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ARTICLE

VuWiki: An Ontology-Based Semantic Wiki for Vulnerability Assessments

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Abstract Three decades of vulnerability research have generated a complex and growing body of knowledge. The concept of vulnerability, as well as its implementation in vulnerability assessments, is used in various disciplines and contexts. Correspondingly, a multitude of ideas and frameworks about how to conceptualize and measure vulnerability exists. To provide a structured representation of vulnerability, we have set up an ontology-based semantic wiki for reviewing and representing vulnerability assessments (www.vuwiki.org). Based on a survey of 55 vulnerability assessment studies, we first developed an ontology as an explicit reference system for describing vulnerability assessments. The ontology was then implemented in a semantic wiki which allows for the classification and annotation of vulnerability assessment. The resulting semantic wiki, VuWiki, does not aim at "synthesizing" a holistic and overarching model of vulnerability, but at (1) providing—both scientists and practitioners—with a uniform ontology as a reference system; (2) providing easy and structured access to the knowledge field of vulnerability assessments with the possibility for any user to retrieve assessments using specific research criteria; and (3) serving as a collaborative knowledge platform that allows for the active participation of those generating and using the knowledge represented in the vulnerability wiki.

Keywords Knowledge representation · Ontology · Semantic wiki · Vulnerability assessment

1 Introduction

The notion of "vulnerability" draws on the distinction between a forceful event and something affected by the event, and, subsequently, it emphasizes the object exposed, for example, its characteristics, properties, or quality. 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, Hewitt and Burton 1971; O'Keefe et al. 1976; 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 risk and vulnerability and a key instrument to monitor vulnerability over time. 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 (UNISDR 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

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touchpoint in the debate between research communities in climate change and disaster risk reduction (for example, Bohle et al. 1994; Adger 1999; Kelly and Adger 2000; Thomalla et al. 2006; Kienberger et al. 2009; Birkmann et al. 2013).

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 systems, the triggering events, or drivers specific to certain research fields, such as the vulnerability of transportation, industrial production, and energy supply to hydrometeorological events (Fekete 2009; Lebel et al. 2006) or the vulnerability of buildings to earthquakes (Grünthal 1998). Vulnerable entities of the same kind were assessed, for example, the vulnerability of communities in different regions to climate change (Wu et al. 2002; Hahn et al. 2009) 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; Cutter et al. 2003; Wisner et al. 2004).

When examining vulnerability in the context of natural hazards and disasters from disciplinary, multidisciplinary, and interdisciplinary perspectives, researchers and practitioners have used a multitude of frameworks (for example, Birkmann (2006); Füssel (2007); Hufschmidt (2011), and Birkmann et al. (2013) provide different example frameworks) and a variety of methods and technologies to gather knowledge on the different dimensions. This has resulted in incompatibilities and inconsistencies among vulnerability studies and has made it difficult to discover, access, and use data and information on vulnerability (NRC 2006; Giuliani et al. 2011). Consequently, developing universal metrics for vulnerability assessments across disciplines is challenging, which is partly due to the multi-faceted nature of vulnerability itself, 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).

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 natural hazard risk 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. 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.

In the context of structuring and sharing knowledge, semantic web technologies, such as ontologies and semantic wikis, emerged as a new type of knowledge management (for example, SWEET ontology for organizing the vast knowledge base in earth and environmental sciences or the ontology developed in Ontoverse for managing knowledge and networks in life sciences). Ontologies, in short, are a formal, hierarchical representation of concepts and their interrelations in a specific knowledge domain (Gruber 1993; Raskin and Pan 2005; Mainz et al. 2008). Semantic wikis use ontologies as underlying models to embed formalized knowledge, content, structures, and links in wiki pages via a special markup language (Krötzsch et al. 2007). Currently, they are among the most popular practical application of ontologies (Buffa et al. 2008).

To help address the caveats outlined above, and to provide structured and guided access to the fragmented and scattered knowledge on vulnerability and vulnerability assessments for newcomers in the field, as well as practitioners and researchers from other fields, a web-based, interactive knowledge platform, VuWiki (www.vuwiki.org), 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 and VuWiki, the aim therefore explicitly was not to "synthesize" a holistic or overarching model for vulnerability assessments or to derive an integrated vulnerability framework.

In this article, we present the attempt to develop an ontology for vulnerability assessments in a theoretically controlled manner. Important influences in gaining an abstract understanding of the notion of vulnerability come from outside of vulnerability research, from the direction of systems theory (von Bertalanffy 1950; Luhmann 1995). We take ideas from these theories in order to expose the conceptual problems behind the basic questions of "Vulnerability of What?" and "Vulnerability to What?" Both questions refer to problems of describing and analyzing, on the one hand, the exposed entity (a system), on the other hand, system/environment relations. Systems theory is helpful because it allows one to derive a formal representation of concepts and their interrelations in a specific knowledge domain, which is what we mean by an ontology.

In addition, we present the implementation of the ontology in the semantic wiki platform. First we describe the general method of developing the ontology and the wiki. Then we present the resulting ontology for vulnerability assessments and its implementation in a semantic wiki. The discussion focuses on the methodological challenges of developing the ontology and on the potential application for civil protection and disaster (risk) management. The article concludes with an outlook on further developments of VuWiki, in particular by involving the research and practice community.

2 Methodology

The aim of developing the ontology and the semantic wiki was 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 applied concepts and methods. The development of the ontology and the implementation in the semantic wiki platform was realized in a four step iterative process that built progressively upon each step. First, a survey of existing literature, data, models, and methods to conduct assessments of vulnerability (both qualitative and quantitative assessments) was performed. In this way, we obtained an overview of the use of vulnerability in different research fields and extracted relevant classes and categories to structure the semantic fields. The second step was developing the ontology itself, which (in the sense used here) allows for the explicit description of methods, concepts, and models that are useful for the classification of vulnerability assessments. Third, the semantic wiki knowledge platform was designed and implemented using Semantic MediaWiki (SMW). This also included the development of tools for data search and retrieval as well as information sharing in a manner that provides links to existing theory, data, research, and assessment initiatives. Finally, the wiki was initially populated with 55 assessments. The approach to developing VuWiki is outlined in Fig. 1 and briefly described in the following subsections.

2.1 Survey of Vulnerability Assessments

Work started with a thorough survey of existing vulnerability studies 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 assessments, 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, 55 vulnerability assessments were selected from a broad range of academic disciplines (geography, economics, social sciences, and earthquake engineering). The assessments were made in different fields (development studies, disaster risk reduction, climate change adaptation, and 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 assessment.

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.

2.2 Collaborative 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. Developing the ontology for vulnerability assessments was guided mainly by five development principles: application independence, natural language independence, orthogonality, scalability, and community involvement (Raskin and Pan 2005). The principle "application-

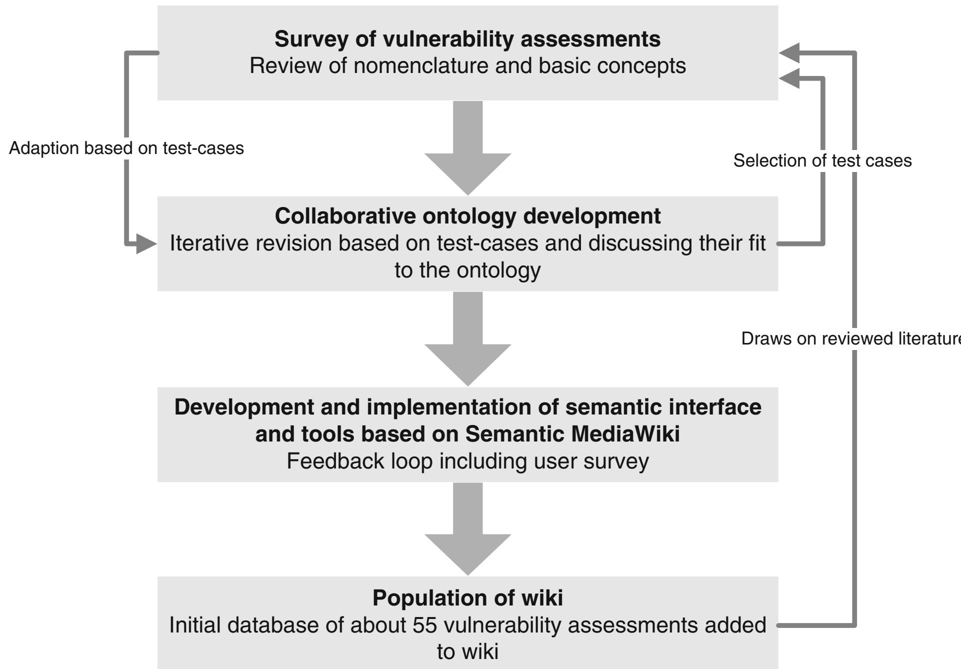

Fig. 1 The work flow in developing VuWiki

independence" means that "the structure and contents of an ontology should be based upon the inherent knowledge of the discipline, rather than on how the domain knowledge is used" (Raskin and Pan 2005, p. 1121). We implemented this principle in our theoretically controlled approach based on general systems theory (von Bertalanffy 1950; Luhmann 1995) to develop the structure of the ontology from an abstract meta-perspective. "Natural language independence" emphasizes representing concepts rather than terms, slang, and technical jargon 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, p. 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 with a background in disaster risk research and informatics at the Karlsruhe Institute of Technology (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 the Systemic Vulnerability Seminar offered at the KIT in the fall of 2012. The use and evaluation of the ontology and semantic wiki platform in the seminar allowed for a collaborative and participatory approach to further improve the vulnerability ontology and related tools to reach the form currently presented in this article. It should be noted that developing a comprehensive ontology of vulnerability assessments is an adaptive process, which will continue to grow and increase in scale with more input from the research and practice community.

2.3 Semantic Interface and Tool Development

The next step was to define mechanisms for translating the ontology to represent and visualize the knowledge in a knowledge base platform, such as a wiki. As a unifying interface to analyzing, describing, and compiling various methods for vulnerability assessment, a platform was established according to the state-of-the-art SMW, which is easy to use. While traditional wikis contain only texts that computers can neither understand nor evaluate, semantic wikis add semantic annotations that organize information based on structure that can be understood by computers. This structure is provided by the ontology.

2.4 Populating the Wiki

So far, 55 assessments have been added to VuWiki as an initial database. As an effect of the selection of the 55 assessments for developing the ontology, most studies in VuWiki focus on vulnerability of the social system. However, some studies of the vulnerability of ecological and technical systems are also included. The process of populating the wiki with more content is expected to come from researchers and practitioners, as VuWiki is intended to be further utilized through the involvement of a wider research and practice community.

3 Ontology for 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. 2 shows that each vulnerability assessment is the basic object or *Instance* of the ontology, which belongs to a *Category X.* In the later implementation in the semantic wiki, each wiki article also 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.

Four key questions form the first level "branches" or categories of the ontology and correspond to the basic,

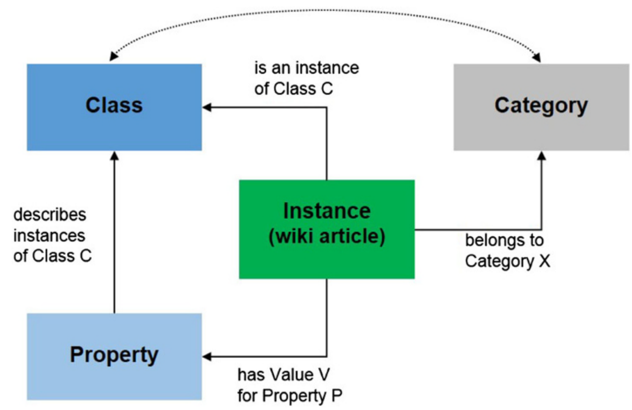

Fig. 2 Relationships among category, class, property, and instance in the ontology

abstract structure of the knowledge domain of vulnerability assessments and, hence, to the entry point of the semantic wiki later on. 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 subsections, 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 independent of technical jargon in the field and regardless of the fact that in some cases the same word (for example, "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.

3.1 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, exposed to or affected by an occurrence (perturbation, stress) and something possesses the potential to change its state, a degree of sensitivity, and

Fig. 3 Ontology for vulnerable systems

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 (von Bertalanffy 1950). Consequently, the ontology on vulnerable systems shown in Fig. 3 explicitly refers to four classes of vulnerable systems: (1) "natural systems" for vulnerability studies referring to a set of subclasses 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 subclasses of population in general (Adger 1999; Carreño et al. 2007), social groups, for example, communities (Cutter et al. 2003; Bollin and Hidajat 2006), functional systems, such as the economy (Patt et al. 2010), the public financial sector (Mechler et al. 2006) or the health sector (Hahn et al. 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; Gallopín 2006) or societal and technical subsystems (Khazai et al. 2013).

Overall, the ontology on vulnerable systems shown in Fig. 3 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). 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 in mainstream vulnerability research. For example, the branches of "Industry," "Agriculture & Forestry," or "Financial System" are certainly part of the overall economic system, 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.

3.2 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 separate 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 contend that in sustaining a boundary, systems cut off many causalities, while simultaneously they must control some, but not all, causalities vital for their reproduction (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 unproductive causes that 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, that is, establish the conditions for maintenance of physical structures or the reproduction 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 a 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. 4, they are further subdivided into three subclasses: geophysical drivers (earthquakes, volcanic eruption, landslides, tsunamis), hydrometeorological drivers (tropical cyclones, tornados, floods, coastal storm surges, droughts, and so on), or biological/ecological drivers (for example, infestation or loss of biodiversity). 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). Our 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 attribute considerable importance to the "social driver" and identify social inequality, governance, war and conflict, and anthropogenic impact as different subclasses of drivers within the "social driver" class (Fig. 4).

Furthermore, the conceptual decisions on the "properties" of the vulnerability drivers should be made clear in every study by using a temporal scope of the drivers (observed as a continuous stressor or discrete shock), spatial scope of the driver (local, regional or global impacts), and, in case of hybrid events where there is more than one driver, the interaction between different drivers (for example, cascading and linked hazards) (Fig. 4).

3.3 Reference Framework

The framework of reference of all vulnerability studies correlates with the answers to the core questions of "Vulnerability of what?" and "Vulnerability to what?" In general, we distinguish three dimensions of assessment—factual (and more specific, spatial), temporal, and social—when describing the reference framework of vulnerability studies (Fig. 5). In this way, the assessments differ in

Fig. 4 Ontology for vulnerability drivers

regard to the scope of assessment in the social dimension (individuals: Adger 1999; households: Turner et al. 2003; Eriksen and Silva 2009; communities: Bollin and Hidajat 2006; Wisner 2006), the spatial dimension (region: Ranci and Migliavacca 2010; country: Brooks et al. 2005; sub-city: Armas 2008), and the temporal dimension (point of time: Kienberger et al. 2009; medium term: Hahn et al. 2009; long term: Li et al. 2010).

An additional class, the "target users" (for example, scientists, policy makers, local authorities, emergency managers, insurance companies) 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 with which researchers operate. To better illustrate some of the distinctions used in the ontology, three examples are presented below for each of the three dimensions (spatial, temporal, and social) used in the reference framework.

3.3.1 *Example 1: Fact/Spatial Dimension in Vulnerability of Critical Infrastructures*

The fact dimension of the vulnerable system in which the spatial aspect is the most important specification refers to the distinction of elements within the system and to spatial distinctions, for example, the spatial realization of interrelated elements. 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 (Birkmann et al. 2011; GAO 2011; Welle et al. 2012), the situation

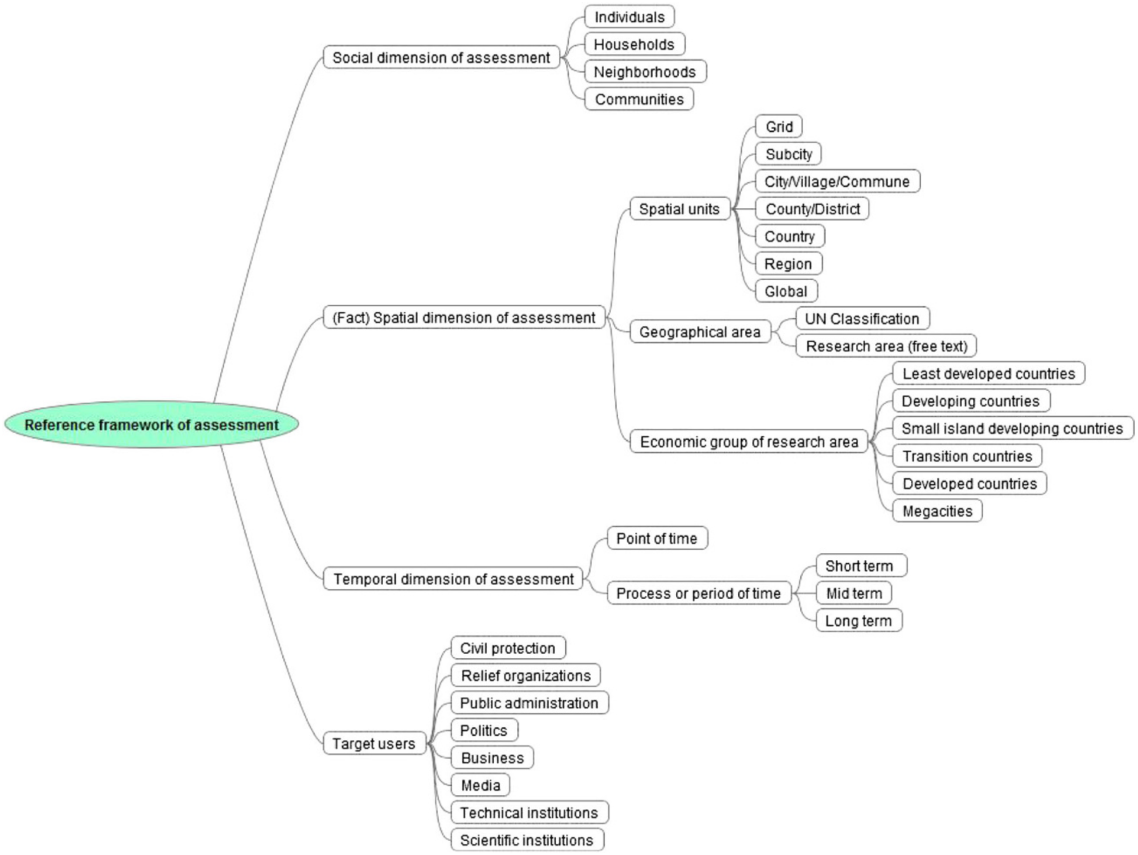

Fig. 5 Ontology in the reference framework of the vulnerability assessment

becomes more complex when the vulnerability of a functional system is assessed. One example is the vulnerability of critical infrastructures, where observers are confronted with the fact that physical installations or communication networks are spread out in a distinctive manner. We find systems, networks of systems, or internetworks (Edwards et al. 2007). Critical infrastructures encompass 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.

3.3.2 Example 2: Temporal Dimension in Vulnerability to Climate Change

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 a distinctive temporal scope 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, p. 4).

3.3.3 Example 3: Social Dimension in Vulnerability

Since the mid-1970s, 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 1983; Blaikie et al. 1994; Bohle et al. 1994; Adger 1999, 2006; Pelling 2003; Wisner et al. 2004). Blaikie et al. (1994) and 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 dimension 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 shape and propagate dynamic pressures and root causes. These forces, 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 scope for empirical research in vulnerability assessments in most cases is related to smaller units, like individuals, households, neighborhoods, and communities. Consequently, we used these levels also as subclasses for the social dimension in the ontology.

3.4 Methodological Framework

The methodological framework domain of the ontology is subdivided into the operational approach and the underlying theoretical concept implemented in vulnerability assessments.

3.4.1 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. This domain of the ontology shown in Fig. 6 provides an overview of all captured aspects of the operational approaches 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 et al. 2009), available socioeconomic 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 nonstandardized 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 interested parties 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 (for example, 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: (1) method of weighting indicators (for example, statistical, expert opinion, multi-criteria decision analysis (MCDA)); (2) method of aggregation of indicators (for example, additive, multiplicative, geometric); (3) selection of indicators that are included in index; and (4) accuracy and validity of the approach.

3.4.2 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

Fig. 6 Ontology for the operational approach

(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 first dimension "sphere" describes whether a vulnerability factor is considered as internal or external, the second dimension "knowledge domain" distinguishes between socioeconomic and biophysical factors, which can and do overlap. Socioeconomic 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 (Fig. 7): (1) Risk hazard approach (Burton et al. 1978; Kates 1985; Hewitt 1997; Füssel 2007); (2) Political economy approach (Adger and Kelly 1999; Pelling 2003); (3) Pressure and release model (Blaikie et al. 1994; Wisner et al. 2004; Rauken and Kelman 2010); (4) 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 (5) 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 made operational. Regarding the definition of vulnerability, the ontology distinguishes whether vulnerability is defined explicitly or implicitly in a vulnerability assessment.

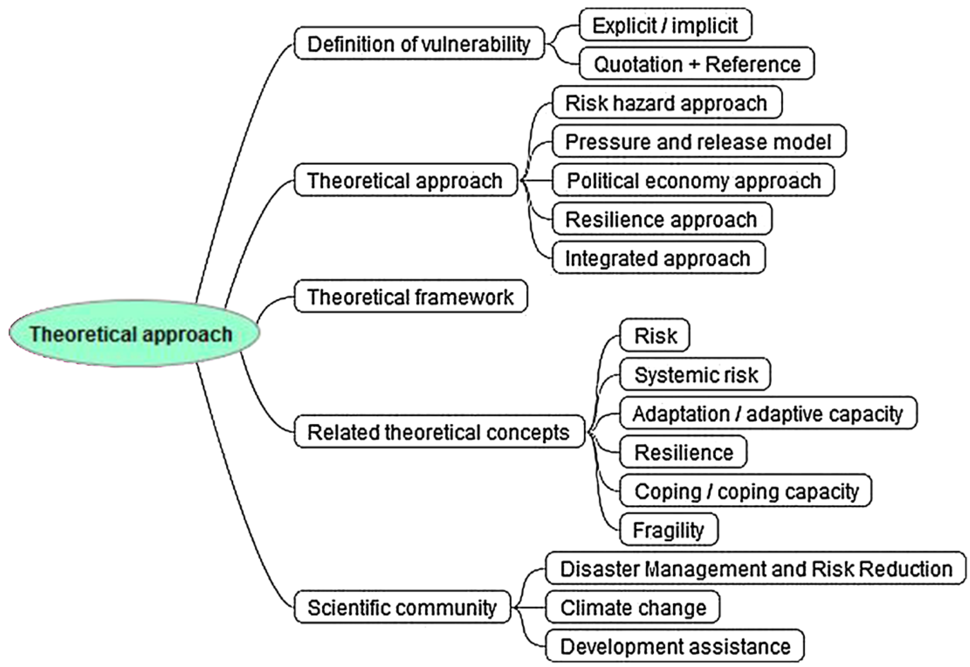

Fig. 7 Ontology for the theoretical approach

It would be too space-consuming to list in this article all the vulnerability assessments encoded in VuWiki. 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.

4 Implementation of the Ontology: VuWiki Platform

The ontology outlined in the previous section allows for the structuring of information on vulnerability assessments in a way that these concepts can be queried or assessed via a structured and rational manner. In this section we describe how the ontology was applied and implemented in the platform VuWiki.

4.1 Semantic Wikis

Currently, semantic wikis are among the most popular practical application of ontologies (Buffa et al. 2008). Semantic wikis use ontologies as the underlying model to embed formalized knowledge, content, structures, and links in the wiki pages via a special mark-up language (Krötzsch et al. 2007). In contrast to this, conventional wikis enable their users to collect and share knowledge by storing and retrieving individual information, but are less appropriate for obtaining aggregated or queried information and their content is often only weakly structured and not easily machine-interpretable.

The rising interest of scientific communities and working groups in the semantic web as a newly emerging type of knowledge management materializes in a growing body of ontologies which are often publicly accessible (for example, the SWEET ontology by Raskin and Pan (2005) for organizing the vast knowledge base in earth and environmental sciences). For implementation of the vulnerability ontology into a semantic wiki, we used the SMW platform, a free, open-source extension of the well-known MediaWiki (which is also used to run Wikipedia). SMW uses the stability and established usage patterns of the existing MediaWiki system for the seamless integration of semantic technologies into a wiki (Völkel et al. 2006; Krötzsch et al. 2007). While many semantic wikis are under development, SMW currently is the only one that has been deployed in large-scale semantic wiki applications and is used widely on public websites (Buffa et al. 2008).

4.2 Ontology in VuWiki

Beyond its functions as a content management system, VuWiki is fitted with a terminological backbone in which the tangible representation of a vulnerability study (a single article/publication) is a unique wiki page specified by numerous properties based on the vulnerability ontology. In the practical implementation of the ontology into the object-oriented language of SMW, we used *Categories* as a simple form of annotation for classification of each vulnerability assessment article into four main categories according to the four entry questions: Category: Vulnerability Driver, Category: Vulnerable System, Category: Reference Framework, and Category: Assessment Method. In turn, each *Category* has a number of *Properties*, *Sub-*

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 scope	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
Birkmann et al. (2011)	Individuals	Earthquake, storms, flood, drought, climate change	Country, global	Individuals	Auxiliary data/official statistics	Multivariate statistics, indexing	Integrated approach
Bollin and Hidajat (2006)	Communities, economy, politics	Earthquake, volcanic eruption, landslide, tsunami, drought		Communities		Indexing	Risk hazard approach
Carreño et al. (2007)	Population in general, communities	Earthquake		Neighborhoods	Auxiliary data/official statistics, 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	Tropical cyclone, drought, climate change		Households	Survey, auxiliary data	Indexing	
Kienberger et al. (2009)	Population in general	(River) flood	Grid		Secondary data, mapping	Modeling/simulation, spatial analysis, indexing	Integrated approach
Schneiderbauer et al. (2013)	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	

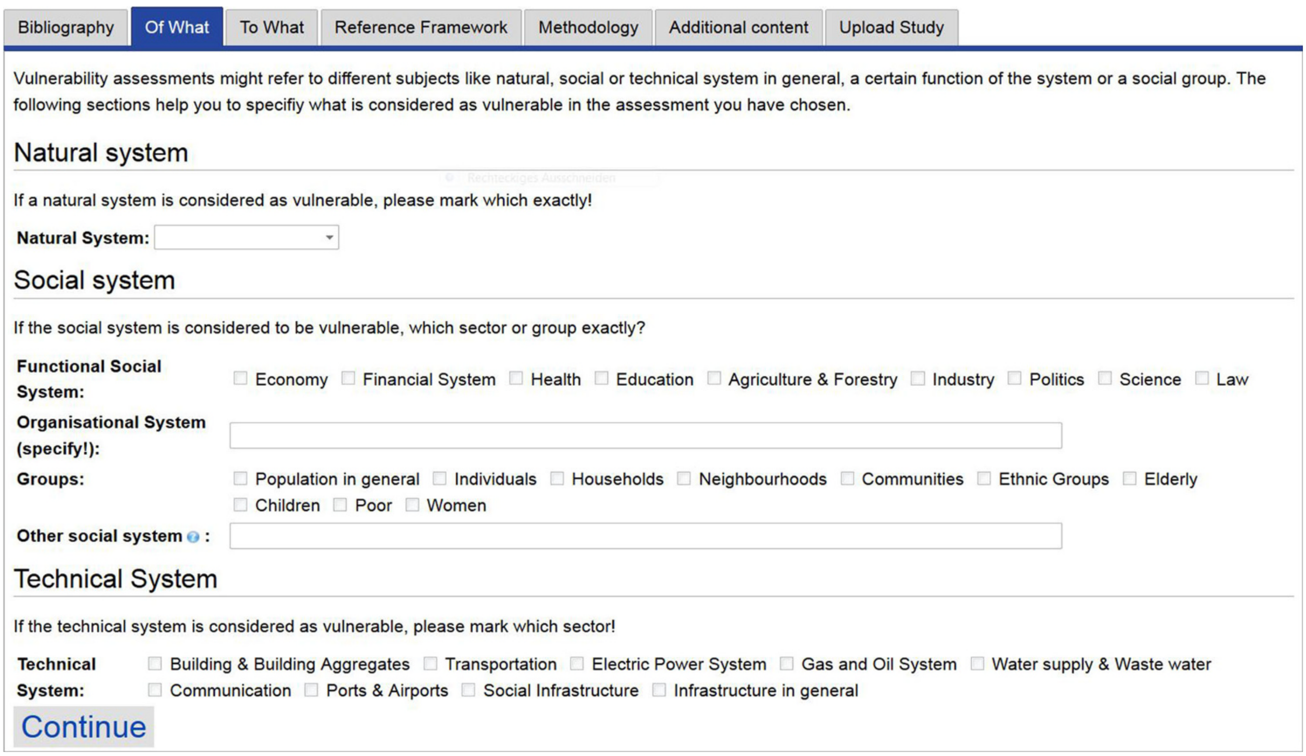

Fig. 8 Screenshot of the semantic form based on the vulnerability ontology and implemented in VuWiki to guide user while adding a new study

Properties, and *Values*. For example, the category "vulnerability driver" can have "natural driver" as a property, "geological driver" as a subproperty, and "earthquakes," "volcanic eruptions," "landslides" or "tsunamis" as values. In this way, the ontology in VuWiki is translated into 4 key categories, 77 different properties and subproperties, and 6,089 unique values.

4.3 Providing Structured Access to and Organizing Knowledge in VuWiki

The SMW platform provides a versatile set of tools that allows users to search, organize, tag, browse, evaluate, and share the wiki's vulnerability assessment content. Strong emphasis was put on embedding user-friendly options to enrich the accompanying database of VuWiki, since this is considered a necessary precondition to create a viable and lively platform. Besides the opportunity to add, edit, and link conventional texts, tables, illustrations or external data sources, several features in VuWiki are highlighted below, which support easy, structured access to existing knowledge and help organize the knowledge according to specific queries of users and add new knowledge.

(1) *Semantic Forms* The "semantic form" (Fig. 8) serves as the backbone of VuWiki. It guides the users through a step-by-step query form with drop-down menus for describing a selected vulnerability assessment. The semantic form thus embeds the ontology and automatically generates the semantic markup that allows users to add new studies or edit and query any of the existing vulnerability assessment methods described in the wiki articles. The semantic form allows for new knowledge to be added to the VuWiki by other researchers or practitioners, for example, new assessment studies or additional information on assessments already stored in VuWiki. These new data can be integrated into VuWiki in a format that can readily be incorporated in SMW and supported by tools such as "Dynamic Tables" or "Wiki Drilldown".

(2) *Dynamic Tables* Users can sort and compare all vulnerability assessments in VuWiki through dynamic tables, which can easily be customized without any actual programming. For example, a table can be generated to provide details about the reference framework of all vulnerability studies in the wiki, showing the geographical areas, spatial unit, temporal scope, and social dimension of assessment of these studies as columns in a dynamic and sortable table. These tables in particular facilitate access by providing a structured overview of the knowledge domain as represented by the assessment studies in VuWiki.

(3) *Wiki Drilldown* The wiki drilldown enables users to "formulate" individual queries by menu options that provide selections from main categories (for example, data, theoretical frameworks, or assessment standards) through a hierarchy of properties, subproperties, and values. For example, a user can use the wiki drilldown feature to quickly locate all vulnerability assessments that employ an indicator-based approach and filter the information to identify which of these use expert judgment versus statistical methods for weighting indicators or how many use the Hazards of Place model as their theoretical framework.

5 Discussion

In the two previous sections we have presented the ontology as a result of an iterative discussion process and the final application in the VuWiki platform. Correspondingly, the first part of the discussion focuses on the development of the ontology and the second part on possible applications in civil protection and disaster (risk) management.

5.1 Methodological Challenges in Developing the Ontology

During the process of developing the ontology for vulnerability assessments and implementing it in a semantic wiki, a number of challenges were faced in terms of the principles of ontology creation (Raskin and Pan 2005) used for guidance (see Sect. 2.2): natural language independence, application independence, orthogonality, scalability, and community involvement. The principle of natural language independence emphasizes the representation of concepts rather than terms, slang, and technical jargon 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. It is also a generic part of the process of knowledge generation in the domain itself, which in turn challenges the principle of application independence. Creating a 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 VuWiki 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 subcomponents—measured against the demands of a formal structuring process—due to 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), integration into social groups, families, neighborhoods (facing isolation), or 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. But decomposing a complex system, such as social systems, into distinctive subclasses is a process inherently fraught with 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, p. 1121). 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 assessment (disaster risk reduction, climate change, development studies) in the group discussions. Despite selecting key vulnerability assessments from as wide a range of disciplines as possible, the ontology proposed in VuWiki is shaped (1) by the selection of the initial 55 assessments to develop and test the ontology, which has a focus on social vulnerability assessments in the context of disaster risk reduction; and (2) 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 principles of natural language and application independence, the ontology developed here may 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 a conceptual foundation that can 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. In VuWiki, 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 that will continue to grow with more input from the research and practice community. To encourage the exchange of ideas, several discussion pages have been dedicated in VuWiki, also for editing and further developing our ontology. But reflecting the state-of-the-art of the tools available for implementing the principle of community involvement to its full extent, it is also recognized that there is a need for better tools for collaborative ontology development and for manipulation of ontologies in general (Buffa et al. 2008).

5.2 Possible Application for Civil Protection and Disaster (Risk) Management

A successful implementation of disaster risk reduction options and strategies 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 the 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. Consequently, the main intention of making vulnerability assessments comparable by using a practical and structured access to the existing, complex, and growing knowledge field is to foster exchange of knowledge, as well as learning among disciplines. VuWiki can serve as a knowledge management tool for a broad research and practice community and, in this capacity, contribute to interactions between science and practice in terms of knowledge transfer. VuWiki also comprises the potential to bridge the "implementation gap" by serving as an interactive platform that helps sort through and convey the relevant knowledge for a specific context so that the knowledge is used and put into practice. For example, a national authority that may want to develop new guidelines for community flood risk management based on risk and vulnerability assessments can use the features in VuWiki such as wiki drilldown (see Sect. 4.3) to get an overview of the relevant parameters for flood vulnerability at the community scale of assessment and be able to discern which of the many studies are the most applicable to their particular needs. It should be noted that the usefulness of VuWiki in this regard is dependent on community involvement criteria, and the depth and extent to which the wiki is populated with additional vulnerability assessments beyond those currently represented. Second, VuWiki is "just" a tool that provides access to knowledge in a structured way. Due to copyright reasons, data licensing, and other legal limitations, it cannot provide the actual journal articles itself.

6 Conclusion

In this article, we presented the development of an ontology for vulnerability assessments and its implication in a collaborative semantic wiki platform vuwiki.org. The ontology proposed in VuWiki was developed iteratively and revised in numerous sessions by the authors based on its "fit" in classifying the vulnerability studies in the literature, which were selected to be organized by it. The ontology was subsequently validated with a group of experts at KIT who were not involved in the creation of the ontology and later evaluated by students who used VuWiki as a learning tool in a seminar offered on Systemic Vulnerability Analysis in the fall of 2012 at KIT.

The aim of VuWiki development was not to synthesize a new overarching model of vulnerability, but to address the relations between the existing vulnerability studies through developing an ontology that can ultimately be used as a comparative reference system for vulnerability assessments. In the end, the ontology itself, as provided and implemented in the semantic media wiki platform VuWiki, is not just a database for collecting vulnerability studies, but also a heuristic for qualifying vulnerability studies. The vulnerability ontology that forms the backbone of VuWiki helps identify the decisions and assumptions made by the researchers concerning theories, concepts, and methods used in their assessments. In this sense, VuWiki supports scholars in determining the explicit and implicit assumptions made in a particular assessment with respect to a comparative reference system. VuWiki does this by asking the authors (or the person annotating the study) to trace the conceptual lineage(s) of the study and distinguish key components, such as the vulnerability drivers, vulnerable systems, spatial scope, temporal scope, and target users addressed (or not addressed) in the study at hand.

VuWiki is online and available at www.vuwiki.org, and we invite interested practitioners, researchers, and students to visit, use, and enrich the site. With easy accessibility to structured knowledge and the chances associated with being a semantic and collaborative wiki platform, VuWiki can contribute to the dissemination—and use—of existing knowledge as well as to the promotion of data identification, access, interoperability, and the sharing of key sources of information on vulnerability assessment methods throughout the world. Due to the collaborative wiki platform, VuWiki has the potential to link together experts, institutions, and programs that focus on vulnerability assessments, and it is intended that the platform and database will be utilized by the research and practice community. The sustainability of the VuWiki itself depends on its ability to create benefit for its users, but also on its ability to incorporate new knowledge. This means VuWiki must be flexible enough to adapt vulnerability studies from other contexts, for example climate change adaptation, and expand the ontology to make it usable for other vulnerability-related concepts, such as resilience—thereby testing the scalability of the ontology. Furthermore, VuWiki is built on the premise of collaborative authoring, which relies on social incentives and community building to grow and mature as a useful tool for researchers. Thus, a central task in the next stage is to develop and disseminate a promotion strategy in targeting practitioners, academics, and other stakeholders interested in vulnerability assessment to actively contribute and enrich the knowledge base. This will require community-building work, recognition of active contributors, and integration of tools that allow for community-driven ontology development.

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