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ORIGINAL RESEARCH

A Pattern Driven Approach to Knowledge Representation in the Disaster Domain

Allan Mazimwe[1] · **Imed Hammouda**[2] · **Anthony Gidudu**[1] · **Bernard Barasa**[3]

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Abstract

Access to integrated disaster-related data through querying is still a problem due to associated semantic barriers. The disaster domain largely relies on the top–down approach of ontology development. This limits reuse due to associated commitments and complex alignments within ontologies. Therefore, there is a need to utilize a bottom-up approach that reuses patterns for representing disaster knowledge. To bridge the availability gap of patterns for representing disaster knowledge, this study identifies existing and emerging patterns for reuse while organizing disaster data from multiple sector stakeholders. Based on the eXtreme Design (XD) methodology and key informant interviews, competency questions (CQs) were elicited from domain stakeholders. The CQs are matched with existing patterns from other contexts. Emerging patterns (e.g the Event Classification and Quality Dependence Description for Objects) are also developed for CQs not captured and subsequently tested using SPARQL queries characterising the CQs. It is in this context that this paper presents a characterisation of disaster risk knowledge using CQs and corresponding patterns (reusable and emerging) covering the knowledge. Accordingly, we illustrate a pattern-driven use case to organise drought hazard data for early warning purposes. This provides a powerful use case for adopting a pattern-based approach to knowledge representation in the disaster domain.

Keywords Ontology design patterns · Hazard · Vulnerability · Risk

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✉ Allan Mazimwe
allanmazimwe@cedat.mak.ac.ug

Imed Hammouda
imed.hammouda@medtech.tn

Anthony Gidudu
agidudu@cedat.mak.ac.ug

Bernard Barasa
barasa@kyu.ac.ug

[1] Department of Geomatics and Land Management, Makerere University, Kampala, Uganda

[2] Mediterranean Institute of Technology, South Mediterranean University, Tunis, Tunisia

[3] Department of Geography and Social Studies, Kyambogo University, Kampala, Uganda

Introduction

The world is changing fast due to climate change-induced hazards like floods, droughts, landslides etc. The impacts of these hazards are felt most by vulnerable communities resulting in disasters. Managing disasters require integrated efforts from multiple domain actors who play different but complementary roles across spatial and temporal scales to reduce community risks [1, 2]. However, these efforts are often difficult due to the lack of a common understanding among actors with different roles and profiles which further limits integration and access to disaster-related information. This is because 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 [3, 4]. Ontologies can be used to provide a unified semantic representation of the disaster domain as well as maintain the disaster knowledge base necessary for information integration and retrieval.

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The top–down ontology modelling approach based on foundational ontologies has been widely used as a common denominator in the disaster domain [5, 6]. Such ontologies are associated with undesired commitments that will often make their reuse in other contexts difficult. An example of such commitments includes; complex alignments, lack of comprehensive coverage of domain requirements [7, 8] and expressivity etc. To overcome these limitations, a bottom-up approach that composes a set of proven best practices known as ontology design patterns (ODPs) has been elaborated in [9]. These best practices allow disaster domain experts to learn from similar ontology design problems already faced by others. For instance, patterns developed in a non-disaster context can be specialized and reused to model knowledge in a drought hazard task. Composition of ODPs to create the hazard-specific ontology minimizes ontological commitments. Moreover, this makes it easy for disaster domain experts to integrate and reuse existing knowledge bases without the assistance of knowledge engineers. Therefore, ODPs have the potential to provide flexible and reusable building blocks for modelling reoccurring ontology design tasks in the disaster domain.

While the ODPs community has a pattern catalogue that supports ontology engineering, there is still a lack of critical mass of patterns/proven best practices [9]. 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 domain knowledge. Therefore, the contributions of this paper are as follows. First, we characterise disaster risk knowledge and identify reusable patterns for representing it. Secondly, we propose emerging patterns that can be reused to represent the classification of event and quality dependence for objects participating in a hazardous event. Finally, we provide a pattern-driven use case scenario illustrating the integration of data associated with a drought hazard for early warning purposes.

The remainder of this paper is organized as follows. Section "Related Work" presents related work. Section "Methodology" introduces our research methodology. Section "Results and Discussion" presents and discusses our results. Finally, Section "Conclusions and Future Work" concludes the paper and outlines areas for future research.

Related Work

To support the interdependent roles amongst actors, multiple international agencies have long emphasized the importance of a unified understanding of the disaster management domain by creating common glossaries, vocabularies and thesauri [10, 11]. However, these are not expressive enough to explicitly capture domain knowledge [5]. This makes it difficult to retrieve and integrate data/information meaningfully.

Ontologies in the Disaster Management Domain

A large corpus of literature exists on the use of formal ontologies to formalize knowledge in the disaster management domain. In the Hazard, Vulnerability Risk (HVR) portion of the disaster management cycle, work has been done to conceptualize hazard [12], vulnerability [13] and risk [14–16] concepts. Additionally, surveys conducted by [5, 6] show that there exists several formal ontologies and vocabularies for capturing, representing and integrating heterogeneous data in the emergency management sub-domain. Artificial Intelligence (AI) logic rules lack expressivity to sufficiently capture domain knowledge [17]. Therefore, previous studies have also demonstrated ontology creation for organising knowledge in AI systems to enable effective answering of questions and generation of hypotheses during disaster response operations. For instance, [18, 19] used ontologies for crisis event detection on social media streams, knowledge extraction from satellite imagery for disaster monitoring [20, 21], and probabilistic hazard analysis [22]. Additionally, learning algorithms have also been used to generate new ontologies from disaster corpus but with limited expressivity [8].

Typically, the creation of new ontologies is either motivated by the fact that existing ontologies and terminologies are discipline-specific and consequently not comprehensive [7, 8] or by the lack of expressive power to capture requirements in the disaster management domain [5, 23]. Therefore, the commitments and possibly complex alignments associated with these disaster ontologies make them not easily reusable in other contexts. This implies that disaster domain experts will often have to create ontologies from scratch with the help of knowledge engineers. To overcome these limitations, [24] has introduced the bottom-up engineered concept of reusable ODPs created in different contexts.

While ODPs provide an opportunity for domain experts to reuse existing best practices without requiring the help of knowledge experts, limited literature exists on their identification and reuse in the context of disaster management. Existing disaster context specific work on the identification of patterns includes the hazardous situation [25], the modified hazardous situation [26] used to represent hazardous situations, and the referent qualities [27].

Ontology Representation of Disaster Risk Knowledge

Actors in the disaster management domain are refocusing their attention from reactive response to proactive preparedness and prevention [2]. The disaster risk reduction (DRR) domain comprises key concepts namely; disaster, risk, hazard, vulnerability, and resilience [28] that are critical to this observation. Sales et al. [16] provided a conceptualization of "pure" risk assessment for which vulnerability is an essential component. Various frameworks in the literature [2, 29, 30] define vulnerability as a function of resilience, resistance or susceptibility concepts. These concepts are fuzzy and are not easily operationalizable in the real world.

Vulnerability in itself is a disposition that cannot cause a disaster event to occur but rather describes base characteristics of a community for which exposure from a triggering event will induce a disaster. Based on Guarino's arguments [31] for qualities in Descriptive Ontology for Linguistic and Cognitive Engineering ontology (DOLCE) against dispositions represented by Basic Formal Ontology (BFO) foundational ontology, vulnerability and capacity can be perceived as qualities of an object. The referent quality ODP, a specialization of the Quality Ontology Design Pattern [32] is used by Ortmann and Desiree [27] 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. The monitor project [14] proposed conceptualisation of disaster risk knowledge and suggests that detailed examination of capacity/resilience and vulnerability will result in the vague and fuzzy vulnerability conceptualization. A limitation of Kollarits et al. [14] is that they neither adopt a design pattern based approach to ontology development nor provide physical ontology artefacts. This limits reuse of existing domain ontologies in contexts other than disaster management.

In the DRR context, an object/community participating in a hazard event has qualities like damage potential that depends on value (perceived as social-economic) and vulnerability of the same object. There exists work from [33, 34] on ODPs for representing causation in events. Therefore, to the best of our knowledge, there is no generic ODPs for representing quality causation and event types which can be reused in other contexts. In this paper, we do not only illustrate the use of ODPs to organise disaster data but also identify emerging patterns that can be reused in other contexts to represent quality dependence on other qualities of the same object and event classifications.

Methodology

This paper is a normative case study based on the context of Uganda, a country which experiences several hazards. These hazards include drought, earthquakes, floods, land conflict, landslides, and epidemics that affect the most vulnerable communities. Under the "national policy for disaster preparedness and management for Uganda" of 2011, particular institutions lead the monitoring and reporting of risks for each hazard. The lead institutions work in close collaboration with other relevant sectoral bodies and co-opted stakeholders. Through the National Platform for Disaster Risk Reduction (DRR)[1], the department of disaster preparedness and management under the office of the prime minister coordinates efforts of multiple stakeholders in the sector. For actors in the sectors to achieve their complementary roles, integration and reuse of data/information amongst themselves is critical. For example, understanding drought risk will typically require data access from multiple sector stakeholders. Therefore, in this study we answer the following research questions;

1. RQ1: Which "disaster user information requirements" are required/exist among stakeholders in the disaster sector? These requirements are necessary to formulate competency questions (CQs) that characterise knowledge in the disaster domain.
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: Are there any emerging ODPs that can be used to capture disaster management knowledge? CQs not covered by existing ODPs provide motivation for identifying and developing emerging ODPs.

To identify ODPs, we adopt the collaborative eXtreme Design (XD) method [35, 36] shown in Fig. 1. This methodology utilizes the collaborative principle that includes iterative refinement of functional information requirements expressed as CQs and contextual statements by users.

To answer RQ1, four Key informants were purposively selected from staff within the Department of Preparedness and Disaster Management in the Office of Prime Minister for an interview on sectoral information requirements. This study also reviewed key documents in the disaster domain in the country. These include the district multi hazard and vulnerability profiles, the Uganda disaster preparedness and management Policy of 2011, monthly early warning bulletins, Disaster Information Management System (DesInventar) reports, the National disaster atlas for Uganda and minutes of DRR platform meetings between 2012 and 2018. To extract more data for the XD methodology, we constituted five teams with each comprising a pair of domain experts

[1] Also known as the Disaster Sector Working Group (WG) which is an Inter-Agency technical committee comprised of focal point technical officers in stakeholder institutions. This WG is chaired by the Office of the Prime Minister.

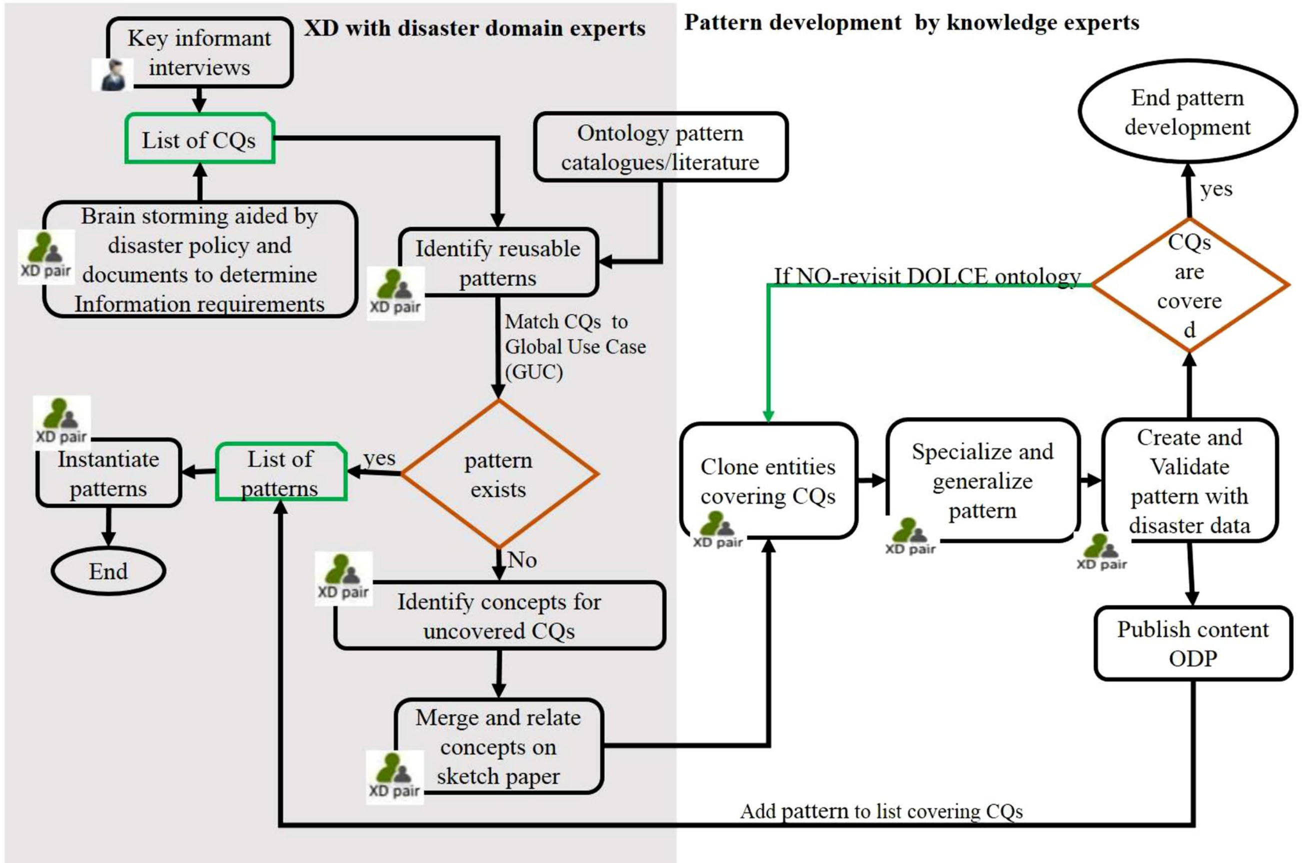

Fig. 1 Methodology used for pattern Identification

(stakeholders in the domain). The teams were tasked with the role of brainstorming information requirements in the context of disaster risk management in Uganda. The resulting information requirements were coded into themes and converted into CQs. 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 and merged with their relationships sketched on papers. An agreement was also reached on restrictions before axiomization was done by a 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 and related restrictions. The CQs were then cloned and composed with other Content Patterns (CPs). Specialization and generalization were also done to introduce a partial order between CPs defined in terms of their taxonomic order. The resulting patterns were tested with disaster domain data against CQs 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. To illustrate the pattern-driven approach for disaster risk domain, we used a concrete data integration scenario amongst stakeholders to achieve the goal of early warning for meteorological drought hazard.

To ensure pattern quality, we considered functional suitability, reuse and interoperability indicators in Karl [37]. We performed functional suitability by running the pattern OWL file (see links to owl files in Tables 5 and 6) in Protege HermiT owl reasoner to prove axiom satisfiability[2]. Also, patterns were validated against specific requirements [36] by constructing SPARQL queries (see Section "RQ3: Emerging Patterns for Representing Disaster Risk Knowledge") that characterise pattern competency questions. Emerging patterns were triplified with domain data and queried with SPARQL queries to generate information covered by the respective Competency Question.

[2] http://www.hermit-reasoner.com/

Table 1 Ontology design patterns covering the domain CQs

ID	Competency questions (CQs)	Pattern
1	Where did hazards occur in 2013?	
2	Which hazards occurred between 2013 and 2018 in Uganda?	Event (ID 1–3)
3	When did the 2010 hazard (e.g landslide) take place?	
4	Where did the hazard event occur? Which areas are prone to hazards?	Place (ID 4)
5	What are the elements at risk that participate in a hazard Event? E.g population, infrastructure Agriculture, environment	Participation (ID 5)
6	What events are classified as hazardous events? When is it expected to re-occur (return period)	Emerging (ID 6–7)*
7	What is the magnitude/ intensity of a hazardous event?	
8	What event is likely to be triggered by changes in another event e.g Extreme weather event (EWE)? (Cascading/compound/complex disasters)	Activity specification (ID 8–12)
9	What activity is triggered by a change in weather events? e.g rockfall triggered by EWE	
10	What activity triggers an event/state? e.g rockfall triggers landslide	
11	What class of objects could satisfy precondition for rockfall? e.g above-average rainfall leads to a rockfall	
12	What triggers DRF for a hazard event?	
13	How was the disaster/emergency funded? E.g. who funded compensations?	Funding (ID 13–15)
14	What role do the actors perform E.g. PI, donor, AgencyProgrameManager	
15	Which communities/households should receive disaster risk financing (DRF)?	
16	What are the key stakeholder organizations in disaster risk management in Uganda?	Organisation (ID 16)
17	Who are the actors/agents involved? in disaster risk management?	AgentRole (ID 17, 18)
18	What role do the actors perform? E.g donors, response etc. In what event?	
19	How vulnerable are communities to the impacts of a given hazard?	
20	What is the social economic value of elements that could be affected by hazard?	Quality (ID 19, 20)
21	What is the damage potential for elements participating in hazard event?	Participation (ID 21)
22	What is the paramerization of a quality (vulnerability, value, damage potential) regions?	RegionParameter (ID 22)
23	Which qualities (value,vulnerability) affect the outcome of another quality (damage potential) of the same element at risk?	Emerging (ID 23, 24)*
24	What is the interpretation of the causation relationship between qualities (i.e value/vulnerability/damage potential) of an object participating in a hazard event?	
25	What is the potential risk of an object that participates in an event ? Note: Risk is dependent on damage and hazard potential.	Emerging (ID 25, 26)*
26	What is the interpretation of relationship between qualities (Risk/damage potential/hazard potential)	
27	What is the parameterisation of risk i.e low, medium, high?	RegionParameter (ID 27)
28	Which communities need to be sensitized about what? when? which media?	News Reporting (ID 28–32)
29	Which media should be used for sensitization? e.g radio, TV, News bulletins etc	
30	Who reports the actual event?	
31	What is the affiliation of the reporter	
32	When was a hazard event reported for the first time	

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

Qualitatively, pattern reuse is supported by documentation in Tables 5 and 6 as proposed by Karima et al. [38]. Moreover, we express the patterns using DOLCE foundational ontology concepts to facilitate pattern reuse in different domains as well as alignments during instantiation (interoperability).

To ensure construct validity and reliability, methods of data collection were triangulated (i.e through the use of key informant interviews and document review) in the XD methodology. Interviews with disaster management stakeholders were open-ended to allow the participants to contribute elaborate responses. This facilitated the extraction of as much domain requirements as possible to overcome threats due to the invalid interpretation of concepts during pattern identification.

Results and Discussion

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

RQ1: Information Requirements for Capturing Disaster Knowledge

Table 1 shows a list of functional information requirements captured as CQs 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 two (32) 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 1 are limited to understanding disaster risk for early warning and preparedness purposes. Identified patterns typically reflect disaster risk information requirements. Through rigorous elicitation of information requirements, from the broader disaster domain[3], more emerging patterns could be identified for development.

RQ2: Patterns for Capturing Disaster Risk Knowledge

Table 1 shows patterns with the corresponding CQs covered by the patterns. Ten (10) patterns[4] were identified for reuse while representing disaster knowledge based on identified CQs in Table 1.

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 ODPs. This calls for research efforts towards a mature implementation 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 instantiation. In Table 1, CQs (e.g CQ 6, 7 and 22–26) that were not covered by existing ODPs 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. For instance, the specialization or template-based methods in Hammar [40] can be used to create ontologies for organising disaster-related data.

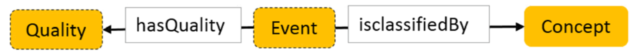

Fig. 2 EventClassification Pattern

RQ3: Emerging Patterns for Representing Disaster Risk Knowledge

This section presents emerging patterns for CQs with no covering patterns (see Table 1) and illustrates their instantiation to organise disaster risk domain data. These patterns allow integration of multi-sectoral data to support early warning efforts.

Event Classification Pattern

A simple event has a single direct quality of temporal location and an indirect quality of spatial location inherited from objects that participate in the event [32]. Similarly, there exist events that can be classified by a concept (a kind of social object) and have additional unique qualities. For instance, an Event classified as a hazard will typically have qualities such as magnitude, probability and hazard potential in addition to those provided in the simple event (i.e. time and place). In this case, we suppose an event inherits indirect qualities of a social object. Therefore, the classifying ODP is specialized to accommodate the event entity and abstract qualities that are generically represented by the quality stub.

For the benefit of intuition, Fig. 2 presents the emerging EventClassification pattern wherein stubs represented with dotted boundaries can be instantiated as stand-alone patterns. The EventClassification pattern is further formalized in OWL2 DL profile (see core axioms in Eqs. 1–4) due to expressivity and decidability considerations.

Core Axioms

$$hasQuality \equiv isQualityOf^{-} \tag{1}$$

$$classifies \equiv isClassifiedBy^{-} \tag{2}$$

$$Event \sqsubseteq \exists hasQuality.Quality \tag{3}$$

$$Disjoint(Event, Concept, Quality) \tag{4}$$

Global use case (GUC) CQs

The following global use case CQs (CQs) characterise the knowledge in the EventClassification pattern.

[3] Other sub domains include emergency response and relief, disaster recovery and reconstruction, etc.

[4] Find existing patterns here: http://ontologydesignpatterns.orghttp://odps.sourceforge.net, Geolink Pattern collection [39].

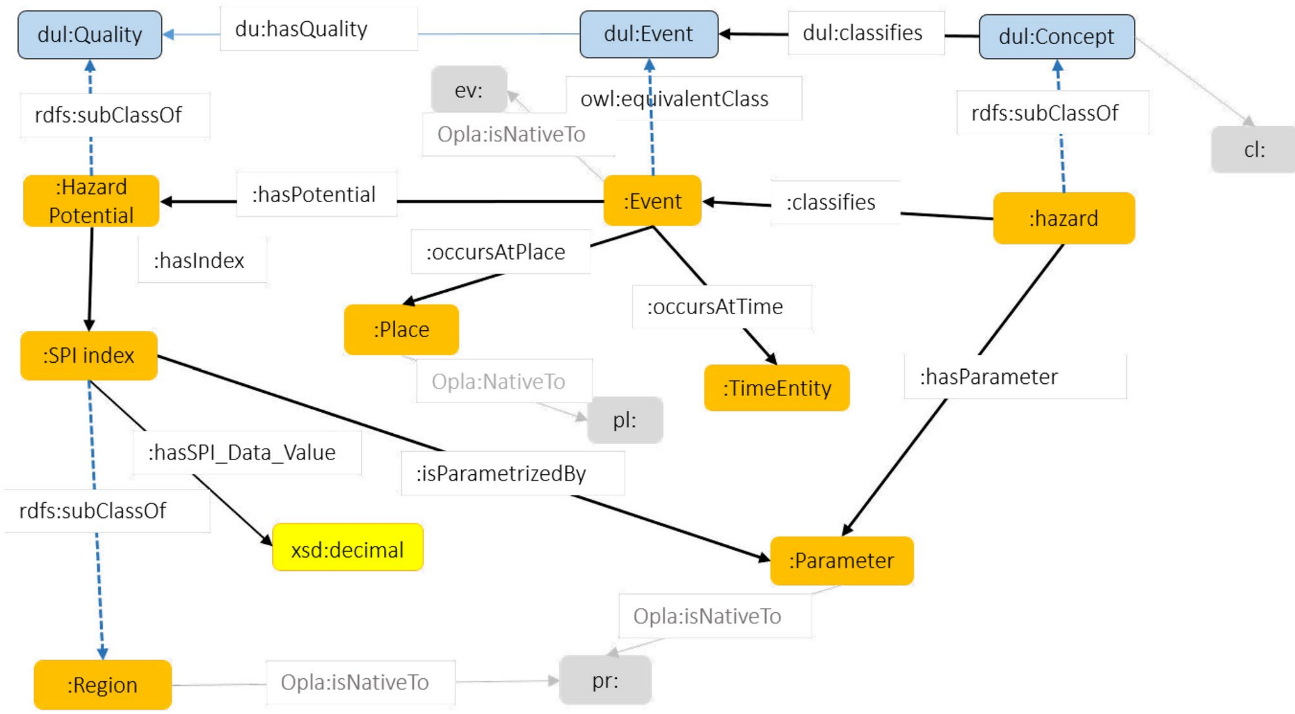

Fig. 3 Instantiating of ontology design patterns to organize meteorological data

1. Which Concept is used to classify/categorize an Event?
2. What are the Qualities of an event classified by a Concept?

The EventClassification pattern uses DOLCE foundational ontology concepts with a minimal number of classes and axioms to avoid over-commitment and support pattern re-usability in different contexts. Proof of satisfiability for axioms 4–7 is achieved by running the pattern[5] in HermiT reasoner. The SPARQL query queries triplified EventClassification pattern to generate expected results as characterised in the CQs[6].

```
PREFIX ecp:<http://w3id.org/gicentre/onto/EventClassification_v1.0#>

SELECT ?x ?y  ?q
WHERE {
      ?x rdf:type ecp:Event;
                  ecp:isClassified ?y;
                  ecp:hasQuality ?q.
        }
```

[5] Find EventClassification pattern implementation at https://w3id.org/gicentre/onto/EventClassification.owl.

[6] Find triplified EventClassification pattern example data here w3id.org/gicentre/onto/EventClassificationTest.owl.

Table 2 Prefixes for instantiation in Fig. 3

	Prefixes
Opla:	http://ontologydesignpatterns.org/opla#
:	http://w3id.org/gicentre/onto/HazardousEvent#
pr:	http://www.ontologydesignpatterns.org/cp/owl/parameterregion.owl#
cl:	http://www.ontologydesignpatterns.org/cp/owl/classification.owl
pl:	http://schema.geolink.org/dev/place#
ev:	http://schema.geolink.org/dev/event#
dul:	http://www.ontologydesignpatterns.org/ont/dul/DUL.owl#

Local use case scenario

To further test the pattern in Fig. 2, we explored the use of a local use case example to infer potential events (e.g risky and hazardous events) from extreme weather events. In this paper, we particularly use inference of drought hazards from extreme weather events to illustrate the instantiation of the EventClassification pattern. A weather event that occurs in time and place can be classified as hazardous if it possesses a set of qualities which include the hazard potential that is dependent on severity, magnitude/intensity of harm to exposed elements. To define a drought from extreme weather events, we represent the potentiality of its occurrence using the Standardized Precipitation Index (SPI) [41]. The World Meteorological Organization (WMO) [42] provides a guideline for parameterizing the magnitude of weather events and subsequently infer drought events based on SPI threshold values (see Table 4). Thresholds for SPI values are dependent on historical values for a period of 1 to 3 months for which values less than -1 are droughts.

To infer drought events, we instantiate the EventClassification pattern in Fig. 3 together with associated patterns such as Event, Place, Quality and RegionParameter patterns. The pattern composition is annotated with OPLa ontology by Hitzler et al. [43] using the *Opla:isNativeTo property* to enable automatic identification for reused ontology design patterns. Table 2 presents prefixes to the pattern composition in Fig. 3. Besides, the resulting Ontology is aligned to DOLCE top-level concepts to ensure interoperability (see alignments in Tables 7 and 8). The ontology is then triplified with meteorological data to create a knowledge base[7] from which we can infer hazardous events using the SPARQL query below.

```
prefix : <http://w3id.org/gicentre/onto/HazardousEvent#>

SELECT ?x ?conc  ?SPIvalue ?par
           WHERE {
             ?x rdf:type :Event;
      ##event has potential
            :hasPotential ?p;
##event classification by concept
           :isClassifiedBy ?conc.
        ?p :hasIndex ?spi.
        ?spi :hasSPI_Data_Value ?SPIvalue.
##parametrisation of Standardized precipitation index  values
        ?spi :isParametrizedBy ?par.
}
```

[7] Find the full triplified ontology at http://w3id.org/gicentre/onto/HazardEventClassificationData.owl.

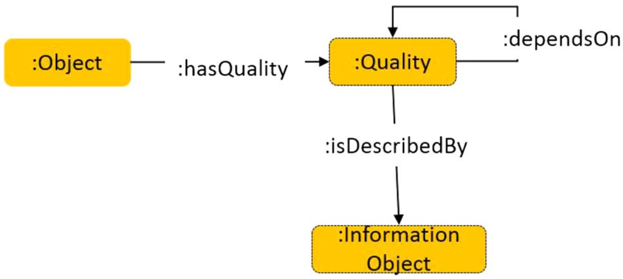

Fig. 4 QualityDependence ODP

Using the SPARQL query above, we can answer the following local use case questions.

- What Concept is used to classify/categorize a hazardous Event? Such concepts include drought, dry spell, late start, etc that characterise extreme weather events.
- What is the potential/magnitude of an event classified as hazardous?

Since we have achieved an instantiation and answered questions in another context (known scenario), the pattern in Fig. 2 is finally documented using the standard pattern template in Table 5 and with the ontology design pattern annotations schema[8]. Similarly, the pattern in Fig. 2 can be used to represent the qualities of other potential hazard events. For example, such hazard events include extreme precipitation, heat/cold waves, and flooding among others in the context of disaster risk. These potential hazard events have qualities which include spatial, temporal and magnitude/intensity probability of occurrence.

Quality Dependence Description for Objects

In Lehmann et al. [44], objects possess qualities (e.g. colour, shape) whose changes can affect (or be affected by) other aspects of that or another object. For instance, a change in the size of an object will cause a change in spatial location but not vice versa. Similarly, an object that participates in a hazard event has qualities such as vulnerability, Value[9] of objects affected before exposure and damage potential after exposure. Typically, highly valued and vulnerable objects will potentially result in more damage to the environment/object when exposed to a hazardous event.

Consequently, there is a backward multiple dependence of damage potential on Value and Vulnerability but not vice versa. However, each of these qualities can be described and realized differently due to different frameworks, implementation formula and assumptions that exist. Based on these facts, we identify a recurrent pattern for representing descriptions and realizations for qualities of an object that depend on each other. For the benefit of intuition, Fig. 4 presents the emerging pattern which defines qualities of an object that depend on each other, together with their information objects and realization. A maximum of one information Object implemented by the InformationObject pattern describes a quality. In this pattern, an object has some quality that depends on another quality of the same object. The property "dependsOn" is considered transitive. The resulting pattern is a specialization of the affected by pattern that includes an information object about each quality. In Fig. 4, the doted stubs represent existing patterns.

Core axioms

$$Object \subseteq \exists hasQuality.Quality \tag{5}$$

$$hasQuality \equiv isQualityOf^{-} \tag{6}$$

$$Quality \subseteq \exists dependsOn.Quality \tag{7}$$

$$dependsOn\ o\ dependsOn \subseteq dependsOn \tag{8}$$

$$Quality \subseteq (=1) isDescribedBy.InformationObject \tag{9}$$

$$Disjoint(Object, Quality, InformationObject) \tag{10}$$

The Global Use Case CQs

The following CQs characterise knowledge in the qualityDependenceDescription pattern.

1. Which quality of an object is dependent on other qualities of the same object?
2. What is the interpretation/description of a quality and its dependence on other qualities?

The SPARQL query below answers CQs characterising knowledge in the pattern[10].

[8] http://www.ontologydesignpatterns.org/schemas/cpannotationschema.owl

[9] The value represents the measurable dimension of the social-economic value of an object participating in an event.

[10] Find triplified pattern here http://w3id.org/gicentre/onto/QualityDependenceDescription.owl.

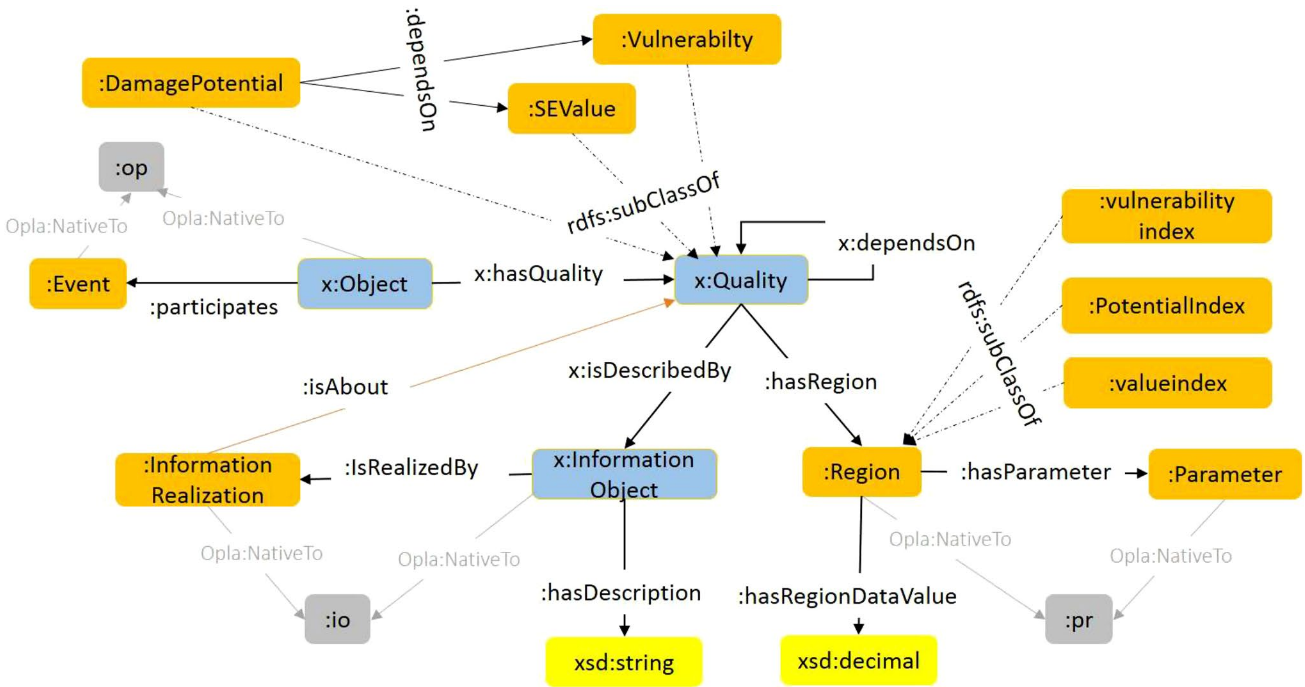

Fig. 5 Pattern composition to organize sectoral vulnerability and potential damage data

Table 3 Prefixes of vulnerability and damage potential ontology composition in Fig. 5

	Prefixes
:	http://w3id.org/gicentre/onto/VVD#
op:	http://www.ontologydesignpatterns.org/cp/owl/participation.owl#
pr:	http://ontologydesignpatterns.org/cp/owl/parameterregion.owl#
x:	http://w3id.org/gicentre/onto/dependencePattern#
io:	http://www.ontologydesignpatterns.org/cp/owl/informationrealization.owl#

```
Prefix x: <http://w3id.org/gicentre/onto/dependencePattern#>

 SELECT ?o  ?pot ?Q ?y ?d WHERE {
      ?o rdf:type x:Object;
           x:hasQuality ?Q.
#query for quality descriptions
            ?Q x:isDescribedBy ?y.
          ?y x:hasDescription ?d.
#query quality dependence
            ?pot x:dependsOn ?Q
}
```

The local use case

As noted in Section 2, vulnerability is difficult to operationalise though we shall assume that it is definable especially when looked at not in detail. Thus a more practical definition from [14] is adopted for characterising vulnerability i.e "Vulnerability is defined as the quality of an

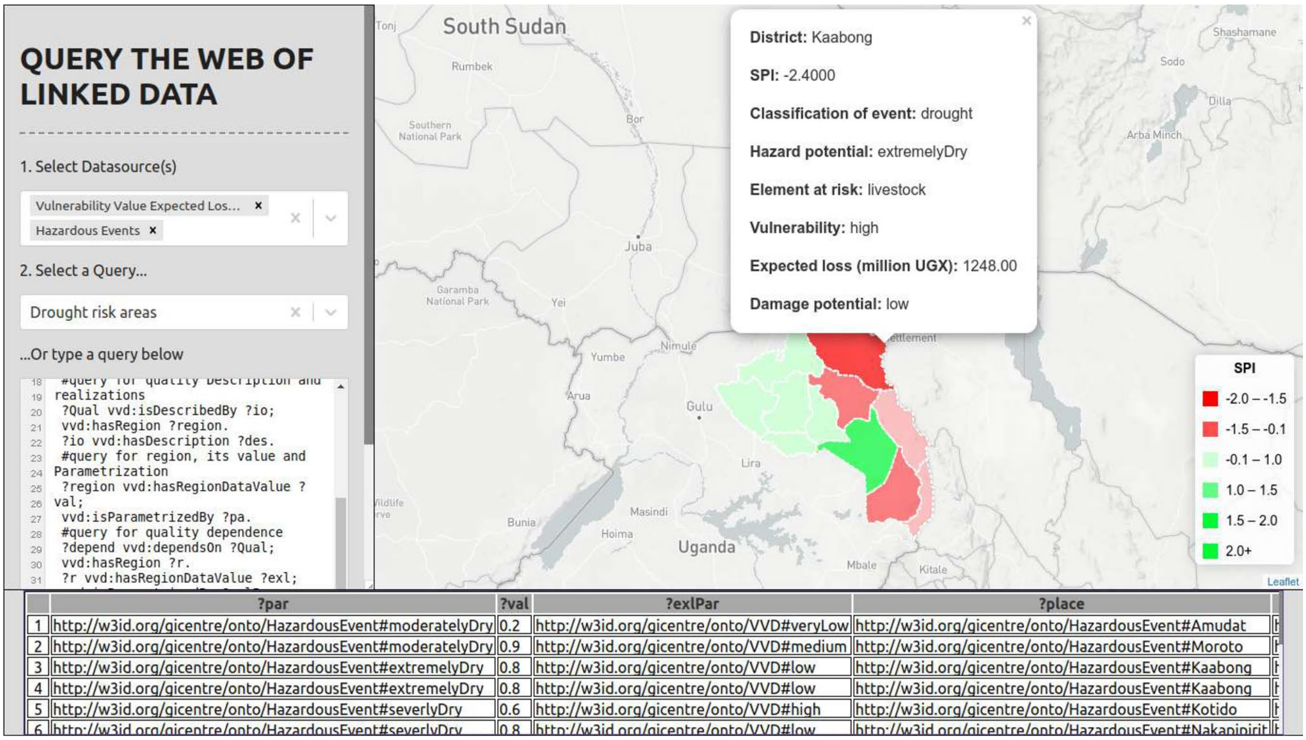

Fig. 6 Illustration of integrated access to hazard data organised using ODPs

object[11], that describes its probability of getting harmed in an event".

From the definition above, damage potential (P) as a quality of an object is dependent on vulnerability (Vul) and value (V) of the same Object participating in a hazardous event i.e there is a causal relationship between (Vul, V) and P. Each of these qualities can be described and realized differently due to different risk/vulnerability frameworks, implementation formula and assumptions that exist. Therefore, each quality carries an information object showing the description and its realization. In Fig. 5, we illustrate the local use scenario by instantiating the quality dependence description pattern to represent DRR knowledge by composing it with the Quality ODP via the quality stub, RegionParameter, Participation and Event patterns[12]. Similarly, the composition uses the *OPLa:isNativeTo* property to enable automatic identification for reused ontology design patterns.

Table 3 presents prefixes to the pattern composition in Fig. 5 to organize vulnerability, value and damage potential data.

The SPARQL query below on the triplified pattern composition will typically answer the following questions about an object participating in a hazardous event.

1. Which of these qualities (vulnerability, value and potential) of an object affects the other?
2. What is the description/interpretation of qualities of the community/object (i.e vulnerability, value and damage potential) and their dependence?

```
prefix :<http://w3id.org/gicentre/onto/VVD#>
SELECT * WHERE {
                ?o rdf:type :Object;
                       :participates ?ev;
                      :hasQuality ?Qual.
#query for quality Description and realizations
                 ?Qual :isDescribedBy ?io;
                    :hasRegion ?region.
                 ?io :hasDescription ?des.
                    #:isRealizededBy ?IR
#query for region, its value and Parametrization
                 ?region :hasRegionDataValue ?val;
                        :isParametrizedBy ?pa.
#query for quality dependence
                  ?depend :dependsOn ?Qual.
}
```

[11] The concept of vulnerability can be applied on either physical and social objects.

[12] Find the pattern composition here; http://w3id.org/gicentre/onto/QualityDependenceCompositionData.owl.

Furthermore, the query above will answer the following questions based on the composition in Fig. 5 (i.e. composition comprises the QualityDependenceDescription, Quality, RegionParameter, Participation, and InformationObject patterns).

- How vulnerable is the community/object that participates in a hazardous event?
- What is the socio economic value of objects/community that could be affected?
- What is damage potential (expected losses) of the community/object that participates in a hazardous event given the value and vulnerability?

The composition in Fig. 5 uses DOLCE foundational concepts that act as glue during instantiation (see alignment in Tables 9 and 10). After successfully testing CQs for local use case scenario, the QualityDependence description pattern is finally documented using standard pattern template in Table 6. The pattern implementation is also annotated with the ontology design annotation schema.

Implications for Research and Industry

Table 1 presents CQs characterising disaster risk knowledge together with corresponding patterns from other contexts. We also present emerging patterns for organising vulnerability, economic value and expected loses/damage potential data for communities (object) participating in hazardous meteorological events. Future work could explore the characterization of knowledge and identification of patterns in other sub-domains of disaster management cycle. other than HRV. Such sub-domains include disaster prevention and mitigation, disaster early warning and preparedness, disaster relief and emergency response (humanitarian crisis response), etc. This will enable disaster domain experts reuse existing ontology patterns to create high-quality ontologies with ease while at the same time solving the lack of comprehensive and expressive ontologies [5] for reuse.

In Section 4.3, we develop emerging patterns for 1) classifying hazardous extreme weather events, 2) representing quality dependence (i.e. vulnerability, value and damage potential) regardless of framework and realization. These patterns are queried with SPARQL to answer CQs characterising the knowledge they represent. The local use case scenarios achieved by instantiation with associated patterns are critical to ensure trust during identification. Therefore, two local use case ontologies (Figs. 3, 5) characterising disaster risk knowledge are created. This implies that not all patterns in Table 1 are instantiated considering that they belong to the greater disaster risk domain. The hazard classification, vulnerability, value and damage potential composition scenarios in Figs. 3 and 5 provide a powerful use case example for disaster sector stakeholders to further instantiate other identified patterns.

Data from multiple stakeholders can be organised with patterns and decentralized at an organisation level based on different policies. Examples of such data includes; administrative data provided by the local government, agricultural price data by organisations like Kimetrica, vulnerability by sectoral departments, and meteorological data by the meteorological authority. A federated query on decentralized data pods (see architecture in Mazimwe et al. [45] can be made to answer more meaningful questions in the sector than would be possible by single datasets. In this way, patterns provide building blocks for domain experts to support case by case data integration in the disaster sector depending on the availability of policies. This is key in promoting sustainable and seamless data integration that is critical for objective allocation of resources and coordination of efforts for disaster prevention, preparedness and mitigation.

Figure 6, illustrates a prototype user interface implementation based on an integration of the Comunica [46] and React-Leaflet APIs. This prototype allows federated querying for linked data pods belonging to different DRR stakeholder institutions via a web browser (the code is accessible from http://tiny.cc/leafletrdf). Examples of drought early warning questions supported through querying over data pods include;

1. Which areas have weather events inferred as droughts based on SPI values?
2. What is the hazard potential of the drought?
3. What elements are at risk (i.e. exposed to the extreme weather event)?
4. How vulnerable are these elements that participate in the extreme weather event? What is the interpretation of the vulnerability (e.g. framework used)?
5. What is the expected loss (depends on value and vulnerability)? What is the classification of damage potential?

Risk is determined by the Hazard potential, Vulnerability, and Exposure (Value) wherefrom a combination of value and vulnerability represents damage potential. Therefore, risky areas in Fig. 6 are those areas where a federated query[13] over extreme weather data[14] and Vulnerability data[15] indicates colocation of high hazard potential and damage potential. Nevertheless, the creation of the SPARQL query above is tedious given that Comunica provides no module support

[13] https://mazimweal.inrupt.net/public/federatedQuery.txt.

[14] Find an example of meteorological data for Karamoja region in Uganda here https://mazimweal.inrupt.net/public/HazardousEvent.ttl.

[15] Find vulnerability and damage potential data here https://mazimweal.inrupt.net/public/vulnerabilityValueExpectedLosses.ttl.

for reasoning over RDFs and expressive OWL logics in which the patterns are encoded. The presence of a reasoner is critical to simplifying queries that will generate meaningful results over data in multiple pods organised using ODPs on the web.

Also, querying over decentralised data pods assumes that data is all should be accessible by clients/apps. Thus there is no flexibility in the choice of data that should be expected and made accessible. The concept of shapes is useful in expressing assumptions about the structure of data that the client can expect. These could be stored as footprints of pattern views that can be accessed depending on the consumer access requirements/type. The concept of shape constraints works well with closed world assumption while ODP based data organisation is based on the open-world assumption. Thus future work will explore trade-offs for pattern-based footprints and Shapes against linked data validation, access and reuse.

Conclusions and Future Work

Managing community disaster risk requires meaningful integration of data from disaster domain actors who play different but complementary roles. The use of ontology design best practice solutions is critical to ensuring semantic integration and publication of heterogeneous disaster sector data. Using ODPs to organise disaster data allows domain experts to learn from similar ontology design problems already faced by others without re-inventing the wheel. However, there is still a limited amount of patterns available as well as their use case scenarios for representing knowledge in the disaster management domain. Therefore, in this paper, we answer the following questions; 1) What disaster risk knowledge requirements exist in the disaster domain? 2) What patterns can be reused from other contexts to represent disaster risk knowledge? 3) Are there any emerging ODPs that capture disaster risk management knowledge? To characterize disaster risk knowledge, we elicit thirty-two (32) competency questions and identify ten (10) matching patterns for reuse from other contexts. Furthermore, we develop the Event classification and quality dependence description ODPs as emerging patterns for knowledge representation in the disaster domain. Finally, the paper presents a data integration use-case scenario for a drought hazard utilizing patterns identified and developed. This use case is a powerful driver for the community to systematically reuse patterns for knowledge representation in other sub-domains of disaster management. However, future work could focus on the characterisation of knowledge and identification of patterns for other sub-domains. These include disaster subdomains relief and emergency response; preparedness and early warning; prevention and mitigation etc. In the Disaster risk subdomain, it would be interesting to instantiate other patterns to infer knowledge about other aspects e.g compound/complex/cascading events. Finally, there still exists a gap in the use of shapes to express assumptions on data integrated with patterns taking into consideration the structure that clients can expect. Future work could also focus on validation of ODP based data on the web and assessing the resulting tradeoffs concerning interoperability, access and reuse by clients/apps.

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Compliance with Ethical Standards

Conflict of interest This work is an extended paper [47] of the 28th IEEE WETICE conference that took place in Anacapri, Naples, Italy, June 12–14, 2019. The authors declare that they have no other conflict of interest.

Appendix

WMO Classifications (See Table 2)

See Table 4.

Table 4 WMO, guidelines on the parameterization of extreme weather events as droughts

	Standardized precipitation index (SPI)	WMO paremeterization
1	SPI < − 1	Drought
2	SPI ≥ 2.0	Extremely wet
3	1.5 ≥ SPI > 2	Severely wet
4	1 ≥ SPI > 1 .5	Moderately wet
5	− 1 ≥ SPI > 1	Near normal
6	− 1.5 ≥ SPI > − 1	Moderately dry
7	− 2≥ SPI > − 1.5	Severely dry
8	SPI <= − 2	Extremely dry

General Description for Emerging Patterns

See Tables 5 and 6.

Table 5 General description of Eventclassification pattern

Name:	EventClassification
Submitted by	Allan Mazimwe
Also Known As:	
Intent:	To represent event classifications and their qualities.
Domains	
Competency Questions:	1. What concept is used to classify an event? 2. What are the qualities of an event classified by the concept?
Solution description:	stub
Reusable OWL Building Block:	https://w3id.org/gicentre/onto/EventClassification.owl
Consequences:	This CP allows designers to make assertions on qualities of a socio object (i.e Concept) that classify an event. Given that events in DOLCE have only the spatial and temporal characteristics, they can inherit additional qualities from a socio object that classify it.
Scenarios:	1. What hazard concept (e.g droughts , extreme precipitation, heat or cold waves) classifiy extreme weather events? 2. What is the magnitude/intensity, severity of a hazardous extreme weather event?
Known Uses:	Classification of hazardous events in the disaster risk domain
Web References:	
Other References:	
Examples (OWL files):	http://w3id.org/gicentre/onto/HazardEventClassificationData.owl
Extracted From:	http://www.loa-cnr.it/ontologies/DUL.owl
Reengineered From:	
Has Components:	
Specialization Of:	Classification ODP
Related CPs:	Simple Event pattern, Quality pattern, RegionParameter pattern

Table 6 General description for qualitydependence description pattern

Name:	QualityDependence Description pattern
Submitted by	Allan Mazimwe
Also Known As:	
Intent:	To represent objects with qualities that depend on other qualities of the same object together with description of these qualities
Domains	Disaster risk
Competency Questions:	1. Which quality of an object are dependent on other qualities of the same object? 2. What is the definition/interpretation of this causation/dependence between qualities?
Solution description:	stub
Reusable OWL Building Block:	http://w3id.org/gicentre/onto/QualityDependenceDescription.owl
Consequences:	This CP allows designers to make assertions about the quality of an object being dependent on multiple qualities of the same object and descriptions depending on adopted definitions and conceptual frameworks
Scenarios:	Vulnerability, value and damage potential are qualities of an object that participates in a hazardous event. All these qualities could be established based on different conceptual frameworks, implementations and formula therefore it is important to include a description of how each quality should be interpreted
Known Uses:	representation quality dependence and descriptions for risky and hazardous events in the disaster risk domain
Web References:	
Other References:	
Examples (OWL files):	http://w3id.org/gicentre/onto/QualityDependenceDescription.owl
Extracted From:	http://www.loa-cnr.it/ontologies/DUL.owl
Reengineered From:	
Has Components:	
Specialization Of:	AffectedBy
Related CPs:	Participation, Quality pattern, RegionParameter, InformationObject pattern

Class and Property Alignments

See Tables 7, 8, 9 and 10.

Table 7 Alignment for core classes instantiated in Fig. 3

Hazardous event class	Alignment axiom	DOLCE class
:HazardPotential	owl:subClassOf	dul:Quality
:Event	owl:equivalentClass	dul:Event
:Concept	owl:equivalentClass	dul:Concept
:Parameter	owl:equivalentClass	dul:Parameter
:Region	owl:equivalentClass	dul:Region

Table 8 Alignment of properties to DOLCE in Fig. 3

Hazardous event property	alignment axiom	DOLCE property
:hasIndex	owl:subPropertyOf	dul:hasRegion
:hasSPI_Data_Value	owl:subPropertyOf	dul:hasRegionDataValue
:isParameterizedBy	owl:equivalentProperty	dul:IsParameterizedBy
:hasParameter	owl:equivalentProperty	dul:hasParameter
:classifies	owl:equivalentProperty	dul:classifies
:hasQuality	owl:equivalentProperty	dul:hasQuality

Table 9 Alignments for classes in the composition (Fig. 5) with DOLCE foundational ontology

QualityDependence description composition	Alignment axiom	DOLCE class
:Object	owl:equivalentClass	dul:Object
:Event	owl:equivalentClass	dul:Event
:Quality	owl:equivalentClass	dul:Quality
:Parameter	owl:equivalentClass	dul:Parameter
:Region	owl:equivalentClass	dul:Region
:InformationObject	owl:equivalentClass	dul:InformationObject
:InformationRealization	owl:equivalentClass	dul:InformationRealization

Table 10 Alignments for properties in the composition (Fig. 5) with DOLCE foundational ontology

QualityDependence description composition property	Alignment axiom	DOLCE property
:hasRegion	owl:equivalentProperty	dul:hasRegion
:hasRegionDataValue	owl:equivalentProperty	dul:hasRegionDataValue
:participates	owl:equivalentProperty	dul:isParticipantIn
:hasParameter	owl:equivalentProperty	dul:hasParameter
:isDescribedBy	owl:equivalentProperty	dul:IsDescribedBy
:hasDescription	owl:equivalentProperty	dul:hasDescription
:isRealizedBy	owl:equivalentProperty	dul:isRealizedBy
:isAbout	owl:equivalentProperty	dul:isAbout
:hasQuality	owl:equivalentProperty	dul:hasQuality

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