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Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation

Report

Framework for Social Vulnerability and Impact Quantification from Earthquakes

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Abstract

A unified framework, including an ontology model to evaluate social vulnerability and social impacts from earthquakes has been developed. The model has been operationalized to compute shelter needs caused by earthquake damage and integrates social vulnerability into the physical systems modeling approaches in earthquake engineering using indicators. In particular, physical loss evaluated as building damage ratio are aggravated by indirect socio-economic factors in a comprehensive modeling approach based on multi-criteria decision support, which provides decision makers with a dynamic platform to capture post-disaster emergency shelter demand. This deliverable describes the outputs of Task 15.5 which has the following objectives: (a) develop an integrated framework for obtaining seismic risk; (b) develop an ontology model for describing social vulnerability assessments; (c) operationalization of the integrated risk framework and social vulnerability ontology model for the shelter sector with a case study application in the 2009 L'Aquila earthquake. The overall aim of the work undertaken here was to propose a framework and socio-economic vulnerability relationships in NERA for integrating quantitative probabilistic and deterministic (scenario-based) frameworks for estimating physical risk in earthquake engineering through indicators with the diverse elements that contribute to the vulnerability of society.

Acknowledgments

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1 Introduction

Recent decades have seen an exponential growth in the physical impacts and losses from earthquakes throughout the world. The Great Wenchuan Earthquake in May 2008, the Haitian Earthquake of 2010, and the 2011 Great East Japan Earthquake provide poignant reminders of the susceptibility of communities to devastating loss of lives, livelihoods, and property from earthquake events. These disasters, plus many other smaller ones, illustrate how earthquakes adversely impact people and the communities in which they live, and the impacts of such events occur across geographic boundaries and at multiple scales affecting governments, institutions, economic sectors, livelihoods, and people.

There is a consensus within the scientific community that disasters associated with earthquakes are not wholly the product of the physical impacts of natural hazard events. Rather, these disasters are the outcome of the interaction between the earth’s biophysical systems, the engineered environment, and the social conditions inherent at particular places (Hewitt 1971, Mileti 1999, Wisner et al. 2004). It is increasingly becoming clear that some people and groups are impacted differentially by damaging events, react differently in an event's aftermath, adjust to its circumstances in dissimilar ways, and recover in a differential manner. These circumstances have stimulated great interest in understanding how to manage the associated seismic risk, adverse impacts, and loss.

The current state-of-the-art in earthquake loss estimation (ELE) software provides several parameters of direct socio-economic consequences which are needed to support effective decision making. These include parameters such as casualties, displaced persons, and business failures by industry, for example. However, poor linkages between damage to physical systems and resultant social consequences remain a significant limitation with existing hazard loss estimation models (Bostrom et al. 2008). A new direction with earthquake loss estimation software, which has been developed by researchers of the Mid America Earthquake Center, is the inclusion of social vulnerability (Elnashai 2009). Although definitions and applications of social vulnerability vary within the literature (Cutter 1996), the concept is often described as the potential for harm and the ability of an individual or community to protect itself from damaging events (Cutter et al. 2006, Wood et al. 2010). Given equal exposure to seismic threats, two groups may vary in their social vulnerability due to internal societal characteristics where differences according to wealth, gender, race, class, history, and socio-political organization influence the patterns of loss, mortality, and the ability of communities to reconstruct following a disaster (Burton and Cutter 2008). Inclusion of social vulnerability into quantitative loss estimation frameworks allows for a more holistic measurement of risk. However, more work is needed to develop a systemic approach that quantitatively brings together these disparate research areas in social vulnerability research into a comprehensive modeling tool, which provides decision makers with a dynamic platform to capture post-disaster decisions, interactions and changes over time.

One of the main goals in NERA Task 15.5 of WP15 (JRA5) is to propose a common framework for more holistic assessment of earthquake risk through the integration of both physical and social vulnerability. In this deliverable a conceptual model of integrated risk is proposed as a first step. Attempting to quantify a social vulnerability index and combine with a physical vulnerability index meets several constraints. First, it is difficult to find empirical evidence about social vulnerability itself. Social vulnerability is often hidden, complex and nested in various human aspects and contingencies bound to different levels of society. Second, vulnerability as a concept is conceived in at least two major ways: On the one hand it is perceived as a holistic and generic concept, encompassing many complex interrelations. On the other hand it is seen as a more single-dimensional concept, focusing on one specific item to a specific hazard (Fekete, 2009). In order to bring social vulnerability into an integrated framework with physical risk, a nomenclature accounting for each dimension of vulnerability that is to be accounted for in the analysis is needed. Thus, a comprehensive ontology model of social vulnerability accounting for diverse elements affecting the vulnerability of society was developed as a main thrust of Task 15.5. Finally, the integrated framework and ontology model was operationalized by focusing on a specific aspect of vulnerability – vulnerability of population to displacement after an earthquake. Here, a shelter model was developed that allowed the integration of seismic hazard and risk with a logic model describing the various factors that affect populations when displaced or seeking shelter. The methodological framework, structure of indicators and weights of the selected indicators were then validated through the 2009 L'Aquila earthquake case study.

2 Integrated Evaluation of Seismic Risk

Integrated evaluation of seismic risk centers on the development of a framework that draws from outputs produced in seismic hazard, (physical) vulnerability, exposure and risk components (e.g., predicted mortality and property loss) and arrives at a more holistic computation of risk by including model of social vulnerability an economic vulnerability. Focusing on the development of an integrated framework of seismic risk will permit decision-makers, stakeholders, researchers, and others to address seismic risk in a manner that allows:

1) obtain a holistic view of risk where interactions between natural and social systems are as part of a dynamic system
2) the mainstreaming of socio-economic factors in policy discussions;
3) the evaluation of loss and damage and socio-economic factors at different time and space scales for benchmarking exercises;
4) the recognition that both causes and solutions for earthquake loss are found in human, environmental, and constructed environmental interactions; and
5) the development of a common dialog to reduce risk and strengthen earthquake resilience.

The NERA Risk Framework depicted in Fig. 1 shows that risk quantification is based on the consideration of hazard, vulnerability and exposure. Within, the vulnerability model, the quantification is based mostly on the consideration of physical systems making up the infrastructure (e.g. building and building aggregates). The current document proposes a framework for considering also the social fabric and geographic context that connect social and economic vulnerability to physical vulnerability and risk.

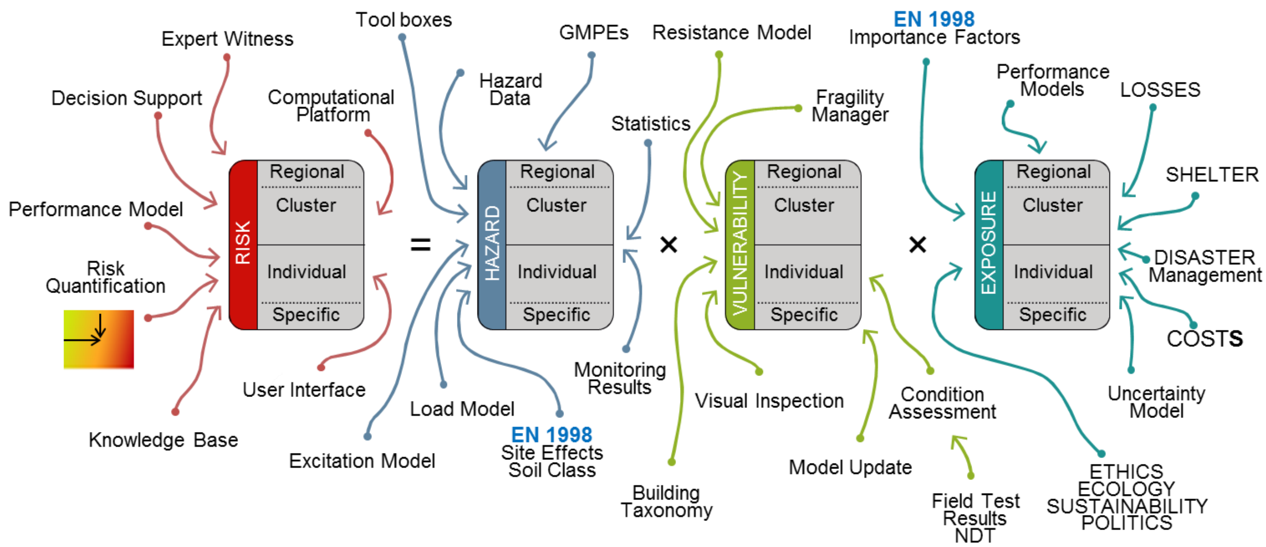

Fig. 1 NERA Risk Framework (status 29.05.2013) for the specification of input

The model of integrated risk proposed here is shown in Fig. 2 and is adapted from Cutter et al. (1996) with inputs from recent literature and is the basis of the integrated risk and social vulnerability framework of the Global Earthquake Model (GEM) (Burton and Khazai, 2013). It is exploratory in nature, but serves as a useful heuristic in understanding the diverse elements that contribute to our understanding of the vulnerability of places. There is an explicit focus on locality within this conceptual framework, for it is place that forms the fundamental unit of analysis. Here, vulnerability is conceived as both a physical domain as well as a social characteristic and response, but within a specific areal or geographic domain. This can be geographic space, where vulnerable people and places are located or social space, who in those places are most vulnerable. Thus, the integrated approach proposed here provides a framework to link the exposure and physical vulnerability of inter-related physical systems to vulnerabilities and coping capacities in society to assess risk. There are various possible interactions of socio-economic models with physical vulnerability/loss estimation models. Fig. 3 shows three possible entry points for socio-economic models. In many earthquake loss estimation models socio-economic models are brought in at the third entry point as linear "damage-consequence functions" for the estimation of direct social and economic losses from physical system parameters, such as, level of building damage. Bringing in socio-economic models at the first entry point shown in Fig. 3 as empirical models, requires the systematic collection of post-event social and economic post-earthquake data which is typically not feasible, given the perishable nature of such data and that it is currently not being collected in a systematic and coordinated fashion.

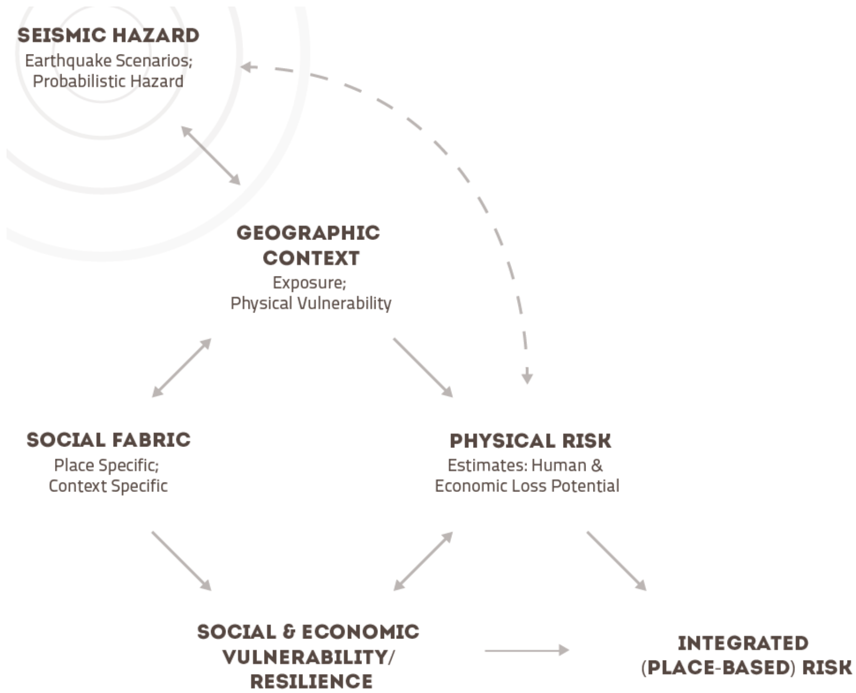

Fig. 2 Proposed Integrated Risk Framework (Burton and Khazai, 2013)

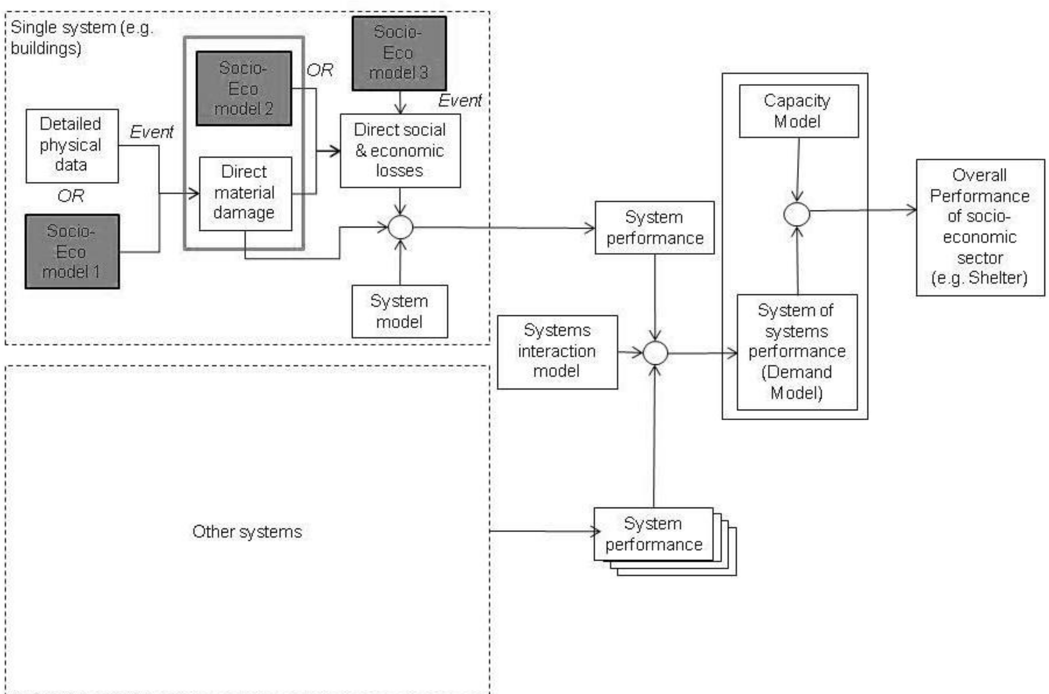

Fig. 3 Possible interaction of socio-economic models with physical vulnerability/loss estimation models

The integrated model implementation discussed later for the shelter sector brought in at the second entry point depicted in Fig. 3. Here, new methods have been developed to compute social losses (e.g., number of displaced people and casualties) as an integrated function of hazard intensity, vulnerability of physical systems and the social vulnerability of the population at risk. In this framework design it is assumed that interactive and causal processes take place between society and the physical systems it interacts with. For example, the loss of building habitability (derived from physical building and utility damage models) will play a major role in the decision to evacuate one's domicile and seek public shelter. Here the interaction between building habitability, environmental factors (e.g., weather conditions) and social factors such as the occupants tenure status (home owner vs. renter), whether the occupant lives in a single family home or a multi-family apartment structure, the level of anxiety of aftershocks, etc., will ultimately form the integrated model that is used to determine an estimate of displaced populations after an earthquake.

3 Framework for Modeling Social Vulnerability

"Vulnerability" as a term and as a concept has been used for the last 30 years and originates from different conceptual lineages, such as political-ecological, political-economic, and risk hazard approaches (for example O´Keefe et al. 1976, Hewitt and Burton 1971, Kates 1985, Blaikie et al. 1994, Hewitt 1997, Cutter et al. 2003, Wisner et al. 2004, Adger 2006, Eakin and Luers 2006, and many more) vulnerability assessments have become a key resource to develop measures and pathways for reducing vulnerability and a means to monitor vulnerability over time. Thus, they have been integrated as a key concept in central documents of global efforts and action plans to reduce disaster risk (such as the Hyogo Framework for Action, ISDR 2005) and climate change impacts (such as the IPCC's Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), IPCC 2012). Moreover, the assessment of vulnerability has increasingly become the touchpoint in the debate between research communities in climate change and disaster risk reduction (for example Bohle et al. 1994, Agder 1999, Kelly and Adger 2000, Thomalla et al. 2006, Kienberger et al. 2009).

In addition, various communities have adopted the concept of vulnerability and adjusted it to the needs of their respective discipline and fields of work. Attempts to describe and to measure vulnerability were made in the context of assessing the vulnerability of vulnerable systems, the triggering events, or drivers specific to certain academic disciplines, such as the vulnerability of industrial production to natural hazards (Khazai et al. 2013) or the vulnerability of buildings to earthquakes (Gruenthal 1998). Vulnerable entities of the same kind were assessed, for example the vulnerability of communities in different regions to climate change (Hahn et al. 2009, Wu et al. 2002) or frameworks were developed to better understand the complex and multi-faceted characteristic of social vulnerability (Hewitt and Burton 1971, Hewitt 1983, Blaikie et al. 1994 and later Wisner et al. 2004, Cutter et al. 2003).

When examining vulnerability in the context of natural hazards and disasters from disciplinary, multidisciplinary, and interdisciplinary perspectives, researchers and practitioners have used multitude of frameworks (for an overview see for example Füssel 2007 or Hufschmidt 2011) and a variety of methods and technologies to gather knowledge on the different dimensions. This has resulted in incompatibilities and inconsistencies in vulnerability studies and has made it difficult to discover, access, and use data and information on vulnerability (NRC 2006; Giuliani 2011 et al.). Consequently, developing universal metrics for vulnerability assessments across disciplines is challenging, which is partly due to the ever-present ambiguity of the concept itself (Birkmann and Wisner 2006), the diverse and dynamic nature of the components, and the changing scales of analysis (temporal and spatial). In addition, various aspects of data availability and knowledge integration may potentially impede the effective and efficient use of vulnerability assessments for disaster risk reduction (Giuliani et al. 2011; Open Geospatial Consortium 2004).

Although definitions and applications of social vulnerability vary within the literature (Cutter 1996), the concept is often described as the potential for harm and the ability of an individual or community to protect itself from damaging events (Cutter et al. 2006; Wood et al. 2010). Given equal exposure to seismic threats, two groups may vary in their social vulnerability due to internal societal characteristics where differences according to wealth, gender, race, class, history, and sociopolitical organization influence the patterns of loss, mortality, and the ability of communities to reconstruct following a disaster (Burton and Cutter 2008).

Developing a universal measurement platform for assessing social vulnerability is challenging given an ever present definitional ambiguity of the concept and its highly multidimensional nature (Cutter et al. 2009). There has been a shift within the field from the development of conceptual models and frameworks to more objective measures based on the use of composite indicators, however. An indicator is a quantitative or qualitative measure derived from observed facts that simplify and communicate the reality of a complex situation (Freudenburg 2003). A composite indicator (or composite index) is the mathematical combination of individual indicators that represent different dimensions of a concept that cannot be fully captured by any individual indicator alone (Nardo et al. 2008). Some advantages of the use of composite indicators (or indices) include the capacity to summarize multidimensional issues in a manner that is easily understood by general audiences, the applicability to use in benchmarking exercises, and the ability to generate ranked lists from large datasets. In addition, they are often used as a basis for setting policy priority and allocating resources.

A variety of methods, metrics, and frameworks exist for assessing social vulnerability and impacts from seismic events. A brief review of frameworks and tools utilized to assess the potential for socio-economic impacts from seismic events was conducted. In recent years, a number of composite indices aimed at measuring social vulnerability have gained prominence in the literature. Among these are indices developed for various purposes that include a social vulnerability component such as the Environmental Vulnerability Index (EVI) which was one of the earliest efforts to measure vulnerability to global environmental change (Kaley et al. 1999) and the Environmental Sustainability Index (ESI) that assesses the sustainability of 146 nations (Esty et al. 2005). Additional indices of this type include the Human Development Index (HDI) that was derived to examine quality of life based on health, education, and income dimensions (UNDP 1990; 2005) and the Human Well-being index (HWI) that includes demographic data and measures of community and social equity (Prescott-Allen 2001).

Other indices have been developed to focus explicitly on social vulnerability or the adaptive capacities of populations. These include the Index of Social Vulnerability to Climate Change (SVA) by Adger and Vincent (2005), the Disaster Risk Index (DRI) (UNDP/BCPR 2004), and the work conducted for the UNISDR Global Assessment Report on disaster risk reduction (UNISDR 2009; 2011). The Prevalent Vulnerability Index (PVI) is an additional social vulnerability index that focuses on social, economic, institutional, and infrastructural capacities to recover from natural disasters (Cardona 2005). In the United States, the Social Vulnerability Index (SoVI) (Cutter et al. 2003) is perhaps the most often utilized comparative metric for social vulnerability. The SoVI uses a broad set of 42 indicators, culled primarily from the United States Census, to explore differences in social vulnerability among places at varying spatial scales of geography. An additional index applicable at local and regional levels was developed by Khazai et al. (2013) to assesses vulnerability drivers in industrial systems as well as social fragilities and coping capacities within communities.

Despite all the differences in theoretical frameworks, metrics, scales, and levels of analysis, a highly fragmented and widespread body of knowledge pertaining to the different dimensions of vulnerability has been created, which may serve as a basis of science-based decision-making by individuals and households, policy makers, emergency managers, and various stakeholders in the private sector. However, before such knowledge can be used or applied by potential users, some conditions have to be fulfilled: The knowledge should be organized, structured, and disseminated effectively; collaboration of the different communities generating and using this knowledge has to be significantly strengthened to facilitate learning and information exchange between them; the information should be relevant to stakeholders and stakeholders have to be motivated to use it. The absence of these conditions can contribute to the underutilization of knowledge, the so-called implementation gap (NRC 2006).

These considerations highlight the need to share knowledge and data sources in an interoperable way and to ensure that they are easily accessible and discoverable for use by different stakeholder communities as often and as widely as possible. Despite the myriad of vulnerability studies, there is currently no knowledge base that focuses explicitly on data, methods, current and past research initiatives, theory, and ancillary information that may be helpful for researchers and practitioners to better understand the varied and contextually specific approaches to vulnerability assessment found in the literature.

To help address the caveats outlined above and to provide a structured and guided access to the fragmented and scattered knowledge on vulnerability and vulnerability assessments for newcomers in the field, practitioners and researchers from other fields, an ontology for vulnerability has been developed as a framework for the description of vulnerability assessments. It allows for the structured storage and retrieval of information by annotation of key categories and properties of vulnerability. Hence, vulnerability assessments are comparable and easily accessible at a glance. When developing the ontology, the aim therefore explicitly was not to ″synthezise‟ any kind of holistic or overarching model for vulnerability assessments, but to conceive *a solution-oriented framework* and through the definition of semantic rules to allow for *a process of comparability across different vulnerability assessments* and the applied concepts and methods.

3.1 Survey of Social Vulnerability Assessments

Work started with a thorough survey of existing vulnerability studies with the aim to determine the principles for organizing and presenting key components of quantitative and qualitative vulnerability assessments in literature. The survey covered over 70 articles and books from the mid-1990s to 2012 and was not limited to standard, widely known tools, but also identified new, integrated multidisciplinary approaches. In general, the initial review focused on both conceptual and operational studies and considered studies on the vulnerability of natural, technical, and social systems taking into account a broad range of determinants of vulnerability as well as the interactions between the different determinants. To develop the ontology, approximately 55 vulnerability assessments were selected from a broad range of academic disciplines (geography, economics, social sciences, earthquake engineering). The assessments were made in different fields (development studies, disaster risk reduction, climate change adaptation, environmental management). The selection process for the basic stock of literature was guided by the following ideas and criteria:

1. To include primarily vulnerability studies that have been operationalized and empirically implemented rather than studies that focus on developing theoretical frameworks of vulnerability.
2. To cover a broad range of vulnerability assessments in order to obtain an overview of the organization of vulnerability in different research fields and to extract relevant categories to structure the knowledge domain.
3. To include studies that – according to how often they are referred to by other studies - represent key references for the knowledge domain of vulnerability assessments.

Due to the authors’ main fields of expertise, the 55 assessments selected for developing the ontology were slightly focused on vulnerability of the social system in the disaster risk reduction context, but it was ensured that enough studies of vulnerability of ecological and technical systems were included.

3.2 Ontology Development

Based on a sub-selection of 45 vulnerability studies, an initial version of the ontology was developed and then later adjusted using another 10 studies from our selection as test cases. Ontologies provide a formal, hierarchical representation of concepts and their interrelations in a specific knowledge domain (Raskin and Pan 2005, Mainz et al. 2008). Developing the ontology for vulnerability assessments was guided mainly by four development principles: Natural language independence, orthogonality, scalability, application independence, and community involvement (Raskin and Pan 2005). Natural language independence emphasizes representing concepts rather than terms, slang, technical jargon, etc. and requires the defining axioms to be logically consistent. Applying this key principle in our ontology development meant the strict distinction between thinking formally in structures that represent the knowledge domain "vulnerability" and thinking in schools or theoretical concepts when referring to the content of the knowledge body. Orthogonality addresses compound concepts, which should be decomposable into their component parts and enable users to reuse them in different contexts. The aim of applying this principle was that the term definitions for the ontology are coherent and clear enough in order to be reused without requiring others to create their own definitions. Scalability refers to the fact that any knowledge body grows and ontologies should therefore be "easily extendable to enable specialized domains to build upon more general ontologies already generated" (Raskin and Pan 2005: 1121). Community involvement, finally, refers to the idea that ontologies as structural, hierarchical representations of a knowledge domain should be developed by involving those who contribute to the knowledge domain and are part of the user community of that knowledge.

As mentioned above, the applicability of the initial ontology was tested against another set of 10 vulnerability studies and subsequently modified in an iterative manner to account for gaps and issues raised in group discussions among the authors through a series of hands-on workshops in 2011. Finally, the ensuing semantic structure and ontology were evaluated during a workshop with a group of researchers at KIT. Additionally, the authors used the ontology as a learning tool for analyzing vulnerability assessments and subsequently interacted with an extended group of researchers and students through a "Systemic Vulnerability Seminar" offered at the Karlsruhe Institute of Technology (KIT) in the fall of 2012. The use and evaluation of the ontology in the seminar allowed for a collaborative and participatory approach to further improving the vulnerability ontology and tools to the form currently presented in this paper. It should be noted here that developing a comprehensive ontology of vulnerability assessments is an adaptive process which will continue to grow and scale with more input from the research and practice community.

3.3 Ontology for Social Vulnerability Assessments

In the context of knowledge sharing, the term ontology is used to mean a formal specification of shared knowledge so that vast amounts of information, data, and concepts can be structured and organized for storage, querying, and retrieval

(Gruber 1993). The structure provided by the ontology can be understood as a formal, hierarchical representation of concepts and their interrelations in a specific knowledge domain (Raskin and Pan 2005, Mainz et al. 2008). Common components of ontologies are individuals, instances or objects (the basis or "ground level" objects), classes (sets, collections, concepts, classes in programming, types of objects, or kinds of things), properties (aspects, attributes, features, characteristics or parameters of the objects and classes), and relations (ways in which classes and individuals can be related to each other). Once developed, this abstract structure enables the user to depict the structure of its knowledge domain by collecting synonyms, capturing hierarchies like in taxonomies, and establishing relations between classes and individuals (Mainz et al. 2008).

The ontology illustrated in Fig. 4 shows that each vulnerability assessment is the basic object or Instance of the ontology which belongs to a Category X. Each article (vulnerability assessment study) is an instance of a Class C and has a value V for Property P. Accordingly, the [[Instance: Vulnerability Study of Electrical Systems]] for [[Category: Vulnerable System]] can be classified to have [[Class: Technical System]] that has [[Property: Infrastructure]] with [[Value: Electrical System]].

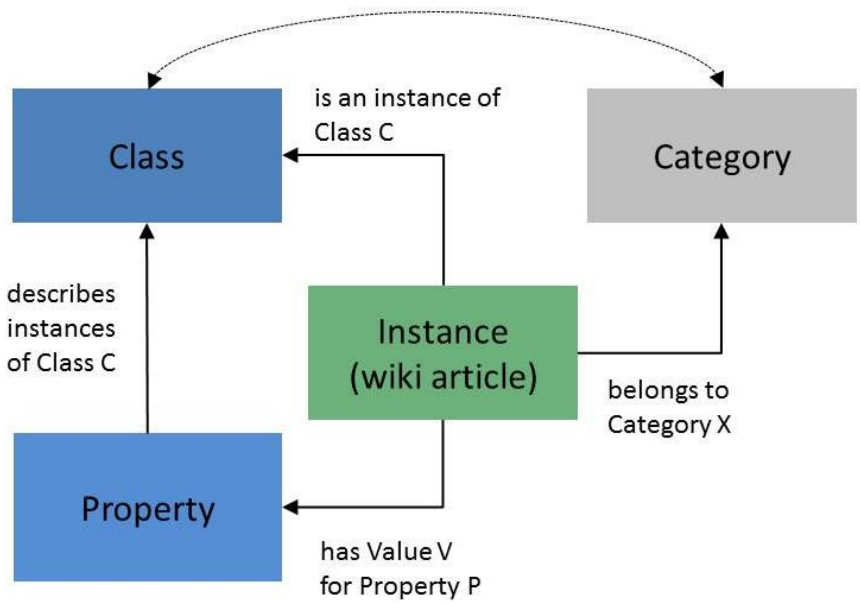

Fig. 4 Relationships among category, class, property, and instance in the ontology

Four key questions form the first level "branches" or categories of the ontology and correspond to the basic, abstract structure of the knowledge domain of vulnerability assessments. The four questions are simple, yet consequential questions, and have been deduced from various theories and concepts from a multitude of disciplines: (1) Vulnerability of what (2) Vulnerability to what (3) What reference framework was used in the vulnerability assessment, and (4) What methodological approach was used in the vulnerability assessment. In the following sub-sections, we introduce and explain the ontology along these four basic questions. While reading them, it is important to keep in mind that when describing the ontology we use language in a formal way independently of the "technical jargon" in the field and regardless of the fact that in some cases the same word (e.g., "driver") might also be used in a certain vulnerability concept with a specific meaning. To avoid misunderstandings, it is therefore important to distinguish between the formal level of the ontology and the content of the knowledge domain described in the ontology.

3.3.1 Vulnerable Systems – Vulnerability of What?

To answer the question "Vulnerability of what", we use a systems approach (system as a collection of parts or subsystems) and begin with the classic concept of "risk" as we find it in natural science or engineering domains: Risk is a function of hazard and vulnerability. While the hazard is commonly referred to as the occurrence potential of a triggering event, the notion of vulnerability designates the predisposition of people, processes, infrastructure, services, organizations, or systems to be affected, damaged or destroyed by the event. In this concept, hazard is the exogenous and vulnerability is the endogenous variable of risk. Something is at risk, at stake, exposed to or affected by an occurrence (perturbation, stress) and something possesses the potential to change its state, a degree of sensitivity, and the capacity of response. This quality exists a priori. In general, the object of observation is thought of in abstract terms as a system. In developing the ontology, it is therefore assumed that every research into vulnerability must imply the distinction of system and environment and must, furthermore, distinguish types of systems and subsystems investigated in the study, as this is the most basic premise in general systems theory (Bertalanffy 1950). Consequently, the ontology on vulnerable systems shown in Fig. 5a explicitly refers to four classes of vulnerable systems: (1) Natural systems for vulnerability studies referring to a set of sub-classes that include physical systems (Calvalieri et al. 2012), biological systems (De Lange et al. 2010), and/or biophysical systems (O'Brien et al. 2004); (2) social systems for vulnerability studies referring to the sub-classes of population in general (Adger 1999, Carreño et al. 2007), social groups (for example, communities: Cutter et al. 2003, Bollin and Hidajat 2006) or functional systems, such as the economy (Patt et al. 2010) or the public financial sector (Mechler et al. 2006) or the health sector (Hahn 2009, Few and Tran 2010), and (3) technical systems, such as vulnerability studies referring to critical infrastructure (Hellström 2007; Kröger and Zio 2011). In addition, the ontology also accounts for a separate class of hybrid concepts referring to interactions between and within systems, such as in societal and ecological (biophysical) subsystems (Turner et al. 2003 and Gallopín 2006) or societal and technical subsystems (Khazai et al. 2013) .

Overall, the ontology on vulnerable systems shown in Fig. 5a mirrors some classic approaches of hazard and vulnerability research, but also includes sociological theory in the form of a strict distinction between modes of operation of natural, social, and technical systems as well as the thesis of functional differentiation of modern society (Luhmann 1997). However, the strictness of this argument (functional differentiation) could not be maintained in some cases, since it would have left out or pushed aside established nomenclature of mainstream vulnerability research. For example, the branches of "Industry", "Agriculture & Forestry", or "Financial System" are certainly part of the overall economic systems, but in most studies they are referred to as complementary systems on their own. In recent years, attempts were made to introduce sociological terminologies in vulnerability research (Zehetmair 2012). It remains to be seen to what extent these attempts will meet with acceptance.

3.3.2 Vulnerability Drivers – Vulnerability to What?

One of the basic traits of the concept of vulnerability is the need to analyze the relationship between system and environment regarding contingent occurrences (shock) or rather slowly developing changes leading to unsafe conditions (continuous stressors). However, there are many nuances in the nature of the correlation between hazard and vulnerability. By asserting that "hazard and vulnerability are mutually conditioning situations and neither can exist on its own", Cardona (2003) raises awareness towards conceptual issues with the a priori existence of hazard and vulnerability separately from each other. Therefore, it is important to highlight the theoretical model behind the vulnerability analysis.

The dominant concept in vulnerability research is that of factor-theoretical models of an explanation of cause and effect relationships, which refer to the idea of "causality". In our ontology, the term "driver" was chosen as an abstract term to answer the second basic question, Vulnerability to what? In the ontology, driver refers to instantaneous events and/or long-term processes as well as to external and/or internal causes. Among many other features, general systems theory claims that systems maintain contact to their respective environment in a very selective fashion, despite sustaining a boundary between the system and its environment. In terms of causality, the arguments goes that in sustaining a boundary, systems cut off many causalities, while simultaneously they must control some, but not all, causalities vital for their re-production (Luhmann 1995). Those productive causes must be employed to some extent within the system (as endogenous factors), while others remain environmental causes (as exogenous factors). In this sense, potentially hazardous effects on the system must be defined as un-productive causes which can occur either outside of (external) or inside the system (internal) . Driver in our ontology therefore indicates how a triggering event or process can influence, affect or deviate the stability/equilibrium of a system, i.e. the conditions for sustaining physical structures or the re-production of living systems. Instead of discussing "negative" and "positive" effects, which is, as a judgment, always observer-related, we can distinguish in a more abstract way a driver as productive or unproductive cause related to the system in focus.

For further structuring the driver in the ontology, we chose the classes natural and social drivers. Typical drivers in natural hazard research, which act outside of a system, are called natural drivers. In the ontology shown in Fig. 5b, they are further subdivided into three sub-classes: Geophysical drivers (earthquake, volcanic eruption, landslides, tsunamis), hydrometeorological drivers (heavy rain, cyclone/hurricane/typhoon, drought, (river) flood, heat wave, snow storm, hail, climate change), or biological/ecological drivers. Additionally, the question whether a system is vulnerable to processes of endogenous risk production (self-endangering) of a system itself is of importance. While for example from the perspective of the field of engineering the dominating canon of vulnerability assessments is concerned with exogenous "natural" hazards (for example, the vulnerability of a building to an earthquake), studies that analyze vulnerability from a societal perspective focus on endogenous processes of social drivers of

vulnerability. Those assessments typically cover social inequalities, political systems, and policies as drivers (for example Pelling 2003, Brooks et al. 2005, Wisner 2006, Hahn et al. 2009) or they concentrate on how decision-making processes contribute to creating vulnerability, like in economics (for example Smithson 1993). Again, the presented ontology tries to integrate classic features of vulnerability research, while remaining open to recent theoretical developments that may be implemented in vulnerability assessments in the near future. Next to the natural driver, we therefore attribute considerable importance to social driver and identify "social inequality", "governance", "war and conflict" and "anthropogenic impact" as different sub-classes of drivers within the social driver class (Fig. 5b).
Furthermore, the conceptual decisions on the "properties" of the vulnerability drivers should be made clear in every study by using a temporal scale of the drivers (observed as a continuous stressor or discrete shock), spatial scale of the driver (local, regional or global impacts), and, in case of more than one drivers, the interaction between different drivers (e.g., cascading and linked hazards) (Fig. 5b).

(a) (b)

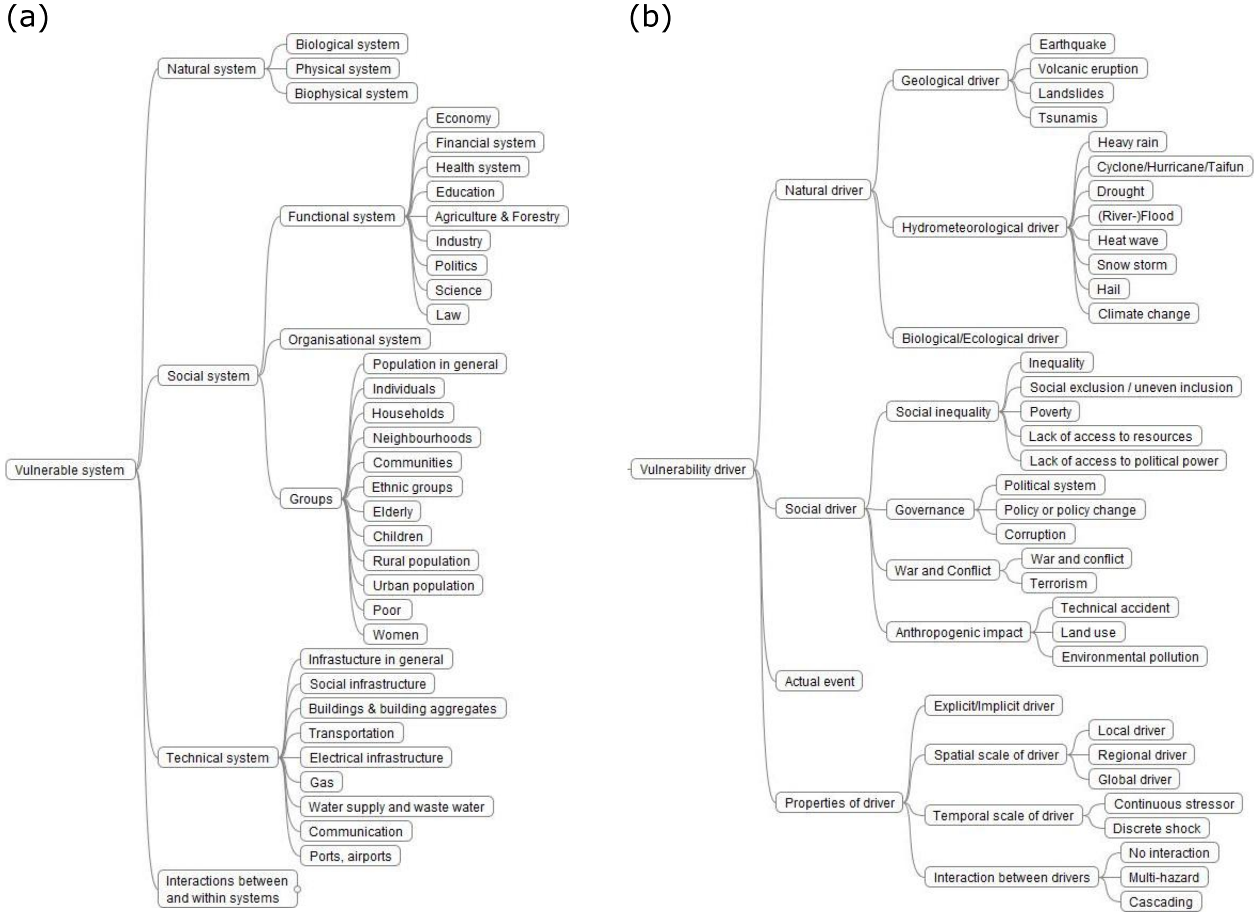

Fig. 5 (a) Ontology for vulnerable systems; (b) ontology for vulnerability drivers.

3.3.3 Reference Framework

The framework of reference of all vulnerability studies correlates with the answers to the above core questions of "Vulnerability of what?" and "Vulnerability to what?" In general, we distinguish three classes – spatial, temporal, and social scale of assessment - when describing the reference framework of vulnerability studies (Fig. 6). In this way, the assessments differ in regard to the social scale of assessment (individuals: Adger 1999; households: Eriksen and Silva 2009; Turner et al. 2003; communities: Wisner 2006, Bollin/Hidajat 2006), the spatial scale (region: Ranci et al. 2010; country: Brooks et al. 2005; subcity: Armas 2008), and the temporal scale (point of time: Kienberger et al. 2009, medium term: Hahn et al. 2009, long term: Li et al. 2009).

An additional class, the "target users" (e.g. scientists, policy makers, local authorities, emergency managers, insurance companies, etc.), for whom the vulnerability assessment is made, is also described in each study. It is an additional class of the reference framework in our ontology. Each class varies regarding the scope of assessment researchers operate with. To better illustrate some of the distinctions used in the ontology, three examples are presented below for each of the three scales (spatial, temporal, and social) used in the reference framework:

Example 1: Spatial Scale in Vulnerability of Critical Infrastructures
First of all, the spatial dimension of the vulnerable system is in the focus. While the spatial dimension of the vulnerability of geographical or political units or entities might be rather simple and the focus of vulnerability analyses might be cities (Pelling 2003; Prasad et al. 2009), regions (Birkmann et al. 2012) or whole nations (GAO 2011), the spatial scale becomes more complex when the vulnerability of a functional system is assessed. An example is the vulnerability of critical infrastructures. Critical infrastructures encompass, for example, more or less locally sited water supply systems (Möderl and Rauch 2011), regionally implemented power grids (Hines 2010), or globally expanding information and communication grids (Hellström 2007). From a methodological point of view, it is very difficult to distinguish sharp boundaries of infrastructure systems, in which technical and social elements are included and interact in a complex manner. Consequently, the analytical framework is somewhat different in each and every study.

Example 2: Temporal Scale in Vulnerability
The temporal dimension of assessments correlates with the system in focus, but especially with the driver a system is exposed to. Research into vulnerability and Climate Change exemplifies the need for distinctive temporal scales of observation. Research in this domain is driven by (at least) two theses: (1) It is widely assumed that climate change and the occurrence of extreme weather events correlate (for example, Kunreuther and Michel-Kerjan 2009). As a consequence, the scope of hazard and vulnerability assessment must include short-term, instantaneous events as well as long-term developments. Scientific estimations of significant changes in the dynamics of the climate system are in the range of decades and centuries (Lenton et al. 2008). (2) Any design and implementation of action plans must also consider distinctive temporal horizons in preparing for immediate threats or for the adaptation to long-term climate change as well as in responding to sudden weather

events and using long-term mitigation strategies (Füssel 2007). For example, researchers call for multiple perspectives when analyzing large urban agglomerations: "A resilient community is one that maintains a current information base to understand potential hazards, and is well informed in the preparation and implementation of its future growth and improvement plans" (Prasad et al. 2009, 4).

Example 3: Social Scale in Vulnerability

Since the mid 1970ies, research into vulnerability has included the analysis of situations of vulnerable people and vulnerable groups (O'Keefe et al. 1976) and increasingly implemented means of assessing social realities (Hewitt 1985, Bohle et al. 1993, Blakie et al. (1994) and later Wisner et al. (2004), Adger 1999, Pelling 2003, Adger 2006) Blaikie et al. (1994) and later Wisner et al.(2004), for example, used a set of variables to distinguish root causes, dynamic pressures, and unsafe conditions and generated a generalized description of "being affected" of individuals or social groups (as families, households, neighborhoods, or groups as "the poor" or "migrants"). Linking vulnerability on the micro level (individuals, households, "groups") to processes and distant root causes on the macro level has been an immense improvement in explanatory power concerning the overall complexity of hazardous situations, yet it is associated with methodological challenges regarding the social scale of assessing vulnerability: When analyzing the vulnerability of small, concrete social units as the level where vulnerability is revealed, the analysis at the same time refers to the level of the larger, more abstract social units and levels that help shaping and propagating the dynamic pressures and root causes that, in turn, determine the unsafe conditions on the small social scale, such as the globally operating economy, the development of large urban agglomerations, or the transformation of modern society driven by functional differentiation.

In the end, the social scale for empirical research the vulnerability assessments are relying on is related to smaller units, like individual, households, neighborhoods, and communities in many cases. Consequently, we used these levels also as sub-classes for the social scale in the ontology.

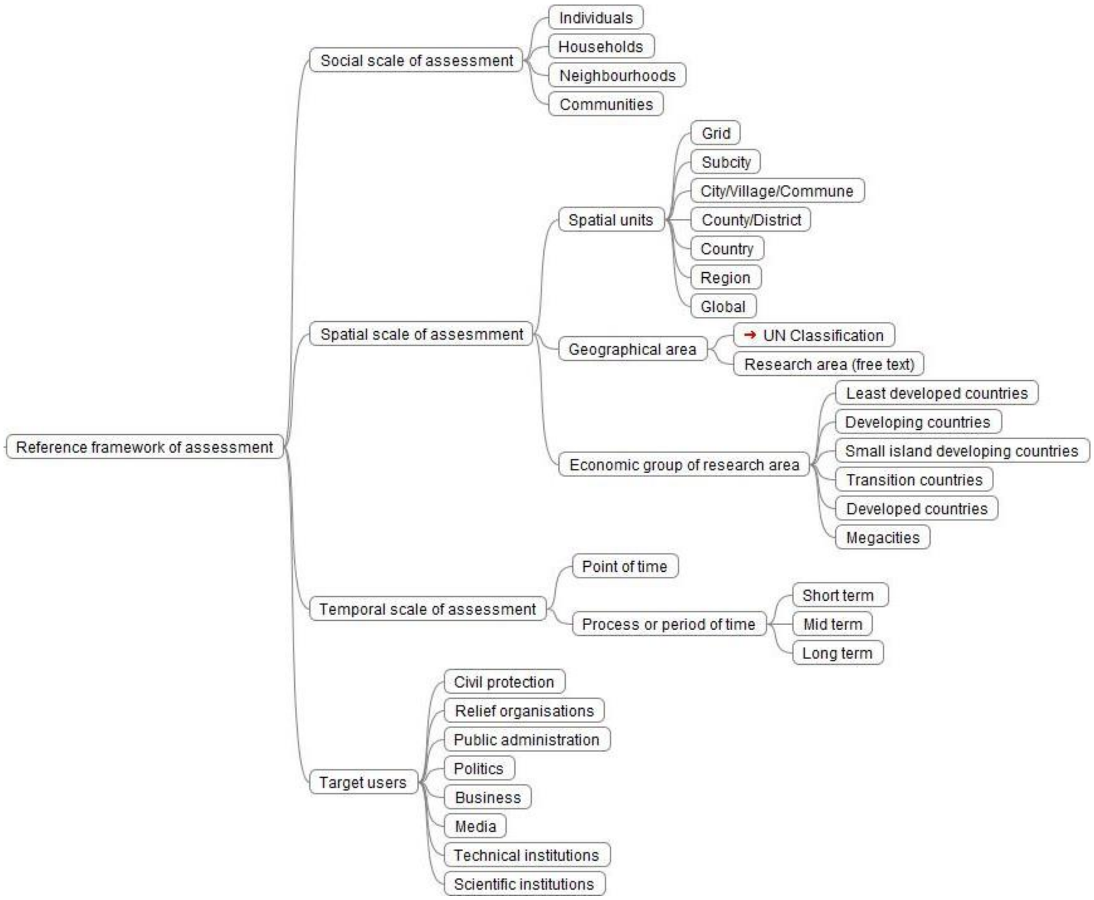

Fig. 6 Ontology in the reference framework of the vulnerability assessment

3.3.4 Methodological Framework

(1) Operational Approach

The ontology for operational approaches used in the vulnerability assessment is characterized by the "Research Design" class: We distinguish between longitudinal, cross-sectional case studies and assessments which have a strong focus on defining indicators that measure vulnerability. Since indicators are a key element in operationalizing vulnerability assessments and have a strong impact on the validity of the assessment, a special class in the operational approach ontology is dedicated to "Indicators" and is used to provide an overview of the actual indicators used in a particular vulnerability study. Sometimes, the choice of indicators is restricted to secondary data provided by official statistics, whereas in other contexts researchers develop ad hoc indicators. The ontology of the operational approach shown in Fig. 7a provides an overview of all captured aspects of the operational approach of vulnerability assessments. In addition to the "Research Design" and "Indicator" classes already described, this includes "Data Collection" and "Data Analysis" methods. The "Data Collection" class describes the methods and sources used to gather information about the vulnerability of a certain place or system. The assessments differ in techniques for data collection, such as remote sensing (Eckert et al. 2011), mapping (Boruff et al. 2005, Collins 2009), available socio-economic data as input for multivariate statistics (Cutter et al. 2000, 2003), focus groups

(Brooks et al. 2005) or content analysis (Turner et al. 2003). Methods of inquiry that focus on in-depth understanding of human behavior and its reasons are labeled as "qualitative". Often, these methods use non-standardized instruments and rather ask "why" or "how" something happened instead of "where", "when" or "what". In some cases, concerned people or stakeholders participate in steps of the research process and the relationship between researchers and them is less or even non-hierarchical. The "Data Analysis" class describes various methods used to analyze data in the various vulnerability assessments. This includes attributes, such as multivariate statistics (e.g. regression analysis, principal component or factor analysis); content analysis; historical or policy analysis; uncertainty treatment; modeling and simulation; spatial analysis; spatial or temporal mapping; and indexing. For the latter, different approaches to aggregating indicators to an index are distinguished: (a) Method of weighting indicators (e.g. statistical, expert opinion, multi-criteria decision analysis etc.), (b) method of aggregation of indicators (e.g., additive, multiplicative, geometric), (c) selection of indicators which are included in index, and (d) accuracy and validity of the approach.

(2) Theoretical Approach

Concepts of vulnerability and the corresponding definitions of vulnerability vary across research domains and determine the choice and design of research instruments. Hence, a discussion of an assessment should always take into account the theoretical framework and the underlying definition of vulnerability. Each conceptual framework can comprise a multitude of factors which determine vulnerability. Unfortunately, these frameworks are incompatible with each other and no overall framework exists. Füssel (2007) argues that terminological confusion mainly results from an unclear distinction between the dimensions sphere and knowledge domain and proposes a minimal structure to classify the multitude of approaches. Whereas the ""sphere" or "scale" describes whether a vulnerability factor is considered as internal or external , the second dimension "knowledge domain" distinguishes between socio-economic and biophysical factors, which can, of course, overlap. Socio-economic factors encompass aspects like access to power and resources, social networks as well as policies, international aid, or economic globalization. In comparison, biophysical aspects of vulnerability refer to topography, environmental conditions, land cover or hazards like earthquakes, storm or sea level rise. Based on Füssel's ideas (Füssel 2007), the vulnerability assessments were classified according to their main conceptual lineage (see Fig 5b): (a) Risk hazard approach (Füssel 2007, Burton et al 1978, Kates 1985, Hewitt 1997); (b) Political economy approach (Adger and Kelly 1999, Pelling 2003); (c) Pressure and release model (Blaikie et al. 1994, Wisner et al. 2004, Rauken and Kelman 2010); (d) Resilience approaches, such as the "MCEER framework" for quantifying resilience (Bruneau et al. 2003) and the "Bric Model" of community resilience (Cutter et al., 2010); and (e) Integrated approaches, such as Cutter's "Hazard of place model" (Cutter 1996), Turner's "Vulnerability Framework" (Turner et al. 2003), and the "BBC conceptual framework" (Birkmann 2006, based on Bogardi and Birkmann (2004) and Cardona (2001). Integrated approaches are not a homogeneous class, but differ from each other in complexity and abstractness of the theoretical concept, hazard conceptualization, and the degree to which they can be operationalized. Regarding the definition of vulnerability, the ontology distinguishes whether vulnerability is defined explicitly or implicitly in a vulnerability assessment.

It would be too space-consuming to list in this paper all the vulnerability assessments reviewed here. A brief general overview referring to a limited number of vulnerability studies using the key components of the ontology described in this section is presented in Table 1.

A B

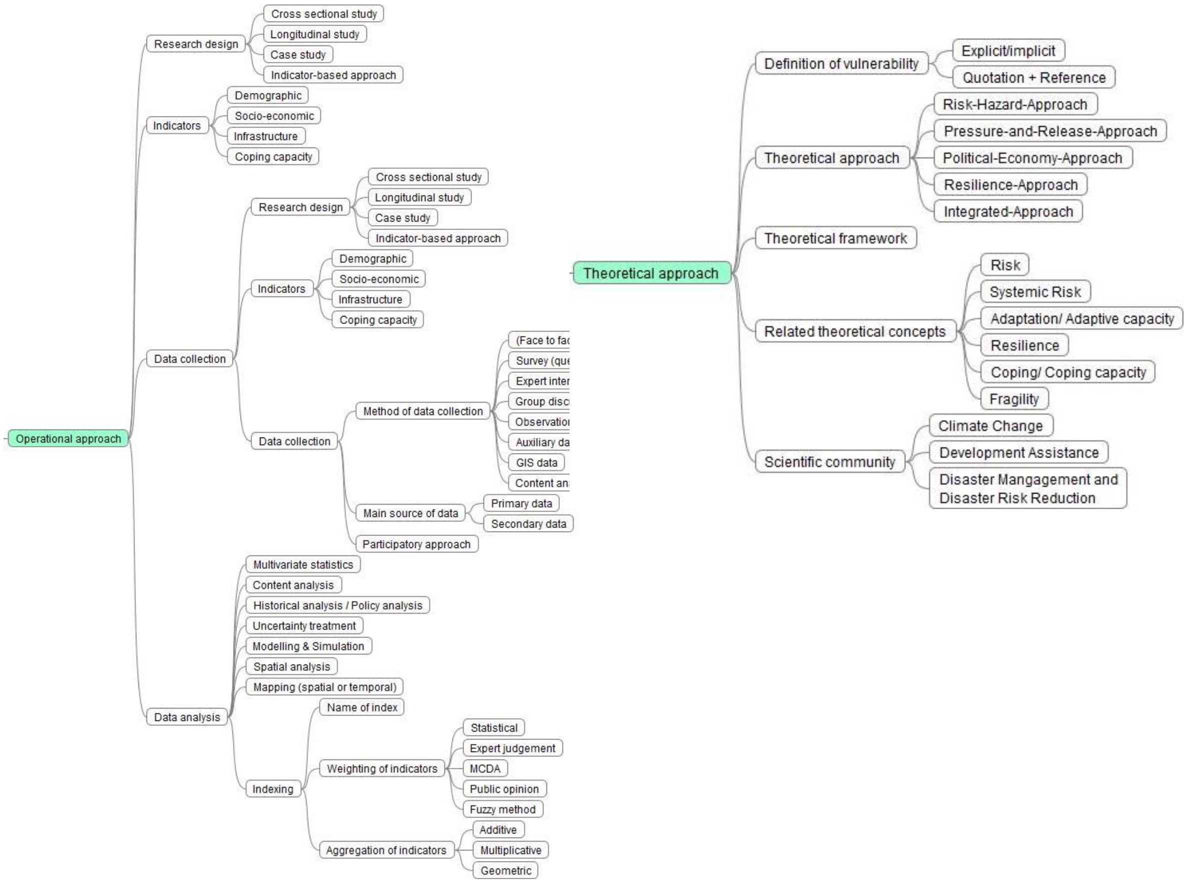

Fig. 7 (a) Ontology for the operational approach; (b) Ontology for the theoretical approach

Table 1 Examples of vulnerability assessment studies organized by key elements of the vulnerability assessments ontology; simplified presentation on the level of all individuals, selected classes, and selected attributes

Vulnerability Assessment Study	Vulnerability of What?	Vulnerability to What?	Reference Framework		Assessment Methods		
			spatial unit	social scale	data collection method	data analysis	theoretical approach
Adger 1999	population in general	tropical cyclone	city/ village/ municipality	individuals, households	survey, expert interviews, secondary data	multivariate statistics	political economy approach
Bollin 2006	communities, economy, politics	earthquake, volcanic eruption, landslide, tsunami, drought		communities		indexing	risk hazard approach
Carreño et al. 2007	population in general, communities	earthquake		neighbor-hoods	auxiliary data / official statis-tics, GIS data	mapping, indexing	integrated approach
Cutter et al. 2003	communities		county, district		auxiliary data / official statistics	multivariate statistics, indexing	integrated approach
Fekete 2009	population in general	(river)flood	Country	communities	secondary data / official statistics	multivariate statistics, indexing	
Hahn et al. 2009	communities, health education	tropical cyclone, drought, climate change		households	survey, auxiliary data	indexing	
Kienberger et al. 2009	population in general	(river)flood	Grid		secondary data, mapping	modeling/simul ation, spatial analysis, indexing	integrated approach
Rashed and Weeks 2003:	communities	earthquake	Communities			modeling/ simulation, mapping,	
Schneiderbauer et al. 2011	agriculture & forestry	climate change	Region		interviews, secondary data, content analysis	indexing	integrated
Wisner 2006:	population, ethnic groups	earthquake, flood, drought	global	communities	content analysis	content analysis	

3.4 Extending the Ontology to Social Impact Assessment

While the ontology framework presented here has been developed primarily for social vulnerability in Disaster Risk Reduction, several key elements of the ontology should be highlighted when considering modelling social losses and impacts of earthquakes. The impact of an earthquake on the society and its built environment (infrastructure) can be most succinctly expressed in terms of three key attributes: Temporal Scale, Spatial Scale and Stakeholder Interest. While each of these attributes have shown to be part of larger over encompassing concepts within the social vulnerability ontology just presented, they are taken here as a concept by themselves to highlight their role to the impact of an earthquake. The impact of an earthquake evolves in space with the time elapsed from the event. Different stakeholders have different interests and play distinct roles in the various phases of the disaster. Correspondingly they look at impact assessments according to their own particular needs and mandates. These three dimensions (time, space, stakeholders) are represented in Fig. 8, which allows the vulnerability and impacts on social and infrastructure systems to be operationalized. In particular, along the time-dimension three periods of a disaster – emergency, recovery and reconstruction - can be identified. The first period constitutes the immediate aftermath of the event and its short-term consequences where the damaged infrastructure operates in a state of emergency. In this phase emergency managers must deal with the demand generated by damaged infrastructure in terms of temporary shelter needs or hospitalization and treatment of victims. In the midterm recovery period, while the infrastructure progressively returns to a new state of normal functionality, the disruptions to businesses might be of interest to stakeholders in the insurance sector. In the long-term reconstruction period, national governments and multi-lateral organizations have to grapple with the costs of permanently rebuilding or upgrading/retrofitting damaged infrastructure, and mitigate the risk from the next event. From the perspective of systemic studies there are two distinct phases which are commonly addressed:

- Emergency phase: short-term (a few days/weeks) at the urban/regional scale (e.g. Franchin et al. 2006, Nuti and Vanzi 1998)
- Economic recovery phase: medium to long-term, at the regional/national scale (e.g. Karaca 2005)

Furthermore, the position on the "time axis" of the analyst/observer with respect to the time-frame changes the goal of the systemic study:

- Outside/before the time-frame: the goal of the system analyst is to forecast the impact in order to set-up preparedness, planning and mitigation measures. It is important to underline how the information basis in this case can be considered as constant.
- Within the time-frame: the goal of the system analyst is that of providing the managers with a real-time decision support system, which updates the Infrastructure state based on the continuously incoming flow of information.
- After the time-frame: the goal of the system analyst is to validate the models against occurred events.

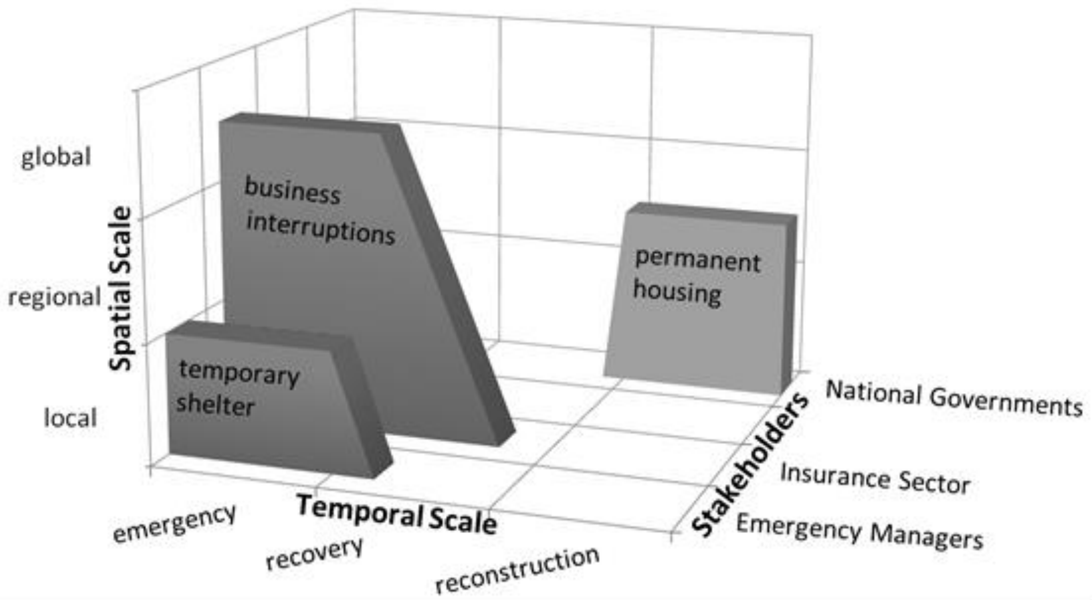

Fig. 8 The three dimensions in an infrastructure vulnerability and impact studies

3.5 Methodological Challenges in Developing the Ontology

During the process of developing the ontology for vulnerability assessments a number of challenges were faced in terms of the principles of ontology creation (Raskin and Pan 2005) used for guidance: Natural language independence, orthogonality, scalability, and community involvement. The first principle of *natural language independence* emphasizes the representation of concepts rather than terms, slang, technical jargon, etc. and requires the defining axioms to be logically consistent. However, when concepts are inherently fuzzy and ambiguous - as in the case of vulnerability -, coming to an agreement on how to present them in a formal structure is challenging and not merely a process of "translation" that needs keeping apart thinking in formal structures and in disciplines, theories or concepts, but a generic part of the process of knowledge generation in the domain itself. Therefore, creating a social vulnerability ontology will represent the biases and influences of the knowledge domain represented by this community. For example, Gallopín (2006) demands a decision on including or excluding "exposure" into/from the concept of vulnerability, because it is consequential for the course of the research and the interpretation of novel insights. If researchers include exposure, the focus of vulnerability analysis shifts towards the relationship between system and environment. If exposure is excluded, vulnerability becomes a property solely of the system and "exposure" as a component contributing to the vulnerability becomes part of the analysis only, if and when the potentially hazardous event or process occurs.

Another principle in ontology design that addresses compound concepts is *orthogonality*, meaning that the compound concepts should be decomposable into their component parts and enable users to reuse them in different contexts. The aim of this principle was that the term definitions developed in the ontology are coherent and clear enough in order to be reused without requiring others to create their own definitions. Yet, while the thrust of the discussions among the authors developing the ontology was to satisfy this requirement, it was not always straightforward to break down compound concepts into their sub-components due to – measured against the demands of a formal structuring process - the lack of conceptual clarity inherent in vulnerability studies. Thinking of vulnerability studies referring to the "human system" or "individuals" as being vulnerable, for example, it is not always clear what aspect of the individuals' existence exactly is susceptible to exogenous influence: The physical (facing damage to the organism) or psychological health (facing damage to mental integrity), or the integration into social groups, families, neighborhoods (facing isolation), or the inclusion into functional and/or organizational spheres of society (facing the danger of exclusion from legal rights, political participation or economic transaction). Obviously, there is a difference in analyzing individuals as a solitary entity or as social beings with characteristic roles and functions in society. However, decomposing a complex system, such as "Social Systems", into distinctive sub-classes is a process inherently fraught with the conceptual difficulties in the field and can be a matter of debate that cannot be solved by developing an ontology.

Since the body of knowledge in the field of vulnerability grows steadily and more and more research fields are intersecting in dealing with vulnerability and related concepts, such as resilience, the ontology should be able to keep pace with this development. This is captured by the principle of *scalability* which refers to the fact that ontologies should be "easily extendable to enable specialized domains to build upon more general ontologies already generated" (Raskin and Pan 2005). This principle was included in keeping a level of openness and awareness of related concepts (such as resilience), but also in the different fields of vulnerability assessments (disaster risk reduction, climate change, development studies) in the group discussions. However, despite selecting key vulnerability assessments from as wide a range of disciplines as possible, the ontology proposed here is shaped a) by the selection of the initial 55 assessments to develop and test the ontology that *has a focus on social vulnerability assessments in the context of disaster risk reduction* and b) by our interpretation of the literature and how the initial 45 assessments and the 10 test cases were used for developing the terminological structure of the ontology. To this extent, like in most taxonomic approaches in vulnerability research or social science in general, we will always encounter some difficulties in "classifying" all potential objects by a predefined set of categories and properties. Due to the principle of scalability and due to our selection and interpretation of the initial assessments, and also due to the principle of natural language independence, the ontology developed here will maybe not satisfy the representation of concepts and their interrelations as used in the strict perspective or technical jargon of one discipline. Nevertheless, we expect that the four key questions that form the basic structure of the ontology (on the first level) capture the core dimensions and approaches in vulnerability assessment regardless of particular disciplinary backgrounds. At the same time, we expect that the ontology provides the conceptual foundation to incorporate a range of additional dimensions and concepts in vulnerability, which currently are not considered, and that the ontology can be extended rather flexibly in a way that will not require a total revision of the existing structure.

In view of these challenges, the principle of "*community involvement"* (Raskin and Pan 2005) gains importance, if the ontology is expected to represent the common state of knowledge in the field. Additional input is needed through involvement and participation of the vulnerability research and practice community in order to extend and populate the ontology with regard to perspectives that were not considered in the current work. We present a first scalable version of an ontology to describe vulnerability assessments, keeping in mind that developing the vulnerability ontology is an adaptive process which will continue to grow with more input from the research and practice community. Reflecting the state of the art of the tools available for implementing the principle "community involvement" to a full extent, it is also recognized that there is a need for better tools for collaborative ontology development and manipulating the ontologies (Buffa et al, 2008).

4 Operationalizing the Integrated Framework

The integration of multiple dimensions of vulnerability with diverse and complex linkages constitutes some of the most challenging questions in store for interdisciplinary research. Contributing to this is the fact that social vulnerability is a fundamentally relative phenomenon and not something that can be directly observed and measured (Birkmann 2006). Thus, one of the main objectives has been the adoption of an indicator system and common nomenclature which posits social vulnerability in relational terms with respect to a single dimension of vulnerability, such as shelter systems. In this regard, indicators are pieces of information that summarize the characteristics of a system or highlight what is happening in a system. An indicator is a quantitative or qualitative measure derived from observed facts that simplify and communicate the reality of a complex situation (Freudenberg 2003). Indicators reveal the relative position of the phenomena being measured and when evaluated over time, can illustrate the magnitude of change (a little or a lot) as well as direction of change (up or down; increasing or decreasing). The mathematical combination (or aggregation as it is termed) of a set of indicators is often termed an index or a composite indicator. Consequently, transparent and validated indicator systems, which characterize the different aspects sectors addressed here (i.e., shelter, health, transportation) have been defined.

The theoretical framework for integration of physical and social performance indicators is founded on the work of Cardona et al. (2005). It provides an overview of not only the expected direct damages, but also the potential for aggravating impact of the direct damages by the social fragility and lack of resilience of the different sectors analyzed here. As shown in Fig. 9 a physical performance index is obtained, for each unit of analysis by interacting with the physical infrastructure models, whereas the total social impact index is obtained by multiplying the direct physical performance indices by an indirect impact factor, based on variables associated with the socio-economic conditions of each unit of analysis. In order to reduce the complexity of the total system for applied purposes, vulnerability in each system is operationalized by a set of discrete indicators, representing social vulnerability and coping capacities. The indicators and sub-indicators have been chosen according to the vulnerability factors and decision criteria identified for each system and are described in the subsequent sections.

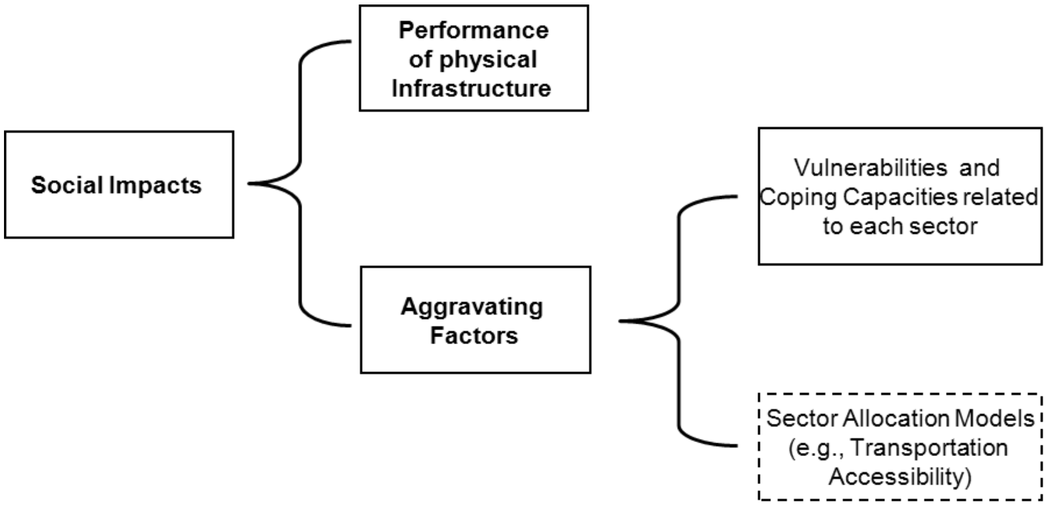

Fig. 9 Structure of the integrated framework for assessment of social impacts

The process of developing an integrated indicator framework for assessment of overall social impacts depicted in Fig. 9 consists of five main steps which should be passed in an iterative manner (Nardo et al. 2005). These development steps are very similar to the main phases of the multi-criteria decision theory (MCDA) or multi-attribute-value theory (MAVT). Therefore, for the development of a hierarchical indicator framework for the shelter needs, the methodological approaches used within a MAVT-Analysis were transferred to the vulnerability for this sector.

5 Shelter Needs Model

To demonstrate the application of the integrated framework described a shelter needs analysis has been developed. The goal here is to demonstrate how such a framework can be applied through with regard to other sectors and additional vulnerability dimensions. The shelter needs model discussed here bring together the state-of-the-art social loss estimation models into a comprehensive modeling approach based on multi-criteria decision support (MCDA). The focus in the shelter needs model is to obtain shelter demand as a consequence of building usability, building habitability and social vulnerability of the affected population rather than building damage alone. The shelter model simulates households' decision-making and considers physical, socio-economic, climatic, spatial and temporal factors in addition to modeled building damage states. A group of proposed socio-economic indicators were harmonized for Thessaloniki based on data available for Europe from the EUROSTAT Urban Audit Database.

To determine shelter needs in Earthquake Loss Estimation, most software follow the HAZUS methodology, where displaced population (determined only from building damage) is multiplied by a factor that considers age, ownership, ethnicity and income to determine demand for public shelters. These four parameters were originally developed by the American Red Cross and were based on expert opinion along with historical data from the 1994 Northridge earthquake (Harrald et al. 1992). New approaches have recently been developed which simulates households' decision-making in seeking shelter and considers socio-economic, temporal and spatial factors in addition to housing damage and lifeline loss to estimate displaced and shelter seeking populations (Chang et al. 2009, Wright and Johnston 2010, Khazai et al. 2011c). For example, the model by Chang et al. (2009) adopts an agent-based approach that utilizes census microdata on households and simulates households' decision-making about post-earthquake shelter on the basis of their dwelling condition, risk perception, mobility, and resources.

A new approach is presented for modeling emergency shelter demand by integrating shelter-seeking logic models into a systemic seismic vulnerability analysis is presented (Khazai et al. 2012a). The selection of socio-economic vulnerability indicators and other factors in the shelter logic model are based on an in-depth literature survey of historic earthquakes and are derived and validated using statistical models. Thus a new advancement to shelter estimation methodology is being explored through three types of key inputs: (1) the "habitability" of buildings which combines inputs from the physical models (building usability, utility loss and climate factors) to provide information on the habitability of a building and can be used as a better determinant in influencing the decision to evacuate than building damage alone; (2) GIS-based shelter accessibility analysis as an input to the shelter seeking model – not discussed here ; and (3) a multi-criteria decision model for implementing a shelter-seeking logic model based on complex socio-economic factors which ultimately lead to the decision to evacuate and seek public shelter. These three inputs are combined into a dynamic shelter model and software tool developed within the EQ-Viz software platform to provide stakeholders an interactive framework in decision-making process for shelter planning and preparedness as well as resource allocation (Khazai et al., 2012b).

5.1 Multi-criteria Shelter Model

The integrated shelter needs model developed here provides a multi-criteria framework which brings together the parameters influencing the physical inhabitability of their buildings, with coping capacities and social fragilities of the at-risk population to determine an index of total shelter need in different neighbourhoods of a city. The mutli-criteria framework can be described schematically in Fig. 10 as composed of the three measures, which will be described in detail here: a) Uninhabitable Building Index (UBI), b) Lack of Resistance to Evacuation (LRE) and c) Shelter Seeking Index (SSI).

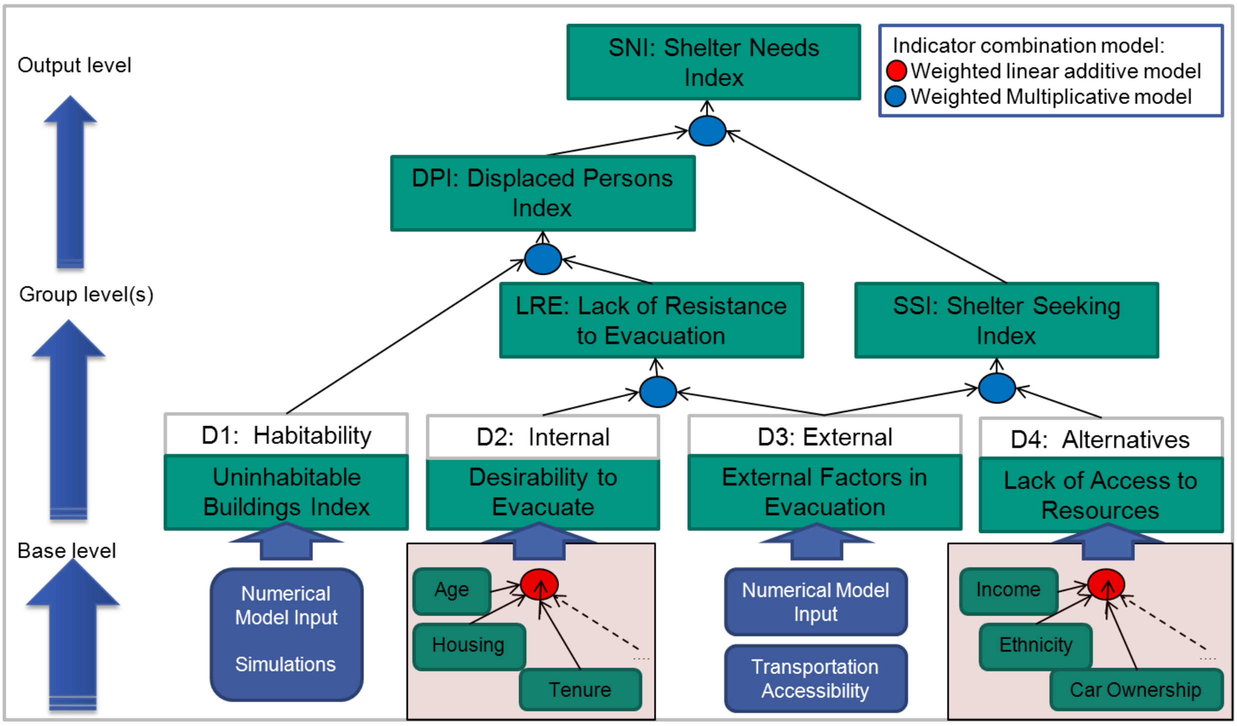

Fig. 10 Hierarchical multi-criteria framework to describe shelter needs

5.2 Shelter-Seeking Decision Model

The basic elements of the logic model for the shelter demand model are based on the ideas of Chang et al. (2009). The shelter model combines each of the decision steps (represented as an output indicator) shown in Fig. 11 in a weighted multi-criteria decision analysis framework according to the following scheme: 1.0 is given by an output indicator as the proportion of population residing in uninhabitable buildings criteria; 2.0 and 3.0 are a combination of a number of internal and external factors and given by an output indicator representing the desirability to evacuate criteria; 4.0 is given by an output indicator representing the desirability to seek public shelter based on the access to resources criteria.

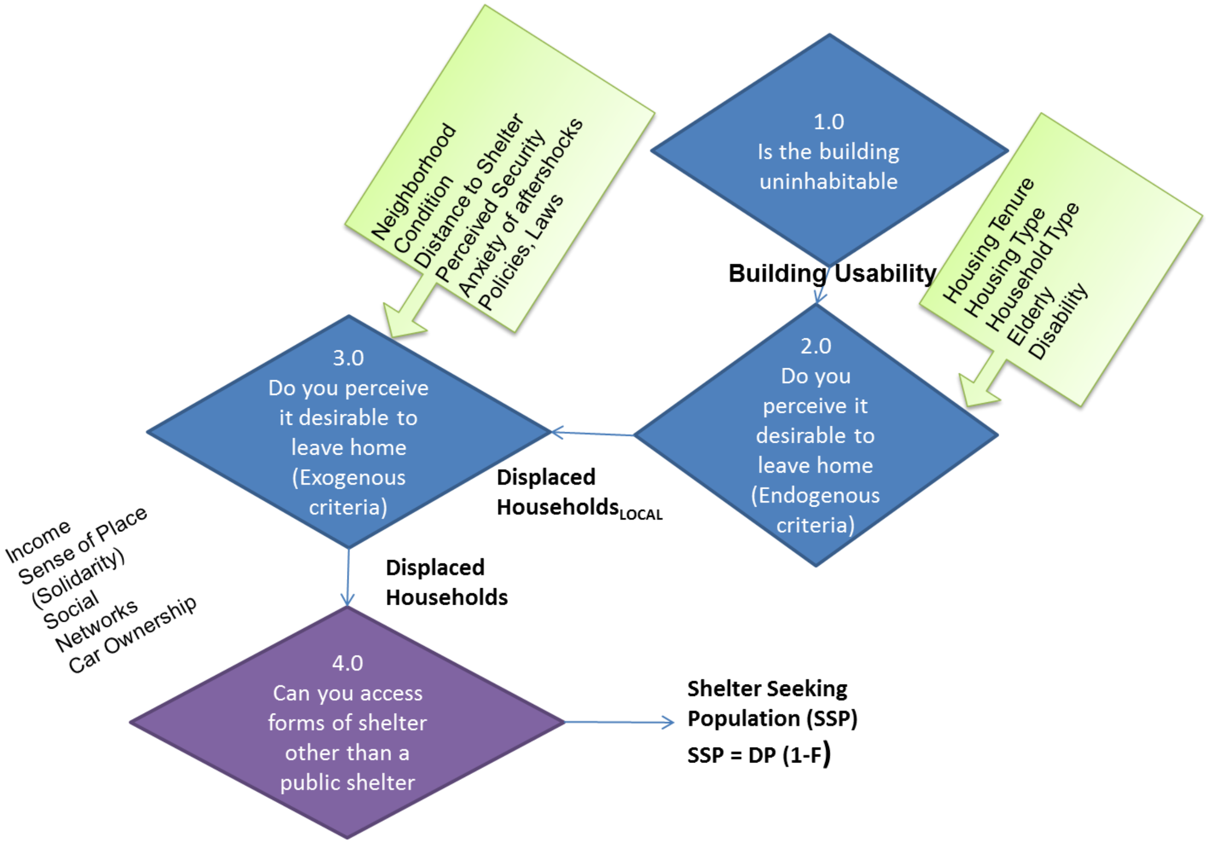

Fig. 11 Proposed model framework for the Shelter Seeking Population Index

Each step is answered by yes or no and leads either to the next decision step or is answering the final destination residents probably choose. Thus, all residents whose home is uninhabitable (1.0) and who have no alternatives will seek public shelter. Also people who have a lower *resistance to evacuation* by either finding it more desirable to leave their home (2.0), and/or are forced to leave their home (3.0), will seek public shelter if they lack other alternatives (4.0). Each of the decision steps are represented by one output indicator which are combined in a weighted multi-criteria decision analysis framework according to the following scheme.

- 1.0 is given by an output indicator as the proportion of population residing in *uninhabitable buildings criteria*.
- 2.0 and 3.0 are a combination of a number of internal and external factors and given by an output indicator representing the *desirability to evacuate criteria.*
- 4.0 is given by an output indicator representing the *access to resources criteria*.

5.2.1 Building Habitability

The first step in the decision to evacuate after an earthquake is based on the structural stability of a building and functional lifeline structures, such as access to water gas and electric power services. Weather conditions can further aggravate potential displacement from damaged buildings with disrupted lifeline services. If a building is only slightly damaged and it is very cold and there are no possibilities to heat, that home will be uninhabitable. During other seasons and weather conditions the same building might be habitable. As shown in Fig. 12 the "displaced persons" model provides an estimate of proportion of persons in habitable and uninhabitable buildings using the following inputs:

- Building Usability (building structural damage which leaves the building unusable, partially usable or fully usable depending on the level of damage and possibility of repairs)
- Utility Loss in each system (water supply, electric power, and gas) defined as one minus the ratio of satisfied to required demand
- Weather conditions (which determine the tolerance to utility loss)

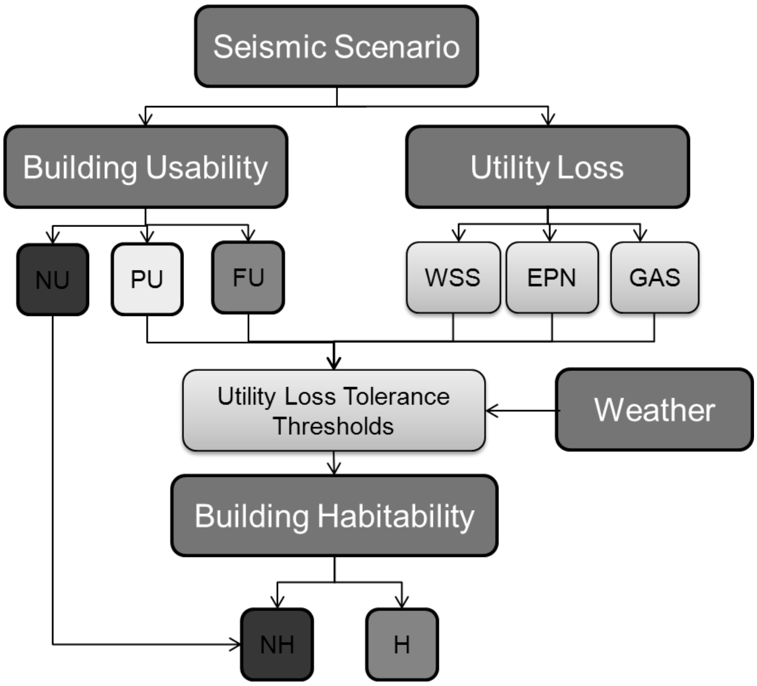

Fig. 12 Modeling of Building Habitability

Building habitability is determined as a combination of the functionality of buildings (building usability), utility services and impending weather conditions and constitutes the first decision step in leaving or staying at home after an earthquake. Building *usability* is derived from a simplified semi-empirical approach as a function of severity of observed damage to structural and non-structural elements of buildings. The usability model was developed based on a detailed survey of 305 buildings in the densely packed suburb of Pettino obtained from the Italian Department of Civil Protection after the 2009 L'Aquila earthquake. The six usability classes considered during the survey were reduced in this model to just three: buildings which are immediately *non-usable* (*NU*), *partially usable* (*PU*) or *fully usable* (*FU*). Using the Pettino database, Usability Ratios (UR) for buildings were derived for each of the three usability classes as a function of the damage data, reported according to six damage states DS0 to DS5, which were also reduced to three damage states (none, yield, collapse). Usability ratios can be used then to estimate the number of persons in each of the three building usability classes (N_{FU}, N_{PU}, N_{NU}). Using the Usability Ratios in

Table 2, the number of persons in each of the three building usability classes can be obtained using the following expression given in Equation 1:

$$N_{FU\ or\ PU\ or\ NU} = \sum_{i=1}^{3} N_i NO_i UR_{i,FU\ or\ PU\ or\ NU}$$

Equation 1

where:

- i = damage level (i = 1, …, 3)
- N_i = number of buildings having damage level i,
- NO_i = number of occupants (at the time of the event) in each building for each damage level i,
- UR_i = usability ratio (UR) for damage level i for each usability class

Table 2 Empirically-derived Usability Ratios

UR	Damage state		
	None	Yield	Collapse
FU	0.87	0.22	0.00
PU	0.13	0.25	0.02
NU	0.00	0.53	0.98

To determine building *habitability* the usability of buildings is considered together with utility loss in a systemic seismic vulnerability analysis (Calvalieri et al., 2012). Non-usable buildings (*NU*) are also non-habitable. If a building is fully or partially usable, depending on the level of residual service in the utilities and the prevailing weather conditions at the time of impact, it can be habitable (*H*) or non-habitable (*NH*). For each of these the utility systems (electric power, water, etc.) the level of residual service is satisfactory when the Utility Loss (UL), defined as one minus the ratio of satisfied to required demand, is lower than a threshold value ($UL_i < UL_{Ti}$). The threshold values depend on Weather conditions and Building Usability and due to the subjective nature of perceptions. (e.g., a utility loss tolerance threshold of 0.9 for fully usable buildings during good weather conditions means that fully usable buildings will be considered habitable for up to 90% utility loss; conversely, during bad weather conditions a partially usable building will be considered habitable only as long as no more than 30% of utility services is lost). The computed number of uninhabitable buildings is sensitive to a defined tolerance threshold for utility loss and importance weights given for each utility system in determining the total utility loss for each building. It must be noted, however, due to the subjective nature of perceptions users may want to change these weights. Thus at the level of "building habitability" changes to subjective user-defined parameters will affect the total output results.

Table 3 Utility Loss Tolerance Thresholds

good weather		***bad weather***	
fully usable	partially usable	fully usable	partially usable
0.9	0.8	0.4	0.3

The total Utility Loss is a weighted average of UL_i on each of the utilities, with weights w_i provided by the analyst, as given by Equation 3:

$$UL = \sum_{j=1}^{N_{UN}} UL_j w_j$$

Equation 3

where:

- j = utility systems (j = 1, ...N_{UN} with N_{UN} = 2 in this application)
- UL_j = Utility Loss in system j
- w_j = weight associated with the importance of loss in utility system j in making the building uninhabitable

The percent of fully or partially usable buildings that are non-habitable (NH_{FU} or NH_{PU}) is thus determined as the portion of buildings which have utility losses greater than the utility loss threshold value ($UL \geq UL_T$). The Uninhabitable Building Index (UBI) is computed as the ratio of occupants of buildings that are uninhabitable to the total population (N) according to the following relationship, given in Equation 4:

$$UBI = \frac{N_{FU}NH_{FU} + N_{PU}NH_{PU} + N_{NU} - N_d}{N}$$

Equation 4

where:

- N_{FU} = number of occupants in buildings that are fully usable
- N_{PU} = number of occupants in buildings that are partially usable
- N_{NU} = number of occupants in buildings that are non-usable
- NH_{FU} = percent fully usable buildings that are non-habitable, where UL ≥ ULT
- NH_{PU} = percent partially usable buildings that are non-habitable, where UL ≥ ULT
- N_d = number of dead persons estimated in a selected casualty model

5.2.2 Desirability to Evacuate

The decision to evacuate one's home after an earthquake and to utilize public shelter is correlated with a variety of social and demographic factors (Tierney et al, 2001). A survey of disaster literature regarding post-earthquake sheltering demand provided an initial basis for selection of relevant socio-economic indicators related to the desirability to evacuate (Khazai, et al., 2012a; Braun, 2011). While the literature survey provides for a comprehensive wish list of indicators, an important requirement for operationalizing the approach is that it should be possible to quantitatively populate the socio-economic indicators based on an approach that can be harmonized at the European level for the urban scale of analysis. To operationalize the shelter needs models for implementation in Europe at the urban scale of analysis, the EUROSTAT Urban Audit data has been analyzed. The Urban Audit database is the only European-wide database that has assembled socio-economic indicators at the urban scale of analysis for a balanced and representative sample of cities in Europe. The Urban Audit indicators were related to the vulnerability criteria of the systemic shelter model and validated with empirical data and expert surveys for the L'Aquila earthquake (see Khazai et al., 2012a).

The resistance to evacuation is also influenced by sociological and economic factors, like having strong social networks, belonging to a minority or being disabled, having enough knowledge and financial resources to protect yourself, and knowing where to obtain information. Other factors influencing the perceived security are conditions such as fear and anxiety of aftershocks or mistrust in safety evaluation of home (green, yellow and red tags) which are more difficult to describe and define quantitatively through indicators. Thus, the desirability to leave is a combination of a complex set of social factors and is ultimately determined by the individual's perception of the importance of each one of these factors in driving the decision to evacuate. While desirability to leave represents an internal driver to evacuation, the resistance to evacuation is also driven by external decisions imposed on the affected population which in some cases may force them to evacuate.

$$DE = EF \times \sum_{i=1}^{n} w_i I_i \qquad \text{Equation 5}$$

where:

- DE = Desirability to evacuate
- w_i = overall weight given to each indicator
- I_i = indicators representing the desirability to evacuate
- EF = External Factors, derived from a GIS analysis and/or different evacuation scenarios. (e.g. in the case of the Thessaloniki application evacuation scenarios were not considered in the analysis)

Table 4 Urban Audit Indicators influencing Desirability to Evacuate

Decision Factors	Urban Audit Indicators for Desirability to Evacuate
Household Tenure (Owner vs. Renter)	-Prop. of households living in private rented housing -Proportion of households living in owned dwellings
Housing Type (Single, Multi-family)	-Number of houses per 100 apartments -Proportion of households living in social housing -Proportion of dwellings lacking basic amenities -Proportion of non-conventional dwellings
Household Type (Large Families with Children, Single Parents)	-Avg. Size of households -Lone-parent households with children aged 18 or under -Proportion of households living in social housing
Age (Children and Elderly)	-Proportion of total population aged 0-4 -Proportion of total population aged 75 and over
Perceived Security	-Total Number of Recorded Crimes per 1000 population

5.2.3 Desirability to Seek Public Shelter

Not all displaced population will seek public shelter, and some may find alternative shelter accommodations (rent motel rooms or apartments), stay with family and friends, or leave the affected area. For estimations of shelter demand it is necessary to account various factors that lead to populations seeking public shelter. Desirability to seek public shelter in this study is given by an indicator model related to the "Access to Resources" which accounts for both "push" factors (such as low income, lack of mobility or having no social networks) and "pull" factors (such as being too far from the shelter sites). The "push" factors are determined in terms of socio-economic drivers, while the "pull" factor is an input from a GIS-based shelter accessibility model (Khazai, et al., 2011b). The question of accessibility relates mostly to residents who are able to choose between different destinations. The proximity and ease of access of shelter locations might be key criteria for these households whose decision of leaving is not founded on aspects of vulnerability but on individual preferences. The Shelter Seeking Index (SSI) is then derived as an additive weighted sum of each of the indicators constituting the shelter seeking population and multiplied by how accessible each of the designated shelter sites are, according to:

$$SSI = AI \times \sum_{j=1}^{n} w_j \, I_j \qquad \text{Equation 6}$$

where:

- SSI = Shelter Seeking Index
- w_i = overall weight given to each indicator
- I_i = indicators representing shelter seeking population
- AI = Accessibility Index, derived from a GIS distance-cost analysis to shelter sites

Table 5 Urban Audit Indicators influencing Desirability to Seek Public Shelter

Decision Factors	Urban Audit Indicators for Shelter Seeking Index
Income	-Percent of households with less than 60% of national median annual disposable income
	-Proportion of households reliant upon social security
Unemployment	-Unemployment rate
Migration/ Ethnicity	-Number of residents born abroad (not only nationals)
	-Residents who are not EU Nationals and citizens of a country with a medium or low HDI
Education	-Prop. of working age population qualified at level 1, 2, 3 4, 5 and 6 ISCED

5.2.4 Displaced Persons Index (DPI)

The integrated shelter needs model developed here is based on a multi-criteria decision theory (MCDA) framework which allows the bringing together of parameters influencing the physical inhabitability of buildings, with social vulnerability (and coping capacity) factors of the at-risk population to determine as well as external factors to determine the desirability to evacuate and seek public shelter. As shown in Fig. 13, the mutli-criteria framework can be described schematically as composed of the two main criteria: overall population at risk of being displaced after an earthquake (DPI) and the proportion of this population likely to seek public shelter (SSI). The Displaced Persons Index (DPI) is given as occupants in uninhabitable buildings (UBI) amplified by external and internal factors related to desirability to evacuate according to Equation 7.

$$DPI = BHI\,(1 + DE) \qquad \text{Equation 7}$$

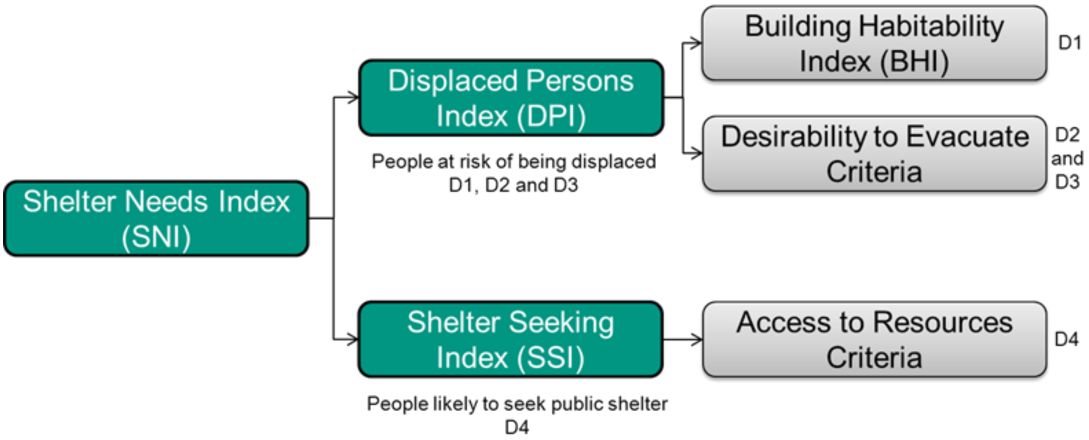

Fig. 13 Hierarchical Model for Computing Shelter Needs Index (SNI) within MCDA framework

5.3 *Shelter demand model implementation*

To demonstrate the shelter methodology it has been applied to the 2009 L'Aquila earthquake, where detailed data on post-earthquake Building Usability (AEDES Survey of 1667 buildings); Socio-economic data for 106 fractions (ISTAT data); and Shelter Population data from April to August 2009 for 107 shelter sites (Ital-ian Civil Defence) was used to validate the model (Khazai et al. 2012c). For each Mixed Operations Centrs (COM), information was collected about the number of shelter sites, the total number of shelters, and the population in the shelters. When shelter population evolution is compared between the different COMs as shown in Fig. 14, it can be seen that in most COMs a drop in shelter population is observed after the first month. The most drastic development is observed in COM 5, where there is a drop of almost 60 percent in shelter population from April to May. Con-trary is the development in COM 1 with an increase in people in shelter until end of June. This increase could partly account for the loss in COM 5 supporting the assumption that migration may have taken place between displaced populations of the different COMs.

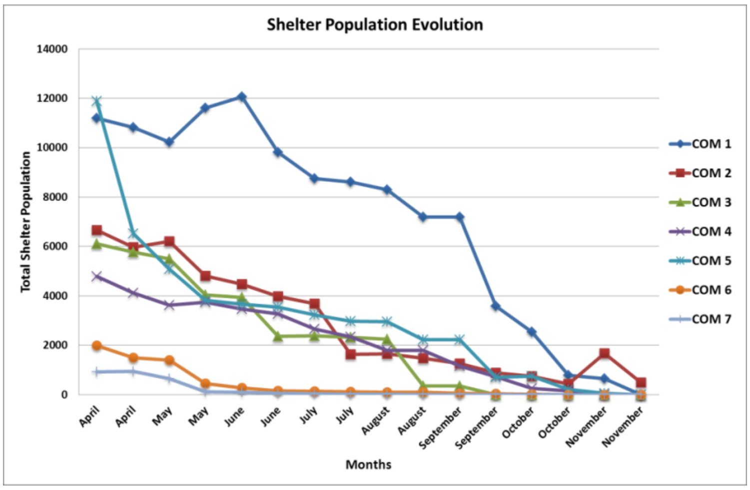

Fig. 14 Shelter Population Evolution in each COM after the 2009 L'Aquila event

The shelter model methodology was implemented into the Multi-Criteria Decision Analysis (MCDA) (Khazai et al. 2012b). The tool will allow stakeholders to display the Shelter Needs ranking of different neighborhoods using various output and visualization formats. The user can assign different importance (weights) to selected indicators and the tool can be used to discuss the weighting outcomes and interactively examine the variability of shelter demand in different areas for different weighting schemes, or for different earthquake scenarios. The rankings for shelter demand after the L'Aquila earthquake are shown in Fig. 15 for the 8 COMs which had the overall coordinating role in their own territories for all rescue and shelter provision operations. First the Displaced Persons Index (DPI) is obtained as the number of occupants living in uninhabitable buildings (BHI) amplified by the Desirability to Evacuate Criteria. In this case, the proportion of persons in uninhabitable buildings was not modelled following the methodology but taken directly based on observed values of partially usable and non-usable buildings in each of the 8 COMs from the AEDES Survey. Furthermore, in the calibration of the shelter model people living in the historical city centre were recommended to evacuate without consideration of unique building stability due to historical buildings and narrow alleys. Accordingly, the Desirability to Evacuate criteria accounts for forced evacuations in COM1, 2 and 5 (Fig. 15b).

To obtain the Shelter Needs Index shown in Fig. 15f, the Desirability to Seek Shelter Indicators (Fig. 15d) were obtained and amplified based on accessibility to shelter sites in the 8 COMs (Fig. 15e). Finally, the Shelter Needs Index (SNI) is obtained as the interaction between the Displaced Persons Index and Shelter Seeking Index (SSI). Fig. 16 shows how the modeling approach can be used to capture the actual shelter demand conditions (given as the observed number of people in shelter camps normalized by total population in each COM). For example, based on building usability alone, COM 3 should have a lower shelter demand than COM 6 and 4. However, given the high desirability to evacuate and seek shelter based on socio-economic indicators, COM3 obtains a more realistic ranking.

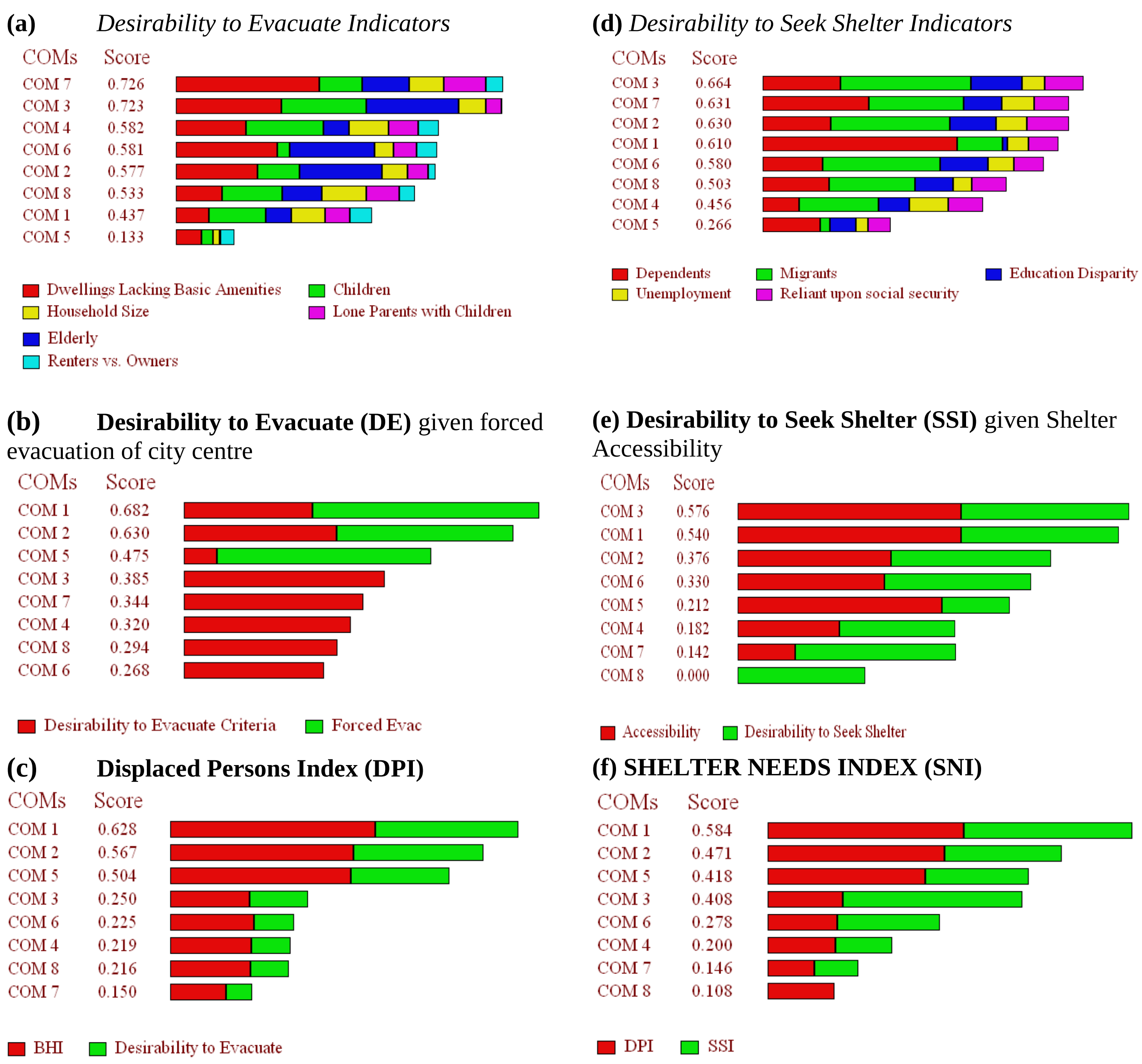

Fig. 15 Ranking of the Displaced Persons (left, 6a-c) based on the Building Habitability Index (BHI) and the Desirability to Evacuate Criteria. Ranking of the Shelter Needs Index (right, 6d-f) based on the Desirability to Seek Shelter (SSI) Criteria.

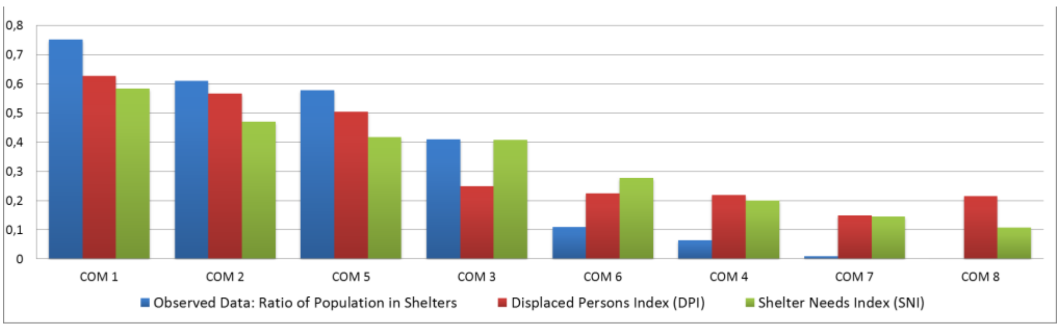

Fig. 16 Ratio of actual population in shelters (Observed data) shown against the ranking of displaced persons and shelter needs in the 8 COMs.

6 Summary

In this deliverable a conceptual model of integrated risk was proposed as a first step. The conceptual model conceives vulnerability as both a physical domain as well as a social characteristic and response, but within a specific areal or geographic domain. Thus, the integrated approach provides a framework to link the exposure and physical vulnerability of inter-related physical systems to vulnerabilities in society to assess risk. Attempting to quantify a social vulnerability index and combine with a physical vulnerability index meets several constraints as the concept itself is complex and nested in various human aspects and contingencies bound to different levels of society. In order to bring social vulnerability into an integrated framework with physical riska comprehensive ontology model of social vulnerability accounting for diverse elements affecting the vulnerability of society was developed as a main thrust of Task 15.5. Finally, the integrated framework and ontology model was operationalized by focusing on a specific aspect of vulnerability – vulnerability of population to displacement after an earthquake. Here, a shelter model was developed that allowed the integration of seismic hazard and risk with a logic model describing the various factors that affect populations when displaced or seeking shelter. The methodological framework, structure of indicators and weights of the selected indicators were then validated through the 2009 L'Aquila earthquake case study.

7 Conclusions

A successful reduction of vulnerability of European citizens and construction to earthquakes – a key objective in NERA - demands appropriate mechanisms to communicate and transfer the overall knowledge on risk and its underlying drivers to the various stakeholders involved in the decision-making process. Vulnerability assessments are product of the state-of-the-art in science and integrate large volumes of data and sophisticated analysis. However, as the knowledge and the volume of scientific works on vulnerability assessments multiply steadily, it is becoming increasingly difficult for the practice and science community to keep track of all these developments effectively and to use it towards disaster risk reduction. Because of the main intention of making vulnerability assessments comparable using a practical and structured *access* to the existing, complex and growing knowledge field of vulnerability assessments, a vulnerability ontology can serve as the basis for a knowledge management tool for a broad research and practice community that work with vulnerability assessments and contribute to interactions between science and practice in terms of knowledge transfer. Such an ontology also has the potential to contribute to bridging the "implementation gap" by serving as an interactive platform that helps sorting through and conveying the relevant knowledge for a specific context so that the knowledge is used and put into practice. Finally, the integrated framework and the application example for the shelter sector has demonstrated the potential for bringing a hidden and complex concept such as social vulnerability, into a quantitative framework and integrate with outputs of a seismic risk analysis.

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