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Operationalizing expert knowledge and stakeholder preferences in integrated natural hazard risk assessment

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Abstract: Integrated natural hazard risk assessment aims at capturing the impacts and diverse consequences of natural hazards on different types of elements at risk (i.e. evaluation criteria). Typically, a risk assessor selects such evaluation criteria relying on expert knowledge. Moreover, legal frameworks, best-practice guidelines as well as manifold requirements by stakeholders should be considered in the assessment process. This is also true for risk mapping. In order to provide useful deliverables for stakeholders, their preferences in regard to content and visualization have to be borne in mind. Developing tools to assist risk assessment may focus on some or all of these aspects. Necessary in this context are solutions which are capable of capturing relevant expert knowledge, but which are also easily adaptable to changing requirements. Ontologies, and knowledge bases built upon these, seem to pose ideal concepts to tackle this objective. Ontologies are formal, sharable and machine-interpretable knowledge representations. They thus seem suitable to capture explicit and formal expert knowledge on natural hazard risk assessment. Ontologies may also serve as knowledge stores for tacit information. This way, stakeholder preferences as well as local knowledge, a knowledge body often untapped, can be captured and made accessible. Ontology building methodologies provide the required means to structure and formalize tacit knowledge. They also allow for an iterative extension and adaption of an ontology as required. We present an ontology which captures core concepts of risk assessment and their relations as well as local knowledge and stakeholder preferences. The ontology is used to enhance a software tool which has previously been employed in flood risk assessment case studies. In doing so, we show how semantics can assist an integrated natural hazard risk assessment, and further evaluate the pros and cons of the proposed approach.

Keywords*:* risk assessment; ontology; operationalization; knowledge integration; local knowledge

1 INTRODUCTION

Despite the existence of comprehensive knowledge on flood risk assessment, risk management and the availability of manifold flood risk models it appears that the consequences of flooding and the response to flood impact especially at municipal level are still strongly dependent on the expertise, experience and knowledge of stakeholders. To date, this body of information remains scarcely tapped, although the integration of different sources and types of knowledge has long been identified as a key research objective to ameliorate risk assessment and to address its complexity and uncertainties (Brouwer and van Ek, 2004; Matthies et al., 2007). This holds especially true for the implementation of tools supporting integrated assessment and decision making (McIntosh et al., 2011). In this context, the operationalization of knowledge continues to be a challenge. Ontologies and ontology building methodologies provide means to capture and blend scientific knowledge with formalized local knowledge in a reusable manner. Moreover, also participation is regarded as an important means to enhance risk assessment and foster the implementation of assessment tools (McIntosh et al., 2011). Participatory means such as face-to-face interviews and round table workshops are indispensable for the elicitation of local knowledge, stakeholder requirements and their preferences (e.g. in regard to assessment items and deliverables). They allow stakeholders to challenge assumptions and model implementation. By this, the acceptance of assessment methods and respective findings is expected to increase (Raymond et al., 2010). In turn, participation also allows developers to tailor tools and deliverables to the requirements and needs of stakeholders and end users, thereby increasing chances of tool adoption (McIntosh et al., 2011). Set against this background, the work in progress which is described in this paper aims to devise an ontology to put scientific, expert and local knowledge, legal and stakeholder requirements as well as their preferences into operation. This includes e.g.

- formalization of flood risk assessment methodology (Meyer et al., 2009);
- implementation of legal requirements such as directive 2007/60/EC (European Parliament and the Council, 2007);
- consideration of best-practice guidelines and case studies (Martini and Loat, 2007);
- implementation of stakeholder knowledge and requirements in respect to risk assessment to obtain results regarded useful by stakeholders to fulfil their duties;
- formalization of stakeholder preferences in respect to form, content and style of deliverables (e.g. assessment indicators, reports, mapping products).

Scope and implementation of the ontology follow a set of use cases which include: i) the definition of core flood risk assessment concepts from an operationalization and stakeholder perspective; ii) the formalization of the underlying risk assessment methodology which is put into operation in form of an accompanying tool; and iii) the integration of local knowledge, needs and preferences of stakeholders. In its final form, the envisioned ontology should serve as a risk assessor's Swiss knife, i.e. providing all the information which is required to deliver useful products to stakeholders. It should foster sharing and reuse of information, thereby allowing others to easily make use of local and stakeholder knowledge. In the remainder of this paper, operationalization aspects of the proposed ontology will be introduced with a special focus on its integration and semantic join with existing ontologies.

2 REVIEW OF EXISTING FORMAL KNOWLEDGE

Ontologies relevant in the field of earth system and life sciences include the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE, cf. Gangemi et al., 2002 and Masolo et al., 2003) and the Semantic Web for Earth and Environmental Terminology (SWEET, cf. Raskin and Pan, 2005) upper-level ontologies as well as various domain ontologies. The DOLCE ontology defines particulars, i.e. descriptive notions of natural language categories to support making conceptual models explicit. For this purpose, DOLCE formalizes abstract, physical and temporal qualities and regions – i.e. value partitions – as well as processes, features, physical and non-physical objects, agents and states (Gangemi et al., 2002). DOLCE distinguishes perdurants and endurants; the former refer to occurrences in time, the latter depict continuants (Masolo et al., 2003). DOLCE further defines qualities which are inherent to any entity. SWEET consists of various orthogonal, faceted upper-level ontologies capturing thousands of concepts describing natural (physical) phenomena, properties, processes, measures, units, human activity and data characteristics (Raskin and Pan, 2005). Various domain ontologies exist in the earth system sciences field; e.g. Williams et al. (2006) proposed domain ontologies aiming to facilitate data annotation, data discovery and data sharing in ecology and ecoinformatics. Refsgaard et al. (2005) proposed a modelling knowledge base for water management. In their study, the water management workflow has been decomposed into steps, tasks and activities which were ontologically structured to guide and advice users for quality assurance. Comparable to their approach is the work of Chau (2007) who implemented a modelling ontology and knowledge-based system for water flow and water quality management. Another modelling ontology describing data and metadata for hydrodynamic modelling has been proposed by Islam and Piasecki (2008). Tripathie and Babaie (2008) extended SWEET by adding hydrogeological concepts and relations, i.e. focusing on the groundwater domain. Most relevant for the work described in this paper is the MONITOR domain ontology (Kollarits and Wergles, 2008). MONITOR captures risk, risk assessment and risk management terms and their relations with an accompanying glossary of terms. It formalizes a conceptual model derived from the definitions of these terms in the mentioned domains. The MONITOR ontology heavily relies on DOLCE; all concepts captured in MONITOR are related to their respective DOLCE equivalent. MONITOR defines several endurants: physical objects and features (e.g. natural or built environment) and non-physical objects (i.e. social or information objects). These objects (e.g. concepts like hazard or damage) are perceived necessary to communicate and work with real-world objects by providing context-specific classifications (Kollarits and Wergles, 2008). MONITOR further defines perdurants encompassing events, states and processes. These MONITOR conceptualizations are extended by qualities where required; e.g. probability and intensity are defined as qualities of an event. Concluding from this section, knowledge on (flood) risk assessment is already captured in various existing ontologies. MONITOR and SWEET are deemed the most relevant for this work. Other concepts of domain relevance are captured in various smaller ontologies with limited scope. Besides such formalized representations, knowledge also exists in other types (e.g. textual) which should be considered. Amongst them are, for instance, various FLOODsite project reports summarizing flood/flood-risk relevant terms and definitions (Gouldby and Samuels, 2005) or best-practice studies (Martini and Loat, 2007).

3 PUTTING THINGS INTO OPERATION OR: WHERE TO REUSE EXISTING KNOWLEDGE?

The proposed risk assessment ontology has been conceptualized following the integrative, holistic risk definition devised by Meyer et al. (2009) and Scheuer et al. (2011). They define flood risk R as a function of hazard probability P, hazard intensity I, quantity and/or value of elements at risk Q and their susceptibility towards flooding S so that $R = f(H, I, Q, S)$. The ontology has been formalized and implemented according to this conceptual risk model. It was aimed at reusing existing knowledge where appropriate. In the current stage of implementation only the SWEET and MONITOR ontologies have been considered. The knowledge integration with MONITOR and SWEET has been realized using taxonomic constructors or equivalence statements where appropriate. This way, predefined properties can also be reused. Additional restrictions have been imposed where necessary to account for the intended meaning of concepts. This has been done e.g. for the core concepts Flood and Event; in the following, these are introduced using the Manchester OWL syntax[1]:

```
Class: Flood THAT
  SubClassOf: Event, SWEET:HydrospherePhenomena, SWEET:Inundation

Class: Event THAT
  SubClassOf: hasRecurrence ONLY RecurrenceInterval AND
     hasRecurrence EXACTLY 1, hasIntensity ONLY Intensity AND
     hasIntensity MIN 1, threatens ONLY ElementAtRisk
  EquivalentTo: sweet:Event
  SeeAlso: MONITOR:Hazard
```

Notably, the Flood concept devised in the proposed ontology has *not* been joined semantically with the concept SWEET:Flood. The latter is defined as:

[1] In the following, the prefix SWEET refers to classes defined in the SWEET ontology. Likewise, the prefix MONITOR denotes MONITOR ontology concepts.

```
Class: SWEET:Flood THAT
  SubClassOf: SWEET:HydrospherePhenomena, SWEET:Inundation
  SubClassOf: hasImpact VALUE SWEET:Hazard
```

with SWEET:Hazard being defined as an instance of SWEET:Impact. Obviously, SWEET defines a flood as an inundation with hazardous impact (i.e. causing damage or loss), albeit SWEET:Impact encompasses additional members such as Severe, Rough, Moderate or Minimal. This notion of Hazard within SWEET appears to be questionable and could be refuted: In flood risk assessment a flood is conveyed to pose a hazard if it has the potential to cause damage or harm. This must not be true for every flood, taking e.g. low-intensity events (possibly having only minor impact) or floods occurring in areas lacking elements at risk (negligible impact) into consideration. This is why the envisaged Flood concept has been declared subclass of SWEET:Inundation and SWEET:HydrospherePhenomena only (cf. http://amor.cms.hu-berlin.de/~scheuese/iemss.pdf). This is also in line with the propositions made in MONITOR where a Hazard is considered as a social object, i.e. the perception of an event as potentially threatening and causing damage or loss.

MONITOR captures a well-adjusted conceptual model of basic risk terms. Due to its heavy reliance on DOLCE some MONITOR definitions appear to be impractical from an operational perspective. For example, MONITOR includes notions on DOLCE Situations: Threat or Danger situations describe the exposure of objects of the natural, built and social environment, rendering them endangered. From a practitioner's perspective, this definition appears irrelevant. Instead, objects of interest – that is, evaluation criteria – should to be assessed to evaluate their exposure, thus classifying them as being in danger or not as an outcome of the assessment. Situations could thus be omitted. We define a complex class ElementAtRisk instead, which encompasses hierarchically structured assessment items relevant to stakeholders. The ElementAtRisk class encompasses objects from the natural, built and social environment. It could be seen as having a common class extension with MONITOR:Environment and is thus defined as an equivalent class:

```
Class: ElementAtRisk
  EquivalentTo: (Infrastructure OR Population OR
     EnvironmentalComponent)
  EquivalentTo: MONITOR:Environment
  SubClassOf: hasValue ONLY ValueOrOccurence, hasSusceptibility ONLY
     SusceptibilityFunction AND hasSusceptibility MIN 1
```

Likewise, the actual members of ElementAtRisk can be mapped to their MONITOR or SWEET counterparts. Stakeholder preferences have especially been considered during the definition of elements at risk. We have e.g. elicited those infrastructure items in interviews and workshops which are most relevant for stakeholders and have formalized them as subclasses the union members of ElementAtRisk respectively (Table 1).

MONITOR defines vulnerability as an Environment's object's quality. Definition of such qualities – according to DOLCE they are the only perceivable or measurable entities – might be sufficient to formalize a cognitive view on risk assessment and risk management; this is what has been done in MONITOR. They require refinement though to be put into operation. This includes e.g. the qualities vulnerability and intensity. The class SusceptibilityFunction, being a SWEET:Function, puts vulnerability into operation as such:

```
Class: SusceptibilityFunction THAT
  SubClassOf: describesSusceptibilityTowards ONLY Event AND
     describesSusceptibilityTowards MIN 1
  SubClassOf: SWEET:Function AND hasInput ONLY Intensity AND
     hasInput MIN 1 AND hasOutput ONLY DamageRatio AND hasOutput
     EXACTLY 1
```

Table 1: Stakeholder-specific elements at risk elicited in the stakeholder analysis.

Purpose	**Element at risk**
Energy-supply	Switchyards, masts, power transmission lines
Water-supply/disposal	Wells, water treatment plants, transmission lines
Gas-supply	Transmission lines, storage facilities
Provisioning	Building yards, depots
Transportation	Roads, railways, bridges, railroad stations, tunnels, potentially blocked pathways
Evacuation	Evacuation routes, meeting points, emergency accommodation
Disaster response	Task force assembling points, logistics, hazard spots

Susceptibility functions and their output – i.e. the damage ratio for each event – are devised to refine the MONITOR conceptualization of vulnerability, which is in line e.g. with the notion of vulnerability by Davidson and Shah (1997). We chose to define a class Intensity to better reflect the underlying conceptual risk model. It is defined as a union of concepts which are suitable to qualify or quantify the intensity of given types of hazards (here: floods). Each union member is semantically joined with its SWEET counterpart, e.g. in the case of the spatial extent of a hazardous event (cf. http://amor.cms.hu-berlin.de/~scheuese/iemss.pdf):

```
Class: Intensity
  EquivalentTo: (InundationDepth OR Duration OR Extent)

Class: InundationDepth THAT
  EquivalentTo: SWEET:Area
```

Susceptibility functions and damage ratio are the basis for the refinement of MONITOR's damage definition. Kollarits and Wergles (2008) define damage as a social construct which is generally dependent on a damage situation, which in turn classifies an event's impact. Concomitantly, MONITOR:Impact has a quality damage extent which encompasses other qualities, e.g. number of people killed or value of property destroyed. For the proposed ontology, these qualities are clearly of interest. They are perceived by the authors as suitable measures to quantify hazard impact. Their magnitude is firstly dependent on vulnerability/susceptibility, which is appraised by a susceptibility function and quantified as damage ratio as described above. Damage to tangible assets (e.g. the value of property destroyed by flooding) is then put into operation as the product of damage ratio and element value and is described as equivalent to the respective damage extent quality defined in MONITOR:

```
Class: AbsoluteDamage THAT
  productOf SWEET:Product THAT hasInput ONLY SWEET:OrderedPair THAT
     hasFirstOperand ONLY DamageRatio AND hasSecindOperand ONLY
     MonetaryValue
  SubClassOf: ofEvent EXACLTY 1 AND ofEvent ONLY Event
  EquivalentTo: MONITOR:value of property destroyed
```

Likewise, intangible damage (qualified e.g. by the affected area or affected number of people) can be put into operation by adding binary susceptibility functions and formulating OWL restrictions on the applicability of concepts as domain and range. Finally, the risk concept needs to be implemented. MONITOR conveys risk as a quality of impact which is generally dependent on the hazard potential and the damage potential. In practice, risk *R* is estimated by (Meyer et al., 2009):

$$R = \sum_{i=1}^{k} \frac{D_{P_{i-1}} + D_{P_i}}{2} \cdot \left| P_i - P_{i-1} \right| \qquad (1)$$

where *D* is equal to the absolute damage of the *i*th event with probability *P* from *k* assessed flood events. *R* is then equal to the area under the damage-probability curve; that definite integral is computed using (eq. 1). Risk is thus dependent on the absolute damage caused by each flood event and the event's probability; this is in line with the risk definition provided by Knight (1921). In the presented ontology, risk is therefore devised as the result of that risk estimation function.

5 DISCUSSION

In this paper we have presented an ontology with a focus on i) operationalization; ii) integration with existing knowledge; and iii) putting scientific and expert knowledge on flood risk assessment as well as local and stakeholder-specific knowledge into operation. This has been done on the basis of an existing risk assessment methodology and a formalized conceptual model of the risk domain (i.e. the MONITOR ontology). In the previous section we have described selected aspects of that ontology. In the examples given we have also discussed the integration with existing ontologies. Integration with SWEET puts the devised conceptualization into a broader context. It became obvious that the operationalization scope of the ontology required a refinement of MONITOR’s domain model. Simplifications had to be made in regard to social concepts and situations. It has been elucidated in face-to-face interviews and stakeholder workshops that such conceptualizations are not of relevance from a practitioner’s point of view. Hence, they have been omitted. It has also been shown that it is necessary to extend and refine MONITOR qualities such as vulnerability or damage. At first, this is a requirement to put them into operation. Secondly, this becomes a necessity for a proper alignment with the conceptual model which has been followed by the authors. For example, Kollarits and Wergles (2008) define the damage potential as being generally dependent on *both* an object's value and its vulnerability. This is contradictory to the author's views who consider the damage potential to be the sum of all asset values at risk, i.e. a function of the types, quantity and value of elements at risk. This view is supported e.g. by Messner and Meyer (2006) and Merz et al. (2007). Hence, selected MONITOR concepts have not or cannot be integrated or represented one-to-one to avoid inconsistencies and contradictions. This is also true for the integration with SWEET. The intended meaning of concepts had to be carefully evaluated to make decisions on the realization of semantic joins. It has been shown why e.g. a semantic join with SWEET's flood concept has been rejected.

The knowledge formalization described in this paper is still a work in progress and is accompanied and complemented by the implementation and enhancement of a software tool (Meyer et al., 2009); the ontology provides the basis for the tool's knowledge base. The tool will allow users to assess risk relying on the codified knowledge and preferences e.g. by user guidance, suggestions, pre-selection and pre-filtering of user choices and the validation of user input. It is envisioned that by these means deliverables can be produced which conform to stakeholder requirements. It is further hoped that knowledge sharing will foster the use of local and stakeholder knowledge, thereby ameliorating risk assessment. Extensive discussion with stakeholders helps to ensure the fitness of ontology and tool to achieve these objectives. Unfortunately, the presentation of that software tool is out of this paper's scope; a short description is available in Scheuer et al. (2011) and a more detailed paper is in preparation by the authors. Uncertainty is another issue to be addressed. Kollarits and Wergles (2008) make the statement that uncertainty is dependent on the reliability of the assessment of hazard and damage potential. Scientific discourse and discussion with experts and stakeholders identify various sources of uncertainty in much more detail, e.g. uncertainty of flood frequency analysis and inundation estimation methods (accounting for the MONITOR's hazard potential) or of asset value estimation and susceptibility functions (i.e. MONITOR's damage potential; cf. Merz and Thieken, 2009). Currently, the proposed operationalization ontology does not make any statements on uncertainty. They will be implemented in forthcoming ontology building iterations once a suitable way has been identified by the authors to formalize uncertainties in an effective manner. Extending the proposed knowledge with additional information will further broaden the ontology's scope, e.g. towards multi-hazard risk assessment and risk assessment under uncertainty in regard to climate change.

6 CONCLUSIONS AND RECOMMENDATIONS

In this paper, we have presented an ontology to put flood risk assessment into operation. The operationalization scope is reflected by the devised classes and their relations. These generally correspond to the risk domain conceptualized in MONITOR; simplifications and omissions have been made to better account for the stakeholder perspective on risk assessment though. MONITOR qualities have been extended and refined where required. Semantic joins have been established with concepts defined in the SWEET ontology to put the devised classes into a broader knowledge context. The ontology lays the foundation for the implementation of knowledge-based tool. By that, it is hoped to foster knowledge exchange and make local knowledge more accessible, thus ameliorating risk assessment. Forthcoming research objectives have been identified in regard to the formalization and implementation of uncertainties and the extension of the proposed ontology to broaden its scope of application.

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