Extending an Ontology-based Search with a Formalism for Spatial Reasoning

Rolf Grütter, Bettina Bauer-Messmer and Martin Hägeli
Swiss Federal Research Institute WSL
An Institute of the ETH Board
Zürcherstrasse 111
CH-8903 Birmensdorf, Switzerland
{rolf.gruetter, bettina.bauer, martin.haegeli}@wsl.ch

ABSTRACT
With the objective of extending an existing ontology-based search with a formalism for spatial reasoning two approaches to a representation of the Region Connection Calculus (RCC) in OWL DL are explored. The exploration results in a representation which is minimal yet still allows inferring the relations between all connecting regions in any of the different RCC species using a sound and complete calculus. The theoretical results are demonstrated in a sample application. The scale of the representation in the sample application is discussed. While the successful approach can be applied to small applications, we conclude that further research is required before applying it to large applications.

Categories and Subject Descriptors
I.1.3 [**Symbolic and Algebraic Manipulation**]: Languages and Systems – *Constraint and logic languages*

General Terms
Algorithms, Experimentation, Languages, Theory, Verification.

Keywords
National Spatial Data Infrastructure, Ontology-based Search, Region Connection Calculus, Spatioterminological Reasoning.

1. INTRODUCTION
In recent years many countries have built National Spatial Data Infrastructures (NSDI). A NSDI is defined as the technologies, policies, and people necessary to promote sharing of geospatial data throughout all levels of government, the private and non-profit sectors, and the academic community [5]. The goals of such infrastructures are to reduce duplication of effort among agencies, to make geographic data more accessible to the public, and to increase the benefits of using available data. In Switzerland the NSDI is currently under construction. An expert application within this NSDI is the Virtual Data Center (VDC) which offers Web-based access to distributed geo-ecological resources [6].

SAC'08, March 16-20, 2008, Fortaleza, Ceará, Brazil.

One of the services offered by the VDC is the "open" (viz. semantic) search. The semantic search is based on a bilingual ontology in OWL DL [2]. By exploiting the relationships between the building blocks of the ontology search terms are semantically expanded before querying the databases. The ontology holds 1155 items (i.e. IDs) which refer to concepts, roles or individuals. Because of the many synonyms and similar terms used to label the items, the ontology holds many thousand terms. These terms denote thematic notions such as endangered species of animals and plants. They also denote spatial notions such as inventory objects (biotopes) and administrative regions.

In order to process queries combining thematic and spatial notions, the semantic search must be extended with a formalism for spatial reasoning. Addressing the core of this extension, we explore how far the Region Connection Calculus (RCC) can be represented in OWL DL. Preliminary results from the exploration of a possible approach have been presented in [8]. The current paper extends this work by exploring an additional approach and demonstrating the results of the exploration in a sample application. We assume that the reader is familiar with OWL [14], DL and DL-based knowledge representation systems [1].

The paper is organized as follows: In section 2 a short introduction to RCC is provided. In section 3 we review a number of recent approaches aimed at combining RCC with OWL and discuss their potential for establishing reasoning with RCC in the Semantic Web. In section 4 we show how the different RCC species and their relations to each other can be represented in the terminology of a DL, supporting property hierarchies such as OWL DL. Section 5 explores two different approaches to a minimal representation of RCC in OWL DL and demonstrates the results in a sample application.[1] Section 6 discusses the results of the exploration and section 7 concludes with an overview of future work.

2. REGION CONNECTION CALCULUS
The Region Connection Calculus (RCC) is an axiomatization of certain spatial concepts and relations in first order logic [15]. The basic theory assumes only one primitive dyadic relation: $\mathsf{C}(x, y)$ read as "x connects with y". Individuals (x, y) can be interpreted as denoting spatial regions. The relation $\mathsf{C}(x, y)$ is reflexive and symmetric.

---

1 The term "minimal" refers to the smallest possible representation supporting a full-fledged combination of spatial and terminological reasoning services.

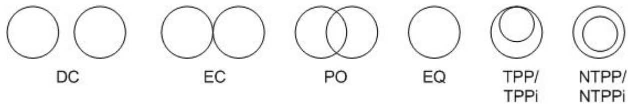

Figure 1. RCC-8 relations (cf. the long names in table 1)

Using the primitive relation C(x, y) a number of intuitively significant relations can be defined. The most common of these are illustrated in figure 1 and their definitions as well as those of additional relations are given in table 1. The asymmetrical relations P, PP, TPP and NTPP have inverses which we write, as Ri, where $R \in$ {P, PP, TPP, NTPP}. These relations are defined by definitions of the form Ri$(x, y) \equiv_{def} R(y, x)$.

Of the defined relations, DC, EC, PO, EQ, TPP, NTPP, TPPi and NTPPi have been proven to form a jointly exhaustive and pairwise disjoint set, which is known as RCC-8. Similar sets of one, two, three and five relations are known as RCC-1, RCC-2, RCC-3 and RCC-5, respectively: RCC-1 = {SR}, RCC-2 = {O, DR}, RCC-3 = {ONE, EQ, DR}, RCC-5 = {PP, PPi, PO, EQ, DR}.

According to [15], regions support either spatial or temporal interpretation. In case of spatial interpretation, there is a variety of models to choose from. The authors provide some examples such as interpreting the relation C ("connects with") in terms of two regions whose closures share a common point or stating that two regions connect when the distance between them is zero.

In order to check consistency of a knowledge base holding spatial relations, so-called composition tables are used (cf. the composition table for RCC-5 in table 2). The entries in these tables share a uniform inference pattern which can be formalized as composition axioms of the general form $\forall x, y, z.\ S(x, y) \wedge T(y, z) \rightarrow R_1(x, z) \vee \ldots \vee R_n(x, z)$ where S, T, and R_i are variables for relation symbols.

A similar approach which is based on the description of topological relations between two spatial regions was introduced as the 9-intersection model in [4]. In this model, eight out of nine relations can be interpreted in the same way as we interpret the RCC-8 relations, namely as spatial relations between polygons in the integral plane [9]. However, since it is based on a topological framework – and not on a logical one – the 9-intersection model is harder to combine with OWL DL than RCC.

3. REVIEW OF EXISTING APPROACHES

In [13] the authors aim at representing qualitative spatial information in OWL DL. On the basis of the (assumed) close relationship between the RCC-8 calculus and OWL DL they extend the latter with the ability to define reflexive roles. The extension of OWL DL with a reflexive property is motivated by the requirement that such a property, in addition to the transitive one, is needed in order to describe the accessibility relation. In order to represent RCC-8 knowledge bases the authors use a translation in which regions are expressed as non-empty regular closed sets. The RCC-8 relations are then translated into (sets of) concept axioms in OWL DL. The classes denoted by the introduced concepts are instantiated by asserting for each concept an individual in the ABox in order to ensure that the classes cannot be empty. This approach requires only a minimal extension to OWL DL which has been considered in the draft to OWL 1.1 [7]. However, the notion of regions as sets in the abstract object domain prevents RCC from effectively combining with domain ontologies. The reason for this is that OWL DL requires type separation: a class cannot also be an individual (or a property) [14]. Yet, in order to classify regions in a domain ontology they must be represented as individuals, and not as concepts.

Table 1. Definitions of the basic RCC relations

SR(x, y)	$\equiv_{def} \top(x, y)$	Spatially Related
C(x, y)	(primitive relation)	Connects with
DC(x, y)	$\equiv_{def} \neg$C(x, y)	DisConnected from
P(x, y)	$\equiv_{def} \forall z$[C$(z, x) \rightarrow$ C(z, y)]	Part of
O(x, y)	$\equiv_{def} \exists z$[P$(z, x) \wedge$ P(z, y)]	Overlaps
DR(x, y)	$\equiv_{def} \neg$O(x, y)	DiscRete from
EC(x, y)	$\equiv_{def}$ C$(x, y) \wedge \neg$O(x, y)	Externally Connected to
EQ(x, y)	$\equiv_{def}$ P$(x, y) \wedge$ P(y, x)	EQual to
ONE(x, y)	$\equiv_{def}$ O$(x, y) \wedge \neg$EQ(x, y)	Overlaps Not Equal
PP(x, y)	$\equiv_{def}$ P$(x, y) \wedge \neg$P(y, x)	Proper Part of
PO(x, y)	$\equiv_{def}$ O$(x, y) \wedge \neg$P$(x, y) \wedge \neg$P(y, x)	Partially Overlaps
TPP(x, y)	$\equiv_{def}$ PP$(x, y) \wedge \exists z$[EC$(z, x) \wedge$ EC(z, y)]	Tangential Proper Part of
NTTP(x, y)	$\equiv_{def}$ PP$(x, y) \wedge \neg\exists z$[EC$(z, x) \wedge$ EC(z, y)]	Non-Tangential Proper Part of

Table 2. RCC-5 composition table

∘	DR(x, y)	PO(x, y)	EQ(x, y)	PPi(x, y)	PP(x, y)
DR(y, z)	T(x, z)	DR(x, z) PO(x, z) PPi(x, z)	DR(x, z)	DR(x, z) PO(x, z) PPi(x, z)	DR(x, z)
PO(y, z)	DR(x, z) PO(x, z) PP(x, z)	T(x, z)	PO(x, z)	PO(x, z) PPi(x, z)	DR(x, z) PO(x, z) PP(x, z)
EQ(y, z)	DR(x, z)	PO(x, z)	EQ(x, z)	PPi(x, z)	PP(x, z)
PP(y, z)	DR(x, z) PO(x, z) PP(x, z)	PO(x, z) PP(x, z)	PP(x, z)	PO(x, z) EQ(x, z) PP(x, z) PPi(x, z)	PP(x, z)
PPi(y, z)	DR(x, z)	DR(x, z) PO(x, z) PPi(x, z)	PPi(x, z)	PPi(x, z)	T(x, z)

(T$(x, z) \equiv_{def}$ {DR(x, z), PO(x, z), EQ(x, z), PP(x, z), PPi(x, z)})

It seems to be more intuitive to define the RCC relations in terms of role descriptions than to translate them into concept axioms. Since current OWL does not provide constructors for role descriptions (apart from inverse), the underlying description logics have to be extended with these constructors. In [12] it is shown that the extension of $\mathcal{SHIQ}$ with complex role inclusion axioms of the form $S \circ T \sqsubseteq R$ is undecidable, even when these axioms are restricted to the forms $S \circ T \sqsubseteq S$ or $T \circ S \sqsubseteq S$, but that decidability can be regained by further restricting them to be acyclic. Complex role inclusion axioms of the unrestricted form are supported by the description logic $\mathcal{SROIQ}$ which serves as a logical basis for OWL 1.1 [10]. However, in order to axiomatize the composition of RCC relations, a language must support an extension of the unrestricted form of role inclusion axioms, namely $S \circ T \sqsubseteq R_1 \sqcup \ldots \sqcup R_n$, as can be seen in table 2 for RCC-5. If decidability should be preserved, complex role inclusion axioms are, therefore, not a solution to the translation problem of RCC. Axioms defining the basic RCC relations require additional role constructors such as intersection and complement. Extensions of $\mathcal{SHIQ}$ with these kinds of role constructors have, to our knowledge, not been investigated so far. $\mathcal{SROIQ}$ supports negation of roles (i.e. complement) but not intersection.

In [3] it is proposed to encode spatial inferences in the Semantic Web Rule Language (SWRL) [11]. Even though not explicitly mentioned, the examples are provided in a RCC-like style. SWRL uses Horn-like rules which are combined with OWL DL (and OWL Lite). Horn rules do not allow complex heads (which refer to the expressions on the right hand side of the implication connective). However, complex heads in terms of disjunctions are required in order to formalize the RCC composition axioms (cf. section 2).

4. COMBINING RCC WITH OWL DL

Considering the result of the review of existing approaches we are combining RCC and OWL at the level of the knowledge representation system and not at the level of the formalisms. This implies that the architecture of a knowledge representation system based on DL is extended with a RCCBox. A detailed account of the resulting hybrid knowledge representation system is provided in [9].

The RCCBox contains the definitions of the RCC relations as introduced in section 2 and the composition tables for RCC-1, RCC-2, RCC-3, RCC-5 and RCC-8. The reasoner uses these definitions together with selected role assertions in the ABox in order to calculate the spatial relations holding between individual regions, and it uses the composition tables in order to check spatial consistency of the ABox. This implies that the names of the relations have previously been introduced as role names in the TBox of the knowledge base. Table 3 shows the terminology introduced in the TBox of the knowledge base with our sample ontology. The DL expressivity of the ontology is that of $\mathcal{ALHI}$.

The numbered axioms in table 3 introduce the relations of the various RCC species as a hierarchy of roles (cf. section 2): RCC-1 ≡ {1}, RCC-2 ≡ {2, 3}, RCC-3 ≡ {3, 4, 5}, RCC-5 ≡ {3, 5, 6, 7, 8}, RCC-8 ≡ {5, 8, 9, 10, 11, 12, 13, 14}. The unnumbered axioms introduce the concept Region as subsumed by the universal concept; they state that regions are spatially related to each other, define the symmetric property of the role connectsWith and the inverse roles.

Note that the terminology does not provide sufficient definitions of the RCC relations except for the inverses. It rather states necessary conditions. For instance, the terminology states that the role discreteFrom is included in (or subsumed by) the role spatiallyRelated (3) which also applies to connectsWith. Instead, a sufficient definition must state that discreteFrom is NOT overlaps (cf. table 1). This cannot be put in terms of OWL DL, since negation of roles is not permitted.

Even though, in principle, all RCC relations can be geometrically computed and asserted in the ABox of an OWL DL knowledge base, it is not favorable to do so for at least two reasons. First, asserting all relations holding between any two regions easily results in a very large knowledge base, thereby bearing on the performance of the system. Second, as discussed in section 3, an OWL reasoner will be unable to check the consistency of the knowledge base w.r.t. spatial references, because the inferences implied by the entries in the RCC composition tables cannot be put in terms of OWL DL axioms [12]. For these reasons we argue in favor of a minimal representation in the ABox of an OWL DL knowledge base and suggest to calculate or infer those relations, which are not represented, only when requested at runtime. There are two different approaches to a minimal representation which shall be explored in the following section:

1. **Asserting the primitive RCC relation** connectsWith for all pairs of regions for which this relation holds and calculating the relations of the different RCC species, when requested, at run time by using their definitions in the RCCBox.
2. **Asserting the RCC-8 relations** for all pairs of connecting regions and, when requested, inferring from them the more general relations of the other RCC species at runtime by using the respective OWL DL axioms in the TBox. Note that this approach does not fulfill the desideratum of generating a knowledge base which can be checked also for spatial consistency by an OWL reasoner.

Table 3. Terminology of our knowledge base in $\mathcal{ALHI}$

	Region ⊑ ⊤	$\text{Region}^\mathcal{I} \subseteq \Delta^\mathcal{I}$
1	spatiallyRelated	$\text{spatiallyRelated}^\mathcal{I} \subseteq \Delta^\mathcal{I} \times \Delta^\mathcal{I}$
	∃spatiallyRelated.⊤ ⊑ Region	$\{a \in \Delta^\mathcal{I} \mid \exists b.\ (a, b) \in \text{spatiallyRelated}^\mathcal{I}\} \subseteq \text{Region}^\mathcal{I}$
	⊤ ⊑ ∀spatiallyRelated.Region	$\Delta^\mathcal{I} \subseteq \{a \in \Delta^\mathcal{I} \mid \forall b.\ (a, b) \in \text{spatiallyRelated}^\mathcal{I} \rightarrow b \in \text{Region}^\mathcal{I}\}$
	connectsWith ⊑ spatiallyRelated	$\text{connectsWith}^\mathcal{I} \subseteq \text{spatiallyRelated}^\mathcal{I}$
	connectsWith ⊑ ⁻connectsWith	$\{(a, b) \mid (a, b) \in \text{connectsWith}^\mathcal{I} \rightarrow (b, a) \in \text{connectsWith}^\mathcal{I}\}$
	⁻connectsWith ⊑ connectsWith	$\{(a, b) \mid (b, a) \in \text{connectsWith}^\mathcal{I} \rightarrow (a, b) \in \text{connectsWith}^\mathcal{I}\}$
2	overlaps ⊑ spatiallyRelated	$\text{overlaps}^\mathcal{I} \subseteq \text{spatiallyRelated}^\mathcal{I}$
	overlaps ⊑ connectsWith	$\text{overlaps}^\mathcal{I} \subseteq \text{connectsWith}^\mathcal{I}$
3	discreteFrom ⊑ spatiallyRelated	$\text{discreteFrom}^\mathcal{I} \subseteq \text{spatiallyRelated}^\mathcal{I}$
4	overlapsNotEqual ⊑ overlaps	$\text{overlapsNotEqual}^\mathcal{I} \subseteq \text{overlaps}^\mathcal{I}$
5	equalTo ⊑ overlaps	$\text{equalTo}^\mathcal{I} \subseteq \text{overlaps}^\mathcal{I}$
6	properPartOf ⊑ overlapsNotEqual	$\text{properPartOf}^\mathcal{I} \subseteq \text{overlapsNotEqual}^\mathcal{I}$
7	inverseProperPartOf ⊑ overlapsNotEqual	$\text{inverseProperPartOf}^\mathcal{I} \subseteq \text{overlapsNotEqual}^\mathcal{I}$
	inverseProperPartOf ≡ ⁻properPartOf	$\text{inverseProperPartOf}^\mathcal{I} = {}^{-}(\text{properPartOf})^\mathcal{I}$
8	partiallyOverlaps ⊑ overlapsNotEqual	$\text{partiallyOverlaps}^\mathcal{I} \subseteq \text{overlapsNotEqual}^\mathcal{I}$
9	tangentialProperPartOf ⊑ properPartOf	$\text{tangentialProperPartOf}^\mathcal{I} \subseteq \text{properPartOf}^\mathcal{I}$
10	nonTangentialProperPartOf ⊑ properPartOf	$\text{nonTangentialProperPartOf}^\mathcal{I} \subseteq \text{properPartOf}^\mathcal{I}$
11	inverseTangentialProperPartOf ⊑ inverseProperPartOf	$\text{inverseTangentialProperPartOf}^\mathcal{I} \subseteq \text{inverseProperPartOf}^\mathcal{I}$
	inverseTangentialProperPartOf ≡ ⁻tangentialProperPartOf	$\text{inverseTangentialProperPartOf}^\mathcal{I} = {}^{-}(\text{tangentialProperPartOf})^\mathcal{I}$
12	inverseNonTangentialProperPartOf ⊑ inverseProperPartOf	$\text{inverseNonTangentialProperPartOf}^\mathcal{I} \subseteq \text{inverseProperPartOf}^\mathcal{I}$
	inverseNonTangentialProperPartOf ≡ ⁻nonTangentialProperPartOf	$\text{inverseNonTangentialProperPartOf}^\mathcal{I} = {}^{-}(\text{nonTangentialProperPartOf})^\mathcal{I}$
13	externallyConnectedTo ⊑ discreteFrom	$\text{externallyConnectedTo}^\mathcal{I} \subseteq \text{discreteFrom}^\mathcal{I}$
	externallyConnectedTo ⊑ connectsWith	$\text{externallyConnectedTo}^\mathcal{I} \subseteq \text{connectsWith}^\mathcal{I}$
14	disconnectedFrom ⊑ discreteFrom	$\text{disconnectedFrom}^\mathcal{I} \subseteq \text{discreteFrom}^\mathcal{I}$

5. REPRESENTING RCC IN OWL DL

5.1 Asserting the Primitive RCC Relation

The relation P(x, y) ("x is a part of y") plays a key role in the definitions of the RCC relations (cf. table 1). Therefore, the first part of our exploration is limited to this relation: only if P(x, y) can be reliably calculated, that is by a sound and complete formalism, the calculation of the remaining relations is expected to be sound and complete. The theory defines the relation P(x, y) as follows:

$$P(x, y) \equiv_{def} \forall z[C(z, x) \rightarrow C(z, y)].$$

Note that from an epistemic viewpoint this definition has the form of a universal proposition. It can, therefore, not be empirically verified but only falsified. It is not possible to test for the infinite number of all imaginable regions z connecting with x if they also connect with y. Conversely, a single observation of a region z connecting with x but not with y is sufficient to falsify the hypothesis that x is a part of y. Following this line of argumentation a calculus for P(x, y) reasoning about a *finite* data structure is not expected to be sound in a formal sense. Instead the question is whether it is complete or not and how good it approximates the spatial setting (the latter will be explored in section 5.3).[2] The following formula adapts the original definition to a finite data structure:

$$P(x, y) = \bigwedge_{z_i}[C(z_i, x) \rightarrow C(z_i, y)] \quad \textbf{(1)}$$

with $1 \leq i \leq n$, n the number of regions represented.

In the minimum case the region x connects only with itself (remember that the relation C is by definition reflexive) and it holds that $x = y = z$. In the maximum case all regions, including x (y, respectively) connect with x (y, respectively). Intuitively, the calculation of P(x, y) is expected to be more precise with a high number of regions z_i represented.

The question whether a calculus using formula (1) is complete or not can be answered by referring to the reflexive and symmetric properties of the primitive relation C(x, y). If $z = y$ and x connects with y the formula $C(y, x) \rightarrow C(y, y) \equiv C(x, y) \rightarrow C(y, y)$ evaluates to true for P(x, y). Thus, the condition that x connects with y is sufficient for hypothesizing that x is a part of y. This means that a calculus using formula (1) is expected to be complete in a practical application.

5.2 Asserting the RCC-8 Relations

The inferences from the RCC-8 relations asserted between the connecting regions in the ABox of the knowledge base to relations of any of the four other RCC species share the uniform pattern of the logical modus ponens:

$$[(R_{RCC\text{-}i+} \sqsubseteq R_{RCC\text{-}i}) \wedge R_{RCC\text{-}i+}(x, y)] \rightarrow R_{RCC\text{-}i}(x, y) \quad \textbf{(2)}$$

where RCC-i+ denotes the RCC species from which is inferred and RCC-i the species to which is inferred with i+, i $\in$ {1, 2, 3, 5, 8} and i+ > i. Note that because of the transitive property of the inclusion operator in OWL DL the following holds:

$$((R_{(RCC\text{-}i+)+} \sqsubseteq R_{RCC\text{-}i+}) \wedge (R_{RCC\text{-}i+} \sqsubseteq R_{RCC\text{-}i})) \rightarrow R_{(RCC\text{-}i+)+} \sqsubseteq R_{RCC\text{-}i}.$$

Different from (1) formula (2) refers to an inference pattern which is quite common in description logics (including OWL DL). Unlike (1) it can, therefore, be processed by any OWL reasoner. Since the soundness and completeness of reasoning services for a great variety of description logics – including OWL DL – have been proven [1], we expect inferences with formula (2) to be sound and complete in a practical application.

5.3 Applying the Two Approaches

In order to demonstrate the theoretical results obtained with the two approaches to a representation of RCC in OWL, we use a sample of 44 two-dimensional spatial regions (polygons) from different GIS layers in the canton of Zurich (cf. figure 2). The regions are asserted as individuals in the ABox of our OWL DL knowledge base. The connections between them – which were identified by cartographic analysis – are asserted as role assertions of type C(x, y) for calculation with formula (1) or as role assertions in terms of the RCC-8 relations for inferences with formula (2). Overall, there are 262 relations asserted in our sample. The OWL reasoner Pellet (version 1.4) is used in order to access and manipulate the knowledge base. An additional reasoner used in order to compute formula (1) is programmed in Java. It accesses the knowledge base by means of standard OWL API.

Using formula (1) the RCC reasoner calculates 153 relations of type P(x, y). The cartographic evaluation results in 27 relations being falsely calculated as P(x, y) whereas they are relations of type EC(x, y). All relations of type P(x, y) verified by cartography are identified as such. As expected, the calculation with formula (1) is complete but not sound in our sample.

To give an example, one of the relations of type EC(x, y) which is falsely calculated as P(x, y) refers to the relation between Geroldswil and Oetwil (cf. figure 2). Since all regions connecting with Geroldswil also connect with Oetwil the relation between them is (falsely!) assumed to be of type P(x, y). As explained above, this is neither a shortcoming of the calculus nor of the theory but a result of the finite number of regions represented. If, for instance, the region in the east of Geroldswil were split into two similar sub regions and the southerly sub region only connected with Geroldswil but not with Oetwil, formula (1) would evaluate to false in this modified sample. That is, the hypothesis that P(Geroldswil, Oetwil) holds would be falsified.

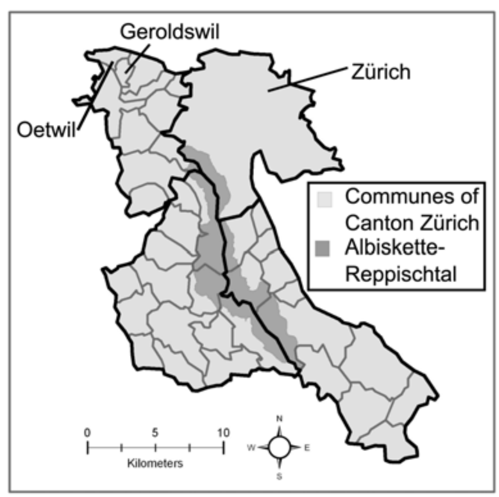

Figure 2. Regions in the canton of Zurich

The dark grey shaded region depicts Albiskette-Reppischtal, a biotope of national interest. Regions with bold borderlines depict districts. Regions with regular borderlines depict communes. Note

[2] Table 1 shows that, if P(x, y) were asserted for all pairs of regions for which this relation holds (and not C(x, y)), there would be a similar problem with verifying the existential proposition used to define O(x, y).

that the district of Zurich and the commune of Zurich share the same geometry, in terms of RCC: EQ(Bezirk_Zürich, Zürich).

Using formula (2) the OWL reasoner properly infers the 126 relations of type P(x, y) – calculated as EQ(x, y) $\vee$ PP(x, y) (cf. table 1) – from the RCC-8 relations asserted in our sample. It further properly infers the less specific RCC-5, RCC-3, RCC-2 and RCC-1 relations in a number of spot samples. As expected the reasoning service is sound and complete in these samples. Since reasoning services based on OWL DL are proven to be sound and complete, this part of our exploration confirms the OWL DL legality of our representation and the conformance of the OWL reasoner with the OWL DL specification.

To give an example, the RCC-3 relation overlapsNotEqual(Zürich, Albiskette-Reppischtal), which is not asserted in the knowledge base, is inferred from the asserted RCC-8 relation partiallyOverlaps(Zürich, Albiskette-Reppischtal) using the theorem [(partiallyOverlaps $\sqsubseteq$ overlapsNotEqual) $\wedge$ partiallyOverlaps(Zürich, Albiskette-Reppischtal)] $\rightarrow$ overlapsNotEqual(Zürich, Albiskette-Reppischtal).

6. DISCUSSION

Our exploration shows that the RCC-8 relations qualify for a minimal representation in order to effectively combine RCC with OWL DL in practical applications. Based on the 262 asserted relations, the OWL reasoner infers a total of 2228 relations. Thus the number of relations asserted as a minimal representation in our sample is roughly one tenth of the number of a full representation without counting the relations between regions which are not connected. The high number of inferred relations can be explained by the fact that for each connecting pair of regions the valid relations in all five RCC species plus the primitive relation C(x, y) are inferred. The high number is also a result of the inverses being inferred where these are defined and the symmetric relations being inferred from both ends.

7. CONCLUSION

The results obtained in section 5 suggest that the second approach can be applied to small applications in general. It requires that the relations between connecting regions are asserted in terms of RCC-8 in the ABox at the outset of the knowledge base. This implies that these relations can be easily determined in practical applications. However, this is not the case in large applications such as those underlying the bilingual ontology introduced in section 1. In these applications the identification of spatial relations involves a series of geometrical computations and relational operations. With the objective of streamlining this process, future work will explore methods for the calculation or approximation of spatial settings based on information which can be easily accessed from geographic information systems.

8. ACKNOWLEDGMENTS

The authors sincerely thank Jürg Schenker and Martin Brändli for the fruitful discussions and leadership that made this research possible. They also acknowledge the thorough proof-reading of the manuscript by Bettina Gutbrodt. This research has been funded and conducted in cooperation with the Swiss Federal Office for the Environment (FOEN). Related research was funded by the European Commission and by the Swiss Federal Office for Education and Science within the 6th-Framework Programme project REWERSE number-506779 (cf. http://rewerse.net).

9. REFERENCES

[1] Baader, F., and Nutt, W. Basic Description Logics. In F. Baader, D. Calvanese, D. L. McGuinness, D. Nardi and P. F. Patel-Schneider (Eds.), *The Description Logic Handbook*. Cambridge University Press, 2003, 47–100.

[2] Bauer-Messmer, B., and Grütter, R. Designing a Bilingual Eco-ontology for Open and Intuitive Search. In J. M. Gómez, M. Sonnenschein, M. Müller, H. Welsch and C. Rautenstrauch (Eds.), *Information Technologies in Environmental Engineering*. Springer, Berlin Heidelberg, 2007, 143–152.

[3] Bishr, Y. Geospatial Semantic Web. In S. Rana and J. Sharma (Eds.), *Frontiers of Geographic Information Technology*. Springer, Berlin Heidelberg, 2006, 139–154.

[4] Egenhofer, M., and Franzosa, R. Point-Set Topological Spatial Relations. *International Journal of Geographical Information Systems, 5*(2) (1991), 161–174.

[5] Federal Geographic Data Committee (http://www.fgdc.gov/ nsdi/ nsdi.html). Reston, VA, 2007, February 20.

[6] Frehner, M., and Brändli, M. Virtual Database: Spatial Analysis in a Web-based Data Management System for Distributed Ecological Data. *Environmental Modelling & Software, 21* (2006), 1544–1554.

[7] Grau, B. C., and Motik, B. *OWL 1.1 Web Ontology Language: Model-Theoretic Semantics. Editor's Draft of 27 November 2006.* The University of Manchester, 2006.

[8] Grütter, R., and Bauer-Messmer, B. Combining OWL with RCC for Spatioterminological Reasoning on Environmental Data. In *OWL: Experiences and Directions (OWLED)*. CEUR Workshop Proceedings, 2007.

[9] Grütter, R., and Bauer-Messmer, B. Towards Spatial Reasoning in the Semantic Web: A Hybrid Knowledge Representation System Architecture. *Lecture Notes in Geoinformation and Cartography*, Springer, Berlin, 2007.

[10] Horrocks, I., Kutz, O., and Sattler, U. The Even More Irresistible $\mathcal{SROIQ}$. In *Proceedings of the 10th International Conference of Knowledge Representation and Reasoning (KR-2006)* (Lake District, United Kingdom, 2006).

[11] Horrocks, I., Patel-Schneider, P. F., Boley, H., Tabet, S., Grosof, B., and Dean, M. *SWRL: A Semantic Web Rule Language Combining OWL and RuleML. W3C Member Submission 21 May 2004.* World Wide Web Consortium, 2004.

[12] Horrocks, I., and Sattler, U. Decidability of $\mathcal{SHIQ}$ with Complex Role Inclusion Axioms. In *Proceedings of the 18th International Joint Conference on Artificial Intelligence (IJCAI 2003)*. Morgan Kaufmann, Los Altos, 2003, 343–348.

[13] Katz, Y., and Grau, B. C. Representing Qualitative Spatial Information in OWL-DL. In *Proceedings of OWL: Experiences and Directions (Galway, Ireland, 2005)*.

[14] Patel-Schneider, P. F., Hayes, P., and Horrocks, I. *OWL Web Ontology Language: Semantics and Abstract Syntax. W3C Recommendation 10 February 2004.* World Wide Web Consortium, 2004.

[15] Randell, D. A., Cui, Z., Cohn, A. G. A Spatial Logic based on Regions and Connections. In B. Nebel, C. Rich, and W. Swartout (Eds.), *Principles of Knowledge Representation and Reasoning*. Morgan Kaufmann, San Mateo, CA, 1992, 165–176.