain, 199 and for an overall SVI- is then repeated for the individual communities.

200 Others social vulnerability index (SoVI) (Cutter, 1996; Cutter et al., 2000) can be used as well, such 201 as the one proposed by Cutter that integrates exposure to hazards with the social conditions that 202 make people vulnerable to them.

203

204 Environmental/Ecosystem

205 In the PEOPLES Framework, the environmental and ecosystem dimension measure the capability of 206 the ecological system to go back to its pre-event condition defined as its basic functionality. This

207 dimension measures the capability of an ecosystem to deal with disturbance, but also the amount of 208 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.

212 One possible functionality-performance metric for this dimension is the *Normalized Difference* 213 *Vegetation Index* (NDVI), which is evaluated from satellite-derived remote sensing images that 214 analyze the density of green vegetation across an area (Rouse et al., 1973). The NDVI index (≤ 1) is 215 given by

216

217
$$NDVI = (NIR - \text{Red})/(NIR + \text{Red})$$

218

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.

232

(3)

233 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

248

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

249 where WT_0 is the waiting time in normal operating conditions, while WT is the waiting time during 250 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).

258 Discipline and proper reaction are guaranteed by emergency plans, training activities, exercises and 259 mutual aid agreements that encourage action toward common goals (Weick, 1995; Weick et al., 260 2005). Agility, flexibility, adaptability, and improvisations are entities which enhance resilience of 261 a society, through volunteers, spontaneous helping behavior, and emergency groups which infuse 262 resources and creativity into disaster response activities (Stallings and Quarantelli, 1985; Drabek and 263 The emergency management system following a disaster involves different groups McEntire, 2002). 264 such as the emergency response teams, the volunteers, the mass media, the economic network etc. 265 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 266 267 In fact, the experience in the field has shown that decentralized networks with flatter disasters. 268 organizations and less hierarchical structure are quicker in responding to disasters because they 269 promote a free flow of information (Simoniello and Quarantelli, 1985).

270

271 **Physical infrastructure**

272 The physical infrastructure dimension includes facilities (e.g. housing, commercial and industrial 273 facilities, and cultural facilities) and lifelines (food supply, utilities, transportation, communication 274 networks etc.) within a built environment (Cimellaro et al., 2014b). While facilities are traditional 275 essential life support for its population, lifelines are essential utilities which serve communities 276 across all jurisdictions such as: (a) energy utilities (e.g. power and natural gas networks (Bruneau et 277 al, 2003, Cimellaro et al., 2014a)); (b) transportation systems (e.g. highways, railroads, airports, 278 seaports etc.); (c) water, storm-water and sewerage pipelines; (d) communication systems; and (e) 279 health care facilities (e.g. hospitals, etc) (Cimellaro et al., 2011), etc. Functionality of physical 280 infrastructures has an important impact on the restoration process following a disaster; therefore, the 281 organized government services work actively to restore their functionality. Such interactions are 282 essential in resilient communities.

283 For example, following Hurricane Katrina in 2005, after the evacuation of New Orleans, attention 284 has shifted towards the restoration of the physical infrastructures. The pictures of damages have 285 been used to communicate to the media in the world the consequences of the hurricane and of the 286 subsequent flood (e.g. collapse of critical facilities such as churches, schools, and hospitals). The 287 critical facilities were not able to provide their services without water and electricity. The damaged 288 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 289 290 in the region could not restart, because even if shops and companies re-opened they could not be 291 accessible and even if they relocated for a short term, the previous customers were having some 292 difficulties in finding the new location.

293 After a disaster, the restoration of physical infrastructures remains a technical problem that is also 294 related to the socio-political events and the economic situation. The resilience dimension of physical 295 infrastructure should also take into account the interdependencies between the different types of 296 infrastructures and sectors during the analysis (Cimellaro and Solari, 2014c). Different functionalityperformance metrics for this dimension are available in literature (Cimellaro et al., 2014a-b-c) and 297 vary for every type of infrastructure (e.g. gas, water, transportation, etc). 298 However, a general 299 definition of functionality-performance metric (Q_{ph}) for this dimension which applies to every type 300 of infrastructure is given by

301
$$Q_{Ph}(t) = \frac{\sum_{t_{0E}} n(t)}{n_{TOT}}$$
(3)

t

302 where n(t) is the number of households without service at a given instant t and n_{tot} is the total 303 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 307 *communication networks* might be the (i) acceptable linkages between official and unofficial 308 information sources, (ii) the number of ties between the mass media and the emergency management 309 entities, (iii) the sufficiency of measures for communicating the public's need and information after 310 the disaster (Tierney, 2009).

311

312 Lifestyle and Community Competence

313 Lifestyle Community competence dimension deals with flexibility, creativity and problem solving 314 skills of a community through also political partnerships (Norris et al., 2008). Principal elements of 315 this dimension include collective actions and decision making, collective efficacy and empowerment 316 and quality of life. This dimension captures both the raw **abilities** of a community (e.g., skills to find 317 multifaceted solutions to complex problems through the engagement in political networks) and the 318 perceptions of a community (e.g. perception to have the ability to do a positive change through a 319 common effort that relies on peoples' aptitude to resourcefully envision a new future and then move 320 in that direction) (Brown and Kulig, 1996). In fact, the societies that believe that they can restore, 321 renew and rebuild themselves are expected to be more determined when facing a disaster or in 322 general, any type of changes.

323 Quality of life surveys can be used as indicators of this perception, because they reveal whether 324 people inside the community are devoted to their community and willing to engage in the activities 325 necessary to maintain the community alive, before or after the disaster strikes. Examples of 326 performance metrics for the community competence in normal condition before the disaster might be 327 the number of immigrants, the number of citizens involved in politics, etc.

328 Specific performance metrics for this dimension directly related to the disaster might be the 329 extensiveness of community warning procedures and plans, measured using for example the number 330 of citizens involved, the number of organizational disaster training programs, etc. (Tierney, 2009).

331

332 Economic development

333 The economic development dimension is composed of both a static and a dynamic assessment. The 334 static assessment is the market activity of the current economy of a community, while the dynamic 335 assessment corresponds to the economic development which is the community's ability to 336 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 337 338 words, they are associated to the employment, the variety in production and services. The economic 339 dimension consists of three sub-categories: (i) the production within the industry, (ii) the distribution 340 of employments within the industry, and (iii) the financial services.

341 The key indicators of the economic development dimension can be: (i) the percentage of the 342 inhabitants that are working in the diverse industries, and (ii) the variability of the distribution of 343 employments in the different industries which are in the community (iii) the literacy rate, (iv) the life 344 expectancy, (v) the poverty rates. Other examples of indicators for this dimension are related to the 345 community performance following a disaster and are: (i) the adequacy of plans for inspecting 346 damaged buildings following disasters, (ii) the extent of evacuation plans and drills for high-347 occupancy structures, (ii) the adequacy of plans for post-disaster commercial restoration, etc. 348 (Tierney, 2009). Because of these indicators, this dimension is interdependent with the Population 349 and Demographics dimension.

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

351

352
$$Q_E = \frac{per_inco + med_inco + emply + hsg_value + buss + insurance}{6}$$
(3)

353

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.

357

358 Social/cultural capital

359 The Social/cultural capital dimension includes numerous sub-categories such as: (i) education 360 services, (ii) child and elderly services, (iii) cultural and heritage services, (iv) community 361 participation etc. The key indicators in normal condition for this dimension are: (i) the number of 362 members belonging to the diverse civil and community organizations, (ii) the surveys of leaders and 363 their perception. The key indicators in emergency conditions are: (i) the existence of community 364 plans targeting transportation-disadvantaged residents, (ii) the adequacy of post-disaster sheltering 365 plans, (iii) the adequacy of plans for incorporating volunteers into official response activities, (iv) the 366 adequacy of donations management plans, (v) the community's plans to manage various networks 367 (Tierney, 2009).

368 In relation to disaster phases' activities, socio-cultural capital dimension can be measured using the 369 following six components suggested in the literature (Mayunga, 2009):

- Participation in voluntary organizations (volunteerism): this component was measured using
 registered non-profit organizations;
- 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;
- 375 3. *Civic and political participation*: this social capital component was measured using three 376 indicators including registered voters, civic and political organizations, and Census response 377 rates for the decennial population and housing survey;
- 378 4. *Religious participation*: it was measured using religious organizations;
- 379 5. Community attachment: the community attachment component was measured using owner 380 occupied housing units;

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

383 Then a three-step procedure is employed in calculation of the socio-cultural capital dimension: (i) 384 scale adjustment of indicators, (ii) standardization or normalization, and (iii) creation of the socio 385 cultural community resilience index.

386 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 387 388 individuals and their larger neighborhoods and communities" (Norris et al., 2008). In fact, the 389 habitants of a community tend to manifest their sense of community and to bond with other members 390 of the same group by providing social and cultural services. However, this emotional connection to 391 the community is not necessary related only to the residents in those places (Manzo and Perkins, 392 2006). For example, several displaced residents of New Orleans after Hurricane Katrina expressed 393 the desire to return home with a strong "place attachment", regardless the job they had and the 394 people they knew. These residents are an important resource for the community, because if they will 395 be provided with housing and employment after the disaster, they will act in order to restore the 396 community to the initial condition before the disaster. The citizen participation in community 397 organizations (e.g. religious congregations, school and resident associations, neighborhood watches, 398 self-help groups etc.) is a way of demonstrating one's care for their community, one's care for 399 meeting and understanding one's fellow citizens and it increases individuals' circle of influence and 400 perception of control (Norris et al., 2008).

401

402

MATHEMATICAL FORMULATION OF THE PEOPLES FRAMEWORK

403 General description of the methodology and the community hybrid model

404 The main part of the methodology consists in developing a community hybrid model, coupling the 405 *Network models* which will be used to model the *physical infrastructures networks* such as the power 406 and the water, with the *Agent based models* which will be used to model the *socio-technical* 407 *networks* such as the Emergency Medical Technicians and the fire brigade (Figure -2). Inside the 408 ABM models, the emotions in the agents will be modeled using the extended version of Belief-409 Desire-Intention modeling framework proposed by Zoumpanaki (2010) that has been expanded and 410 adapted to the proposed methodology (Figure 3).

411 Both types of models will be integrated in a hybrid framework and a matrix approach will be used to 412 describe the interdependencies between the different layers. Each layer represents an infrastructure 413 (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. $D_{Water \rightarrow Power}$) and it will be obtained 414 415 using an extended version of the Haimes' input-output inoperability matrix (IIM) (Haimes et al., 416 2005). For example, in Figure -2, the hospital is a node of the EMT layer and it is interdependent 417 with the power and the water network. Therefore, a **D** matrix describing the interdependencies 418 between the EMT layer and the water and power layer will be determined using Haimes model.

419 The matrix **D** is composed of constant scalars terms if the system does not change though the time. 420 In reality, the interdependent networks might change through the time their interconnectedness as 421 shown in some applications (Fantini et al., 2014), however the proposed approach can also be 422 applied in this case. The proposed approach will require substantial computational power if the 423 spatial and temporal dimensions of the problem increase, therefore the use of parallel computing is 424 recommended in these cases. Below is shown in simple terms how the agent base models and the 425 network model interact in the proposed methodology. Once the hazard is determined (e.g. 426 earthquake event), the corresponding damage in the infrastructure networks is determined using 427 fragility analysis combined with graph theory in order to identify the nodes of the network that will 428 not be functional following the extreme event. Because of physical infrastructure disservice, also the 429 socio-technical networks operating in the community will be affected. For example the road 430 transportation disservice, might limit the capacity of the emergency rescue teams to move and 431 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 agentbased 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.

437 Da qui

438

439 **Resilience index and performance metrics**

440 Once the hybrid model in Figure -2 is built, it is necessary to identify the performance metrics to 441 estimate the resilience of each infrastructure. Several approaches exist in literature for hospitals 442 (Cimellaro et al., 2011), lifeline structures (Ouyang et al., 2012, Cimellaro et al., 2014c) and cities 443 (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 $\mathbf{D}_{x \to y}$ which is able to identify the exact 444 445 location of the interdependency in the network (e.g. node or link). However, sometimes it is also 446 useful to identify a global index I that measures the degree of interdependency between the different 447 infrastructures, in order to have a global evaluation of the community performance and to assign an 448 unbiased evaluation of the weight (or important factor) to each infrastructure. This index can be 449 determined using time series analysis (Cimellaro et al., 2014c) or from linear algebra manipulation of the $\mathbf{D}_{\mathbf{x}\to\mathbf{y}}$ matrix etc. Then the indices I can be grouped into an infrastructure Interdependency 450 451 Matrix (IM) (Figure 4). The infrastructures considered in the analysis of the community are listed in 452 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 453 454 the sum over the rows gives the *importance factor* of a specific lifeline. Ideally, the target is to 455 realize a community where all lifelines are independent, so IM will be an identity matrix. As 456 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

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

463 where R_i is calculated using Equation (1). For example if it is considered the physical infrastructure 464 dimension, R_i is the resilience indicator of a specific infrastructure, while w_i is the weight factor 465 describing the interdependencies between the different indicators. The coefficient w_i are determined 466 using a time series analysis approach borrowed by the economic field which is based on the analysis 467 of the cross correlation function (CCF). The procedure can be applied to all the components and 468 subcomponents of the PEOPLES framework in order to take into account the interdependencies 469 between the different variables. Further details about the methodology can be found in Cimellaro et 470 al. (2014c).

471 The selection of the proper performance metric for the critical infrastructures plays a key role in the 472 analysis. Even if a realistic and predictive model is developed, the results might be affected by the 473 selection of the final performance function adopted to evaluate the community resilience index using 474 the methodology shown in Figure -2. Different innovative approaches to measure functionality are 475 available in literature and they include agent-based modeling, input-output models, mathematical 476 models and game theory (Pederson et al., 2006). Therefore, once the approach and the geographic 477 scale is selected, the global performance indicator Q_{TOT} can be plotted over the region of interest 478 using a contour plot at a given instant of time t, so the time-dependent functionality maps can be 479 obtained. When also the control time T_{LC} is defined, the resilience contour map of the region of 480 interest can also be plotted. The Resilience contour maps are obtained by integrating the 481 functionality maps over time using Equation (1), therefore the resilience maps will be time

482 *independent*, but they will vary in space from point to point in the selected region. Finally, the 483 community resilience index R_{com} is given by the double integral over time and space as follows

484
$$R_{com} = \int_{A_C} R(\vec{r}) / A_C dr = \int_{A_C} \int_{t_{OE}}^{t_{OE}+T_{LC}} Q_{TOT}(\vec{r},t) / (A_C T_{LC}) dt dr$$
(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.

489

490 **Resilience performance levels**

491 The objective of Performance Based Seismic Engineering (PBSE) is to design, construct and 492 maintain facilities with better damage control, coupling the expected or desired performance levels 493 with the levels of seismic hazard. Generally the levels focus on the performances a structure can 494 hold during the shaking and are related to engineering demand parameters such as deformations. 495 More recently SPUR (Bonowitz, 2009), the San Francisco planning and Urban Research 496 Association, introduced other definitions of performance levels for infrastructures based on recovery 497 target states combining safety and recovery time. Five performance measures for buildings have 498 been identified: (i) Safe and Operational; (ii) Safe and usable during repair; (iii) Safe and usable 499 after repair; (iv) Safe but not repairable; (v) Unsafe.

500 The proposed Resilience Performance Levels (RPL) focus on building performance after the

501 earthquake, recognizing the importance of the temporal dimension (Recovery time T_{RE}) in the

502 assessment of the *RPLs* of structures and communities in general.

503 In this paper a 2-dimensional performance domain consisting of Performance Levels PL(i, j), defined

504 by the combination of *functionality* (index j) and *recovery time* (index i) is proposed. By accounting

505 for the effect of the temporal dimension, a 3-dimensional performance matrix (Figure -5) can be 506 visualized as a set of predefined joined performance domains ("masks") for different seismic 507 intensity level, IM and different RPLs.

508 The resilience performance levels can be defined using expert opinions as well as public interviews 509 which will allow identifying the acceptable and desired performance levels by citizens for different 510 type of infrastructures, for example.

511 **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.

518 **Empirical recovery models** are based on test or field data interpretation and engineering judgment. 519 They can be built using Monte Carlo simulations based on data from past events or *maximum* 520 *likelihood method*. Since the complexity of the problem changes case by case, no specific model is 521 presented in this part.

522 Analytical recovery models are developed using response data from numerical simulations 523 (nonlinear time history analysis, response spectral analysis, etc.) of system models. Few example of 524 analytical recovery models (e.g. discrete event simulation models, metamodels, etc.) for critical 525 facilities like hospitals can be found in Cimellaro et al., (2011, 2014d).

526 Step by step procedure for resilience evaluation

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

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

529 (9) Definition, calibration and validation of the hybrid model of the community;

530 (10) Run the analysis and evaluate the response of the model;

- 531 (11) Evaluate the performance metrics (e.g. losses, restoration time, performance index, resilience 532 index) for different scenarios and compare with different performance levels;
- 533 (12) Recognize remedial mitigation actions (e.g. advanced technologies such as base isolation,
 534 passive dampers, etc.) and/or resilience actions (e.g. resourcefulness, redundancy, etc.);

535 The proposed design approach has analogies with the feedback loop taken from control theory and it 536 can be applied both to communities and single structures (e.g. hospital, city hall, etc).

537 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 etal., 2015), but they are not reported in this paper due to the lack of space.

- 540
- 541

CONCLUDING REMARKS

542 After the recent disasters, the general public became aware that Resilience is the solution to face 543 natural and manmade threats. The paper presents a holistic framework to evaluate the resiliency of a 544 community at various geographical and temporal scales and identifies the gaps in the definitions and 545 quantification of resilience at the community level. The suggested framework summarized with the 546 acronyms P.E.O.P.L.E.S. is combining different dimensions of resilience together using a layered 547 The main contribution in the field is the development of a community hybrid model approach. 548 combining *network models* to model the physical infrastructures (electric power, water, gas etc.) with 549 agent-based models to model the socio technical networks (e.g. Emergency medical technicians, fire 550 brigade, police, etc). Furthermore, special attention is given to the human behavior and its emotions 551 which plays a key role during the emergency and they have been modeled using the extended version 552 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.

566

567

ACKNOWLEDGEMENTS

568 The research leading to these results has received funding from the European Research Council 569 under the Grant Agreement n° ERC_IDEAL RESCUE_637842 of the project IDEAL RESCUE-570 Integrated Design and Control of Sustainable Communities during Emergencies.

571 The research leading to these results has received also funding from the European Community's

572 Seventh Framework Programme - Marie Curie International Outgoing Fellowship (IOF) Actions-

573 FP7/2007-2013 under the Grant Agreement n°PIOF-GA-2012-329871 of the project IRUSAT—

574 Improving Resilience of Urban Societies through Advanced Technologies.

575 **References**

- Adger, W. N. (2000) Social and ecological resilience: are they related? Progress in Human
 Geography 24(3): 347-64
- 578 Allenby, B., and Fink, J. (2005). "Toward inherently secure and resilient societies." *Science*,
- 579 309(5737), 1034-1036.
- Arcidiacono, V., G. P. Cimellaro, et al. (2012) Road network resilience assignment methodology. In:
 6th International Conference on Bridge Maintenance, Safety and Management
- 582 (*IABMAS2012*). F. B. D. Frangopol. CRC Press Taylor & Francis Group, Stresa, Lake
 583 Maggiore, July 8-12, 2012.
- 584 Berche, B., von Ferber, C., Holovatch, T., and Holovatch, Y. (2009). "Resilience of public transport 585 networks against attacks." *European Physical Journal B*, 71(1), 125-137.
- Bonowitz, D. (2009). "The Dilemma of existing buildings: Private property, public risks." San
 Francisco Planning Urban Research Association (SPUR), San Francisco, California.
- 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., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A. M., Shinozuka, M.,
 Tierney, K., Wallace, W., and Winterfelt, D. v. (2003). "A framework to Quantitatively
 Assess and Enhance the Seismic Resilience of Communities." *Earthquake Spectra*, 19(4),
 733-752.
- Cagnan, Z., Davidson, R. A., and Guikema, S. D. (2006). "Post-Earthquake Restoration Planning for
 Los Angeles Electric Power." *Earthquake Spectra*, 22(3), 589-608.
- 598 Chang, S. and M. Shinozuka (2004) Measuring Improvements in the Disaster Resilience of
 599 Communities. *Earthquake Spectra* 20(3): 739-55.

- Chang, S. E., McDaniels, T., Fox, J., Dhariwal, R., and Longstaff, H. (2014). "Toward DisasterResilient Cities: Characterizing Resilience of Infrastructure Systems with Expert Judgments." *Risk Analysis*, 34(3), 416-434.
- 603 Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010a). "Framework for analytical 604 quantification of disaster resilience." *Engineering Structures*, 32(11), 3639–3649.
- 605 Cimellaro, G. P., Reinhorn, A. M., and Bruneau, M. (2010b). "Seismic resilience of a hospital 606 system." *Structure and Infrastructure Engineering*, 6(1-2), 127-144.
- 607 Cimellaro, G. P., A. M. Reinhorn, et al. (2011) Performance-based metamodel for health care
 608 facilities. Earthquake Engineering & Structural Dynamics 40 1197–217.
- Cimellaro, G. P., Villa, O., and Bruneau, M. (2014a). "Resilience-Based Design of Natural gas
 distribution networks." *Journal of Infrastructure Systems, ASCE*, 10.1061/(ASCE)IS.1943555X.0000204.
- Cimellaro, G. P., Scura, G., Renschler, C., Reinhorn, A. M., and Kim, H. (2014b). "Rapid building
 damage assessment system using mobile phone technology" *Earthquake Engineering and Engineering Vibration*, 13(3), 519-533.
- Cimellaro, G. P., Solari, D., and Bruneau, M. (2014c). "Physical infrastructure Interdependency and
 regional resilience index after the 2011 Tohoku earthquake in Japan." *Earthquake Engineering & Structural Dynamics*, 43(12), 1763-1784.
- Cimellaro, G. P., Nagarajaiah, S., and Kunnath, S. (2014d). "Computational Methods, Seismic
 Protection, Hybrid Testing and Resilience in Earthquake Engineering A tribute to the
 research contribution of Prof. Andrei Reinhorn." Geotechnical, Geological and Earthquake
 Engineering Series, C. Springer International Publishing AG, ed., Springer, Netherland, 250.
- 622 Cimellaro, G. P., Tinebra, A., Renschler, C., and Fragiadakis, M. (2015). "Resilience-based design of
 623 an urban water distribution system." *Journal of Structural Engineering, ASCE*, in press.
- 624 Comfort, L. K. (1999) Shared Risk: Complex Systems in Seismic Response. Pergamon, New York.
- Crooks, A. T., and Heppenstall, A. J. (2012). "Introduction to agent-based modeling." Agent-based
 models of geographical systems, C. Heppenstall, See, & Batty, ed., Dordrecht: Springer, 85105.

- 628 Cutter, S. L. and J. T. Mitchell (2000) Revealing the vulnerability of people and places: A case study
 629 of Georgetown County, South Carolina. *Annals of American Geographers* 90(4): 713-37.
- 630 Cutter, S. (1996) Vulnerability to Environmental Hazards. *Progress in Human Geography* 20(4):
 631 529-39.
- 632 Department of Homeland Security (DHS) (2008). DHS Risk Lexicon, Risk Steering Committee,
 633 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.
- Dorbritz, R. (2011). "Assessing the resilience of transportation systems in case of large-scale
 disastrous events." The 8th International Conference on Environmental Engineering, Vilnius,
 Lithuania, 19-20 May 2011, 1070-1076.
- 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.
- Ettema, D., de Jong, K., Timmermans, H., and Bakema, A. (2007). "PUMA: Multi-agent modelling
 of urban systems." 45th Congress of the European Regional Science Association, Vrije
 Universiteit, Amsterdam.
- Fantini, P., Cimellaro, G. P., and Mahin, S. A. (2014). "Measuring lifeline emergency response using
 temporal network models " Proceedings of the 15th U.S.-Japan Workshop on the
 Improvement of Structural Engineering and Resiliency., ATC- Applied Technology Council,
 December 3-5, 2014, Island of Hawaii.
- 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., Horowitz, B. M., Lambert, J. H., Santos, J. R., Lian, C., and Crowther, K. G. (2005).
 "Inoperability input-output model for interdependent infrastructure sectors. I: Theory and
 methodology." *Journal of Infrastructure Systems*, 11(2), 67-79.

- 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.
- Heaslip, K., Louisell, W. C., Collura, J., and Serulle, N. U. (2010). "A sketch level method for
 assessing transportation network resiliency to natural disasters and man-made events." The
 89th Annual Meeting of the Transportation Research Board, Washington, D.C., U.S.A., 1014 January 2010.
- Holling, C. S. (1973) Resilience and Stability of Ecological Systems. Annual Review of Ecology and
 Systematics 4: 1-23.
- 669 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.
- Javanbarg, M. B., Scawthorn, C., Kiyono, J., and Shahbodaghkhan, B. (2012). 'Fuzzy AHP-based
 multicriteria decision making systems using particle swarm optimization." *Expert Systems with Applications*, 39(1), 960-966.
- 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.

- Miles, S., and Chang, S. (2006). "Modeling Community Recovery from Earthquakes." *Earthquake Spectra*, 22(2), 439-458.
- 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.
- 686 Mileti, D. (1999). Disasters by Design: A Reassessment of Natural Hazards in the United States,

587 Joseph Henry Press (May 18, 1999) Washington D.C.

- 688 Miller-Hooks, E., Zhang, X., and Faturechi, R. (2012). "Measuring and maximizing resilience of 689 freight transportation networks." *Computers & Operations Research*, 39(7), 1633-1643.
- 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.
- Ouyang, M., and Duenas-Osorio, L. (2011). "An approach to design interface topologies across
 interdependent urban infrastructure systems." *Reliability Engineering & System Safety*,
 96(11), 1462-1473.
- Pederson, P., D. Dudenhoeffer, S. Hartley and M. Permann. (2006). Critical Infrastructure Modeling:
 A Survey of US and International research, Research Report prepared at the Idaho National
 Laboratory, Idaho Falls, Idaho 83415 INL/EXT-06-11464.
- 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.
- Queiroz, C., Garg, S. K., and Tari, Z. (2013). "A probabilistic model for quantifying the resilience of
 networked systems." *Ibm Journal of Research and Development*, 57(5).
- 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.
- Renschler, C., Reinhorn, A. M., Arendt, L., and Cimellaro, G. P. 'The PEOPLES Resilience
 Framework: A conceptual approach to quantify community resilience.'' *Proceedings of the*

- 710 3rd International Conference on Computational Methods in Structural Dynamics and
- 711 *Earthquake Engineering (COMPDYN 2011)*, Corfu`, Greece, May 26-28, 2011.
- 712 RICSA (2010) RISCA Poverty Project. URL:

713 http://web.uct.ac.za/depts/ricsa/projects/publicli/poverty.

- Rose, A. (2004). "Economic principles, issues, and research priorities in hazard loss estimation."
 Modeling Spatial and Economic Impacts of Disasters, S. C. Yasuhide Okuyama, ed., Springer
 Berlin Heidelberg, 13-36.
- 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):
 719 75-112.
- SEAOC. (1995). "Vision 2000 A Framework for Performance Based Earthquake Engineering ",
 Structural Engineers Association of California, Vision 2000 Committee, Sacramento,
 California.
- 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.
- Tamvakis, P., and Xenidis, Y. (2013). "Comparative Evaluation of Resilience Quantification
 Methods for Infrastructure Systems." *Selected Papers from the 26th Ipma (International Project Management Association), World Congress*, 74, 339-348.
- 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: 1417.

- 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 (Foundations for Organizational Science),
 SAGE Publications, Inc., Thousand Oaks, California.
- Weick, K. E., K. Sutcliffe, et al. (2005) Organizing and the Process of Sensemaking. *Organization Science* 16: 409-21.
- 743 Wildavsky, A. B. (1991). Searching for Safety, Oxford Transaction Publisher, New Brunswick.
- 744 Woods, D. D. (2006) Essential characteristics of resilience, Aldershot, UK.
- Zoumpoulaki, A., Avradinis, N., and Vosinakis, S. (2010). "Multi-Agent Simulation Framework for
 Emergency Evacuations Incorporating Personality and Emotions." Artificial Intelligence:
 Theories, Models and Applications, Springer Berlin Heidelberg, 423-428.

Table -1 Literature review about resilience def	nitions
---	---------

Author	Definition
Holling	Ecological systems resilience is a measure of the persistence of systems and of their ability to absorb
(1973)	change and disturbance and still maintain the same relationships between populations or state variables.
Wildavsky	Resilience is the capacity to cope with unanticipated dangers after they have become manifest, learning
(1991)	to bounce back.
Horne and Orr	Resilience is the ability of a system to withstand stresses of 'environmental loading' [it is] a
(1998)	fundamental quality found in individuals, groups, organizations, and systems as a whole.
Haimes et al.	Resilience is the ability of system to return to its optimal condition in a short period of time. Considering
(1998)	resilience one of four strategies for hardening a system, together with security, redundancy and
	robustness.
Mileti	Local resiliency with regard to disasters means that a locale is able to withstand an extreme natural event
(1999)	without suffering devastating losses, damage, diminished productivity, or quality of life and without a
~ .	large amount of assistance from outside the community.
Comfort	Resilience is the capacity to adapt existing resources and skills to new situations and operating
(1999)	
Adger (2000)	Social resilience is the ability of groups or communities to cope with external stresses and disturbances
Constant of	as a result of social, political, and environmental change.
Gunderson et	Engineering resilience [] is the speed of return to the steady state following a perturbation []
al. (2002)	ecological resilience [] is measured by the magnitude of disturbance that can be absorbed before the
Filsel (2003)	Resilience is the essence of sustainability [] the ability to resist disorder
Tiksei (2003)	Residence is the essence of sustainability [] the ability to resist disorder.
Bruneau et al.	Resilience is defined in terms of three stages: the ability of a system to reduce the probability of an
(2003)	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;
A 11 1 1	economic; and social.
Finle (2005)	Residency is defined as the capability of a system to maintain its functions and structure in the face of
Fink (2005)	Internal and external change and to degrade gracefully when it must.
(2005)	to avoid maximum potential losses
Hollpagel	Resiliance is defined as the intrinsic ability of an organization (system) to maintain or regain a
(2006)	dynamically stable state which allows it to continue operations after a major mishan and/or in the
(2000)	presence of a continuous stress
Manyena	Evaluating all the possible definitions provided from the 90's to nowadays resilience could be viewed
(2006)	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	Evaluating all the possible definitions provided from the 90's to nowadays, resilience could be viewed
(2006)	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	Resilience is the ability of the system to return to a stable condition after a disruption. Distinguishing
(2007)	robustness and resilience, using robustness to imply that the system will remain (nearly) unchanged even
	in the face of disruption.
Tierney and	Resilience is both the inherent strength and ability to be flexible and adaptable after environmental
Bruneau	shocks and disruptive events.
(2007)	
DHS	Resilience is the ability of systems, infrastructures, government, business, and citizenry to resist, absorb,
(2008)	recover from, or adapt to an adverse occurrence that may cause harm, destruction, or loss of national
	significance.
Haimes	Resilience is defined as the ability of the system to withstand a major disruption within acceptable
(2009)	degradation parameters and to recover within an acceptable time and composite costs and risk.
Vugrin et al.	Given the occurrence of a particular disruptive event (or set of events), the resilience of a system to that
(2010)	event (or events) is the ability to efficiently reduce both the magnitude and duration of the deviation
	from targeted systemperformance levels.

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 GOVERNM	IENTAL SERVICES				
a) Executive/Administrative		b) Judicial	c) Legal/Security			
i) Emergency Response and	ii) Health and Hygiene					
	4) PHYSICAL INFRA	STRUCTURE				
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-Terr	m Acute Care (4) Psychiatric			
(1) Distribution Facilities	(3) Manufacturing Facilities	(3) Primary Care (5) Specia	ılty			
(2) Hotels - Accommodations	(4) Office Buildings	iii) Food Supply				
iii) Cultural		iv) Utilities				
(1) Entertainment Venues	(4) Schools	(1) Electrical (2) Fuel/Gas/E	nergy (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) LIFES TYLE AND COMMU	NITY COMPETENCE				
a) Collective Action and Decision Mak	king	b) Collective Efficacy and	c) Quality of Life			
i) Conflict Resolution	ii) Self-Organization	Empowerment				
	6) ECONOMIC DEV	ELOPMENT				
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	xii) Professional and Business				
	Services	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				
 vi) Number of Bank and Credit Union Members vii) Number of Banks and Credit Unions 	vi) Fortune 500vii) Information, Professional Business, Other	(b) Opportunities (c) Placement				
 vi) Number of Bank and Credit Union Members vii) Number of Banks and Credit Unions viii) Savings Account Balances (Personal and Commercial) 	 vi) Fortune 500 vii) Information, Professional Business, Other viii) Leisure and Hospitality 	 (b) Opportunities (c) Placement (2) Transport and Utilities 				
 vi) Number of Bank and Credit Union Members vii) Number of Banks and Credit Unions viii) Savings Account Balances (Personal and Commercial) ix) Stock Market 	 vi) Fortune 500 vii) Information, Professional Business, Other viii) Leisure and Hospitality ix) Manufacturing 	 (b) Opportunities (c) Placement (2) Transport and Utilities (3) Wholesale and Retail 				
 vi) Number of Bank and Credit Union Members vii) Number of Banks and Credit Unions viii) Savings Account Balances (Personal and Commercial) ix) Stock Market 	 vi) Fortune 500 vii) Information, Professional Business, Other viii) Leisure and Hospitality ix) Manufacturing 7) SOCIAL/CULTURA 	 (b) Opportunities (c) Placement (2) Transport and Utilities (3) Wholesale and Retail 				
 vi) Number of Bank and Credit Union Members vii) Number of Banks and Credit Unions viii) Savings Account Balances (Personal and Commercial) ix) Stock Market a) Child and Elderly Services 	 vi) Fortune 500 vii) Information, Professional Business, Other viii) Leisure and Hospitality ix) Manufacturing 7) SOCIAL/CULTURA b) Commercial Centers 	 (b) Opportunities (c) Placement (2) Transport and Utilities (3) Wholesale and Retail AL CAPITAL c) Community Participation 	 d) Cultural and Heritage Services 			
 vi) Number of Bank and Credit Union Members vii) Number of Banks and Credit Unions viii) Savings Account Balances (Personal and Commercial) ix) Stock Market a) Child and Elderly Services e) Education Services 	 vi) Fortune 500 vii) Information, Professional Business, Other viii) Leisure and Hospitality ix) Manufacturing 7) SOCIAL/CULTURA b) Commercial Centers f) Non-Profit Organizations 	 (b) Opportunities (c) Placement (2) Transport and Utilities (3) Wholesale and Retail AL CAPITAL c) Community Participation g) Place Attachment 	 d) Cultural and Heritage Services 			



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



Figure 4 Sketch of a typical IM matrix.

		Recovery Tim	e			•		
		Short term (Emergency)	Midterm	Long term (Reconstruction)	(MI)			
Functionality Performance Levels	Fully Operational (Q1)	Basic Objective	Unacceptable	Unacceptable	e Intensity measures (Performance Objective	Line Line Line Line Line Line Line Line		
	Operational (Q2)	Essential Objective	Basic Objective	Unacceptable		ity mea	ity mea	
	Partially Operational (Q3)	Critical Objective	Essential Objective	Basic Objective				
	Near not Operational (Q4)	Not feasible	Critical Objective	Basic Objective		Performance / Objective		
						Recovery Time (Tre		

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