Ontology Design Patterns for Representing Knowledge in the Disaster Risk Domain

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***Abstract*—The success of disaster risk management efforts depend on the ability of multiple stakeholders to share disaster-related information. Semantic integration of such heterogeneous information requires ontology building. The top-down-approach of ontology building has several disadvantages to knowledge representation. To support the process of ontology engineering, a bottom-up-approach that utilizes modular Ontology Design Patterns (ODPs) with weak dependencies can be used to overcome the disadvantages of the top-down-approach. To bridge the availability gap of patterns for representing disaster knowledge, the study identifies existing and emerging patterns that can be used to organize disaster knowledge. Based on the eXtreme Design (XD) methodology and key informant interviews, Competency Questions (CQs) were listed from domain stakeholders. Consequently, corresponding patterns covering the CQs were also identified and developed. This study identifies emerging patterns such as Event Type ODP for representing risky and hazardous events. The QualityCausation ODP is also identified for representing the causality nature of vulnerability. The resulting patterns are aligned to the DOLCE[1] foundational ontology and can be used to organize data in the disaster domain.**

***Index Terms*—Ontology Design Patterns, Vulnerability, Quality causation, Interoperability**

I. Introduction

The world is changing fast with increasing numbers of both natural and man-made hazards that expose vast vulnerable communities to adverse impacts. Haigh and Amaratunga [12] discuss the need for an integrative approach to disaster management that involves multi-sectoral collaboration to ensure proper management and resourcing of pre-disaster, disaster and post-disaster effort. The success of the integrated disaster management approach depends on the ability of multiple stakeholders to share information so that the right people can make the right decisions at the right time. However, disaster-related information held by different stakeholders is heterogeneous and described in multiple schemas, markup languages, with different vocabularies and conceptualizations. A typical example of such conceptual differences in the domain can be found in [24] and [5]. Ontologies can be used to provide a unified semantic representation of the domain, along with superior capabilities in querying and information retrieval.

Two approaches for ontology engineering exist. First, foundational ontologies have been widely used as a common denominator for ontologies in the disaster domain [19]. These ontologies tend to be abstract, introduce ontological commitments and are difficult for domain experts and novice users to handle [8], [13] without the support of a Knowledge Engineer. Finally, to overcome these limitations, ontology design patterns have been proposed as proven best practices, that are flexible, reusable building blocks for modeling reoccurring tasks [3] thus critical for managing interoperability between heterogeneous data sources. Patterns can also be combined and ultimately aligned with foundational ontologies that act as glue between patterns, making it easy for domain experts to integrate disaster knowledge without the assistance of knowledge engineers. While the Ontology Design patterns(ODPs) community has a portal that lends support to ontology engineering with ODPs, there is still lack of critical mass of patterns/proven best practices [3]. Identification of these patterns could go a long way to supporting ontology engineering, thereby bridging the gap between the demand and availability of ODPs while representing disaster knowledge. While modeling the notion of vulnerability, the problem of modeling forward multiple dependence of quality on other qualities of the same element arises. Therefore, the contributions of this paper are twofold. First, we identify reusable ODPs in the context of disaster management and secondly, we propose a recurrent pattern for representing a quality of an object being dependent on multiple qualities of the same object.

The remaining parts of the paper are organized as follows. Section 2 presents related work on vulnerability, section 3 methods, while section 4 presents results and discussions. Section 5 presents threats to validity and section 6 presents conclusions and future work.

[1]DOLCE - Descriptive Ontology for Linguistic and Cognitive Engineering

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II. Related Work

A. The Concept of Vulnerability

Vulnerability is a key determinant in every "pure" risk assessment [26]. However, multiple definitions and conceptual frameworks of vulnerability have emerged from several distinct groups (such as political economy, social-ecology, vulnerability, and disaster risk assessment, and adaptation to climate change) have different views upon the same concept. The difference in views on vulnerability is a result of the needs confronted by each particular group peculiar issues regarding potential impacts of disasters [7]. Birkman [2] explores the vulnerability spheres (see Fig 1) over the years which indicate an improved understanding of the notion.

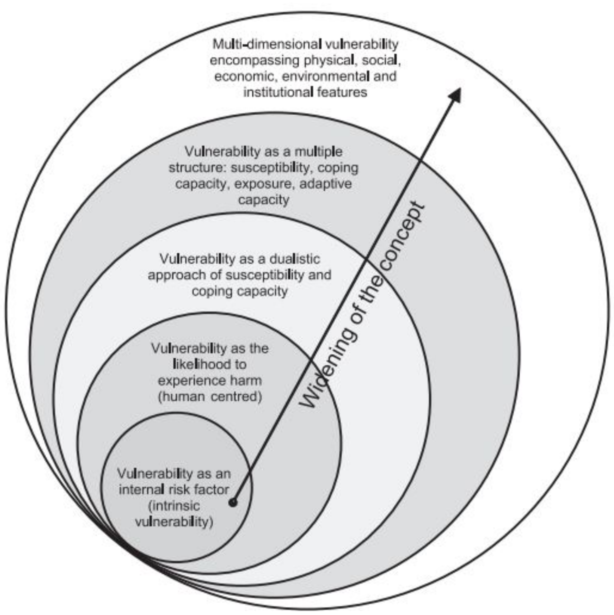

Fig. 1. Key spheres of the concept of vulnerability Source: Birkmann [2]

Despite the existence of various frameworks of defining and assessing vulnerability, at least some common causal factors of vulnerability have been identified [21]. These factors include 1) lack of resilience which constitutes lack of coping and adaptive capacities, 2) susceptibility/fragility as known in disaster risk domain or sensitivity in the climate change domain.

B. Ontology Representation of the Vulnerability Concept

Publishing and retrieval of relevant knowledge or information about hazards, vulnerabilities, capacities requires semantic integration and enhancement of hazard resources to achieve more meaningful results [29]. Multiple international agencies have long emphasized the importance of a unified understanding of the disaster management domain through the creation of glossaries and vocabularies [1], [28]. Vast work also exists on the use of formal ontologies to formalize knowledge in the disaster domain. Some of these ontologies are identified and listed by [10], [19], the Monitor project ontologies [15] etc, . Due to associated commitments and complex alignments, the above mentioned disaster ontologies are not easily reusable in other contexts. This implies that domain experts have to develop new disaster-related ontologies from scratch with the help of knowledge engineers. Gangemi [9] has introduced the concept of ontology engineering based on Ontology design patterns that can be reused as best practices by domain experts. Several ODPs have been developed to represent disaster knowledge notably the hazardous situation [17], the modified hazardous situation [4], the referent Qualities [23] and a host of other reusable patterns developed in other contexts.

Based on Guarino's [11] arguments for qualities in DOLCE against dispositions represented by Basic Formal Ontology (BFO) foundational ontology, vulnerability, fragility (susceptibility) and resilience can be perceived as qualities of an object. The referent quality ODP, a specialization of the Quality Ontology Design Pattern(ODP) [20] is used by Ortmann and Desiree together with the affordance-based theory to represent notions of resilience and vulnerability. The referent Quality ODP asserts that both vulnerability and resilience are qualities of a system defined with reference to an event. Ortman and Desiree [23] adopt the definition of vulnerability as "the extent to which a natural or social system is susceptible to damage", to guide the design. The definition falls short of holistic perspective which indicates both susceptibility and resilience as causal factors of vulnerability explained in [21]. There exists work from [27] and [14] on ODPs for representing causation in events. However, to the best of our knowledge, there is no ODP for representing quality dependence on other quality of the same object.

III. Methodology

This study is based on the context of Uganda which experiences several disasters such as famine, floods, conflict, landslides, and epidemics that affect the most vulnerable communities. Several multi-stakeholder efforts are coordinated by the disaster management office at the office of prime minister. Therefore, in this study we answer the following research questions (RQ);

1) RQ1: What "disaster information requirements" exist among stakeholders in the disaster sector? These requirements are necessary to formulate Competency Questions (CQs) for querying the ontology.
2) RQ2: Which patterns from other contexts can be reused for representing disaster domain knowledge? A number of existing ontologies can be reused to organize disaster-related data, this will enable identify CQs not covered by ontology elements.
3) RQ3: What emerging ontology design patterns can be used to capture disaster management knowledge? CQs not covered by existing ODPs provide motivation for identifying and developing emerging ODPs.

The methodology in Fig 2 adopts the collaborative eXtreme design (XD) method [25] for designing ontology design patterns. This methodology utilizes collaborative principle which includes iterative refinement of functional information requirements expressed as competency questions and contextual statements by users. To answer RQ1, key informant interviews

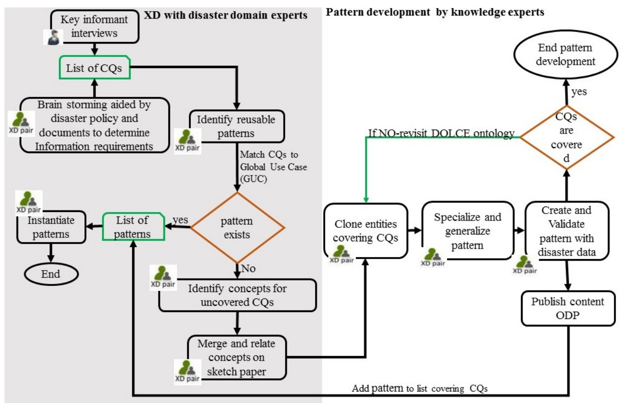

Fig. 2. Methodology used in for pattern Identification

with 4 disaster management officers in office of prime minister was done. In addition five pairs teams of domain experts (stakeholders in the sector) were availed with Uganda disaster management Policy 2010, News bulletins and disaster atlas. Each of the teams was tasked with a role of brainstorming the CQs relevant to disaster management agency and stakeholders in Uganda. The resulting information requirements were coded into themes and converted into competency questions. All the competency questions generated by the teams and key informant interviews were presented to all teams for evaluation until a final list was agreed upon. To answer RQ2, the generated competency question list was used by each of the five teams to identify patterns from existing catalogs. CQs which could not be represented with existing patterns were identified as possible candidates for designing "emerging" patterns. To create new patterns, concepts were identified by each team, merged with their relationships on sketch papers. An agreement was also reached on restrictions before axiomization was done by knowledge expert.

Based on the CQs and sketched relations, we answer RQ3 by exploring the DOLCE top level foundational ontology for ontology elements covering the CQs. The CQs were then cloned and composed with other Content Patterns (CPs). Specialization and generalization was also done to introduce a partial order between CPs defined in terms of their taxonomic order. The resulting patterns were tested with dummy data against competency questions for validation. In case CQs were not fully answered, an error in modeling was assumed to have occurred, thus the process above was repeated until the CQs were sufficiently answered.

IV. Results and Discussions

In this section, the resulting competency questions and patterns for representing disaster knowledge are presented.

A. RQ1: Information Requirements for Capturing Disaster Knowledge

Table I shows a list of functional information requirements captured as Competency questions from key informant interviews and XD brainstorming activity. The Table also shows Ontology Design Patterns that were identified to be existing patterns that were identified during XD as well as emerging patterns which are candidates for formalization. Thirty one (31) CQs were captured in total. The XD methodology presupposes the existence of Competency Questions (CQs) to constrain the scope of knowledge represented by an ontology. However, the CQs in Table I are limited to a section of the disaster community in Uganda. Identified patterns typically reflect information requirements from the community section. Through rigorous elicitation of information requirements, from the broader disaster community, more emerging patterns could be identified for development.

B. RQ2: Patterns for Capturing Disaster Knowledge

Table I shows patterns with the corresponding CQs covered by the patterns. Ten (10) patterns [2] were identified for reuse while representing disaster knowledge based on identified CQs in Table I. During pattern exploration, participants noted an intersection of CQs between different patterns. For instance, the place pattern covering CQs(4) is part of CQs for the Event pattern(CQs1-3) meaning that some ODPs are composed of others. In addition, foundational concepts outside the scope of the CQs left participants confused on which patterns to chose. It would benefit re-usability if such ODPs are expressed in relation to each other. Currently, there is no established mechanism for expressing pattern compatibility and inclusion requirements without making commitments regarding the structure of ODP. This calls for research efforts towards the creation of a pattern language to represent such compositions of patterns, methods and tools for instantiation e.g. the interface based pattern instantiation that would go along way to resolving the impasse of transitivity effects from Owl: imports created during pattern instantiations. In Table I, competency questions (such as CQ 6,7 and 22-26) that were not covered by existing ontology design patterns are labeled as emerging*". The uncovered CQs motivate the need to develop emerging patterns that can be used to represent such notions. Once all possible patterns are identified, they could be instantiated using available methods and tools such as specialization or template based method in XD-webProtege[4] to generate a complete ontology which could be used to create a disaster risk and response application.

C. RQ3: Emerging Patterns for Representing Vulnerability

We scope the study to represent the notion of vulnerability and associated concepts[5] CQs not covered in by existing patterns Table I.

[2]find existing patterns here: http://ontologydesignpatterns.org http://odps.sourceforge.net, Geolink Pattern collection [16]
[4]such as in XD WebProtege http://wp.xd-protege.com/
[5]Find pattern development material here https://mazimweal.github.io/onto/

TABLE I
ONTOLOGY DESIGN PATTERNS COVERING THE DOMAIN CQS

	Competency questions (CQs)	Pattern
1 2 3	Where did hazard occur in 2013? Which hazards occurred between 2013 and 2018 in Uganda? When did the 2010 hazard (e.g landslide) take place? when is it expected to occur?	Event
4	Where did hazard event occur? Which areas are prone to hazards?	Place
5	What are the elements at risk when the hazard occurs? E.g crops, built up areas quantified with land cover/ land use	ValuePartition
6 7	What was the magnitude/ intensity of hazard ? How likely is the hazard occurrence?	emerging*
8 9 10 11 12	What event is likely to be triggered by changes in another event e.g Extreme weather event (EWE)? (Cascading/compound/complex disasters) What activity is triggered by a change in weather events? e.g rockfall triggered by EWE What activity triggers an event/state? e.g rockfall triggers landslide What class of objects could satisfy precondition for rockfall? e.g above average rainfall leads to a rockfall What triggers DRF for a hazard event?	Activity specification
13 14 15	How was the disaster/emergency funded? E.g. who funded compensations? What role do the actors perform E.g. PI, donor, AgencyProgrameManager Which communities/households should receive disaster risk financing (DRF)?	Funding
16 17 18	Which organizations are stakeholders in disaster management? e.g Government of Uganda Who are the actors/agents involved? in disaster management? What role do the actors perform? E.g donors, response etc. In what event?	Organisation, AgentRole
19 20 21	Which communities are more vulnerable to impacts of a given hazard? What fragilities does the community that participates in hazard event exhibit? What coping/adaptive mechanisms are used to reduce vulnerability of an object participating in hazard event?	Quality, Participation
22 23	Which qualities of the community could cause change in vulnerability of the same community? What is the interpretation of the causation relationship between vulnerability, susceptibility/fragility/sensitivity and resilience of a community?	emerging*
24 25 26	Which communities are at risk? should vulnerable groups worry about event x? Whats the likelihood of a risky event will occur and with what impact? e.g low, moderate, High How does risk in a place change over time?	emerging*
27 28 29 30 31	Which communities need to be sensitized about what? when? which media? Which media should be used for sensitization? e.g radio, TV, News bulletins etc Who reports the actual event? What is the affiliation of the reporter When was a hazard event reported for the first time	News Reporting

[3]CQs not covered by existing patterns are denoted by (emerging*) in the Table

Events, as represented by the simple event pattern[6], have only the temporal and spatial parts. However, there are different event classifications (such as the risky and hazardous events) that exhibit extra qualities other than those represented by the simple event pattern. The "EventType" concept (is a kind of social object) that classifies how to interpret an Event in DOLCE is used for pattern creation. In [20], social objects can have abstract qualities. Therefore, the classifying concept (a social object) is specialized to accommodate abstract qualities which are generically represented by the quality ODP in [23]. Fig 3 represents existing patterns with a dotted boundary. The eventType pattern is aligned with the simple Event pattern to access the spatial and temporal parts of the event. Similarly, it can be aligned to the Quality ODP in [23] through the quality stub. The EventType pattern is formalized in OWL2 DL profile (see core axioms in equation 1-5) due to expressivity and decidability considerations. Fig 3 is not the actual pattern but its rather for the benefit of intuition.

[6]Simple event pattern exists at www.ontologydesignpatterns.org

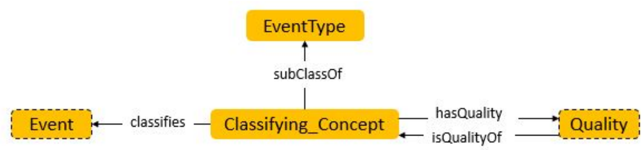

Fig. 3. EventType Pattern

Core Axioms

$$Classifying\_Concept \sqsubseteq EventType \quad (1)$$
$$Classifying\_Concept \sqsubseteq \forall classifies.Event \quad (2)$$
$$hasQuality \equiv isQualityOf^{-} \quad (3)$$
$$Classifying\_Concept \sqsubseteq \exists hasQuality.Quality \quad (4)$$
$$Disjoint(Event, Classifying\_Concept, Quality) \quad (5)$$

Global Use Case(GUC) CQs

1) What are the abstract qualities of a particular EventType that classifies an event?
2) What concepts classify an event?

Local Use Case (LUCs) CQs

The pattern in Fig 3 can be used as solution to local problems such as risky event, hazardous event etc. In hazardous event scenario, the classifying concept "hazardous" is some kind of EventType that classifies an event. The classifying concept hazardous is a socio object/non-physical object that has abstract qualities like magnitude and probability/likelihood.

1) What is the magnitude / likelihood of the earthquake hazard event?
2) What concepts classify an event that is hazardous/risky in nature?

As noted in section II, there exists a causal relationship between resilience, susceptibility/fragility and vulnerability. In the interest of the study the following generic definitions are used in the study.

1) Vulnerability is "the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety

of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt [22].”

2) Resilience is ”The ability of a system to cope with an external factor that undermines it, with the system bouncing back [6].”
3) Susceptibility is defined as the fragilities in a community that influence potential harm from particular hazard impacts.

Vulnerability, susceptibility and resilience are qualities of an object (exposure) that participates in particular hazardous event. Each of these qualities could be represented by combining the Quality ODP and Participant ODP.

However, vulnerability (V) as a quality of an Object is dependent on resilience (R) and susceptibility(S) of the same Object that participates in a hazardous event-(object that could be exposed (E)) i.e V is a function of R, S and E. An increase in susceptibility coupled with an increase in lack of resilience will cause a system/ object to be more vulnerable. However, a change in vulnerability will not cause a change in either fragility or resilience. In effect there is only a forward multiple dependence between resilience, fragility and vulnerability. These notions are qualities of objects that participate in a hazardous event.

We identify a recurrent pattern for representing uni-directional multiple dependence of quality on other qualities of the same object to represent the causal nature of vulnerability (see equation 6-15). To define the QualityCausation ODP, Lehmann et al’s [18] idea of ”specific quality changes can be existentially dependent on others” in DOLCE is adopted. The pattern [7] defines two quality change types (i.e the effect and causal qualities) which **classify** the quality of an object. The ”effect” quality of an object **dependsOn** (one or multiple) ”causal” qualities of the same object. The QualityCausality-Description object is used to **define** each quality change type as indicated in Figure 4.

Core Axioms

$$Cause\_Q1 \subseteq QualityChangeType \quad (6)$$
$$Cause\_Qn \subseteq QualityChangeType \quad (7)$$
$$Effect\_Q \subseteq QualityChangeType \quad (8)$$
$$QualityChangeDescription \subseteq Description \quad (9)$$
$$dependsOn \equiv isDependedOnBy^{-} \quad (10)$$

$$Object \subseteq \exists hasQuality.Quality \quad (11)$$
$$QualityChangeDescription \subseteq \exists defines.QualityChangeType \quad (12)$$
$$Effect\_Q \subseteq \exists dependsOn.(Cause\_Q1 \cup .. \cup Cause\_Qn) \quad (13)$$

$$QualityChangeType \subseteq (=1)classifies.Quality \quad (14)$$

$$Disjoint(Object, QualityChangeType, Quality, Description) \quad (15)$$

The global use case CQs

1) Which qualities could have caused a change in the quality of the same object?
2) What is the interpretation of this causation between qualities?

[7]implementation available at http://w3id.org/gicentre/onto/qualitycausation

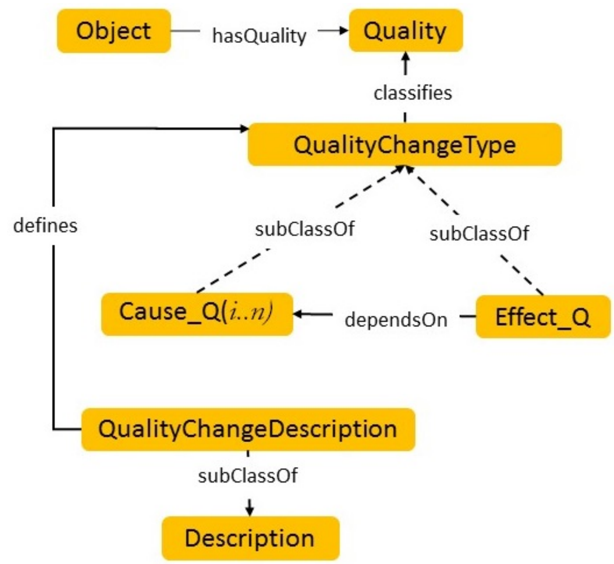

Fig. 4. QualityCausation ODP

3) What quality change types classify quality of an object?

The local use case CQs

1) Which qualities of the community/object that could cause change in vulnerability for the same community?
2) What is the interpretation of the causation relationship between vulnerability, susceptibility/fragility/sensitivity and resilience of a community?
3) What quality change types classify quality of a community?

When this pattern is aligned with the Participant ODP, then it is possible to answer questions in relation to a particular hazard event. For example, which qualities of the community/object that could cause change in vulnerability for the same community that participates in a hazard event? A combination of the Participant and QualityCausation ODPs can be aligned to the hazardous event through event stub in Fig 3.

V. Threats to Validity

Internal Validity: A threat to ”pattern development” is that some patterns become anti-patterns if they are not validated. The patterns chosen for development are validated using SPARQL queries constructed from CQs.

External Validity: The study elicits CQs from the Ugandan context. However, the validated patterns can be reused in other contexts given that classes and object properties are extracted out of the DOLCE foundation ontology[8] which is independent of the local use case. Through continuous rigorous elicitation of functional information requirements with the broader international disaster community, more patterns could

[8]http://www.ontologydesignpatterns.org/ont/dul/DUL.owl
http://www.ontologydesignpatterns.org/ont/dul/IOLite.owl
http://www.loa-cnr.it/ontologies/DOLCE-Lite.owl

be identified for development.

Construct Validity: The XD methods were triangulated with key informant Interviews and literature to overcome threats due to the invalid interpretation of concepts. Interviews with disaster management stakeholders were open-ended to allow the participants give elaborate responses.

Reliability: To achieve reliability of CQs, we involve stakeholders from 5 organizations and triangulate the information requirements with key informant interviews conducted on officers from disaster management agency. Data is also collected by three different paper authors to avoid researcher bias.

VI. Conclusions and Future Work

Semantic integration and publishing for heterogeneous data can benefit from existing and emerging Ontology design patterns to ensure meaningful information search and retrieval. Pattern use will also enable disaster domain experts to populate the global pattern schema based on local use case scenarios depending on data availability, institutional frameworks and policies. The study, identifies possible cases of emerging patterns and develop a quality-causation ODP for representing the causal nature for resilience, susceptibility/fragility and vulnerability. The causal relationship is critical in determining which quality contributes most to vulnerability and risk of the community participating in a hazard event. We conclude that there is a need to develop 1) more emerging patterns from the broader disaster community and 2) mechanisms for representing inclusion requirements for related patterns.

Future work will focus on two aspects. The first aspect will involve continuous and rigorous elicitation of CQs from the broader disaster community, identifying and developing emerging patterns for organizing disaster data. The second aspect will entail the creation of an interface based pattern instantiation mechanism and an ontology-based application for integrating disaster data from heterogeneous sources.

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