Spatio-Temporal Reasoning in CIDOC CRM: An Hybrid Ontology with GeoSPARQL and OWL-Time

Gilles-Antoine Nys

Geomatics Unit, ULiège, Quartier Agora B5a 4020 Liège, Belgium
ganys@uliege.be

Muriel Van Ruymbeke

Geomatics Unit, ULiège, Quartier Agora B5a 4020 Liège, Belgium
mvanruymbeke@uliege.be

Roland Billen

Geomatics Unit, ULiège, Quartier Agora B5a 4020 Liège, Belgium
rbillen@uliege.be

Abstract

Semantic description of cultural heritage information is already widely structured through CIDOC CRM and its different extensions. This shared understanding of cultural heritage information has already proved its usefulness. Until now, despite its spatial and temporal data management proposition, lack standardization limited the possibilities in terms of reasoning and workability. This paper proposes to increase the potentiality offered by the current scheme by including GeoSPARQL and OWL-Time in the framework. The result, as hybrid ontology, allows concurrent spatial and temporal handling. These are used to provide a near-full data management for complex spatio-temporal reasoning and querying through SPARQL queries. Example queries depicting the strength of the approach and allowing knowledge discovery in huge archaeological datasets illustrate its benefits.

2012 ACM Subject Classification Information systems → Ontologies

Keywords and phrases CIDOC CRM, cultural heritage, spatio-temporal reasoning, hybrid ontologies

Digital Object Identifier 10.4230/LIPIcs.COARCH.2018.

1 Introduction

Since several years, CIDOC CRM [14] and its extensions are regularly used to model archaeological data. We recently presented an extension proposal to allow cultural heritage knowledge semantic modelling, taking care of data imperfection [25]. In this paper, we describe the way we link semantic content with spatial and temporal data using standardized formalization. Indeed, CIDOC CRM and compatible extensions offers several possibilities to store temporal and spatial information. These propositions lack standardization, and

2nd Workshop On Computing Techniques For Spatio-Temporal Data in Archaeology And Cultural Heritage.
Editors: A. Belussi, R. Billen, P. Hallot, S. Migliorini

properties are not yet workable in computation algorithms. Consequently, there is no possibility to implement spatio-temporal queries.

To encounter this issue, we seized the opportunity given by an extension of CIDOC CRM: CRMgeo [13]. This module, providing links with GeoSPARQL [18] vocabulary for representing geospatial data, handles spatial content. About time, we opted for OWL-Time vocabulary [8] because of the non existence of management of temporal data in GeoSPARQL (see section 3.2).

Our paper will be organized as following: after a short presentation of the ontological context, we describe the way we articulate spatial and temporal classes and properties in the terminology of our formal ontology (Terminological box - TBox). After that we explain how we made the spatial and temporal properties workable combining GeoSPARQL and OWL-Time in an hybrid ontology. We will go on with the description of the instantiation of the assertion set (Assertional box – ABox). Finally, we finish by illustrating all these considerations giving three examples of complex queries run on our knowledge base structured around the proposed formal ontology.

2 Ontologies background

Thinking process about definition and description of the concepts used in cultural heritage domain began in the early nineties. Museum professionals took charge of these problematic under the aegis of ICOM-CIDOC (International Council of Museums – International Committee on Documentation). At that moment, the main goal was to create a common and interoperable framework for IT developments dedicated to museum activities.

A first version of the CIDOC Conceptual Reference Model was published in 1998 [9]. In 2006, it became an official standard (ISO 21127:2006). After that, the revised ISO standard (ISO 21127:2014) provided an update and is available since 2014. The current version [14] was published in early 2018.

Over the years, CIDOC CRM was deeply transformed and improved. It was adapted to match with Semantic Web standards and it was expanded to span the entire field of cultural heritage documentation. This includes archaeology, architecture, intangible heritage and so on (examples taken of [6], [23], [15], [16], [17]). Moreover, compatible models and collaborations have fleshed it out in specific aspects. It is notably the case: CRMsci for Scientific Observation Model [11], CRMinf for Argumentation Model [23], CRMarchaeo for Excavation Model [10], CRMba for Archaelogical Buildings [20], CRMgeo for Spatio-temporal Model [13] and FRBRoo for Functional Requirements for Bibliographic Records [5].

Recently, we proposed an extension dedicated to store fuzzy, incomplete, incoherent and imprecise data: EPA (Expansion Proposal A) [25]. This proposal relies on principle of separation between phenomenal and descriptive worlds defined in CRMgeo. In this approach, spatial and temporal data is considered as information given about real chronology and localization of phenomenal objects. After having tested and validated our extension with semantic content, we turned to testing it with geometrical and chronological content.

From a computer science point of view, terminological box (TBox) [3] structures the conceptualization in a specific domain within a graph structure and controlled vocabularies. CIDOC CRM creators proposed therefore several possibilities to store spatial and temporal information related to cultural heritage objects [17]. The illustration of facts, TBox-compliant statements, populates the graph: it is the assertional box (ABox). TBox concepts and ABox facts statements constitute a knowledge base (see Figure 1).

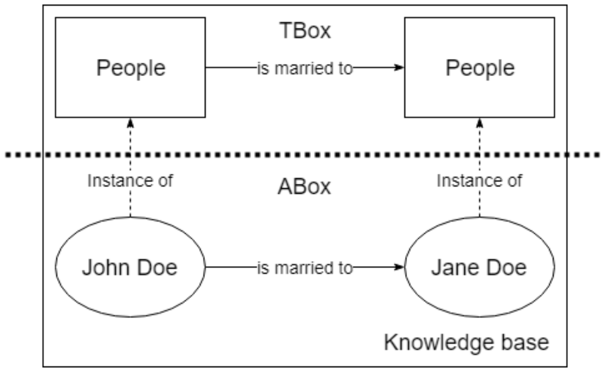

Figure 1 Generic structure of a Knowledge Base

3 Terminological box - TBox

CIDOC CRM provides a TBox which defines cultural heritage concepts and describes their relationships. Besides CIDOC spatial classes (*E53 Place*, *E44 Dimension*, *E47 Spatial coordinates* and *E94 Space Primitive*), the model offers properties which fulfil most common topological spatial relations (Dimensionally Extended nine-Intersection Model (DE-9IM) [12] [7], Region Connection Calculus (RCC8) [19]). Some temporal classes are also provided (*E49 Time Appellation*, *E50 Date*, *E52 Timespan*). Temporal properties, range from P114 to 120, and their inverses overlay Allen's intervals [1] [2] are also part of the proposition. In addition, properties from P173 to P185 allow dealing with relations between time intervals with fuzzy boundaries. Finally, CIDOC defines class *E92 SpaceTime Volume* that designates four dimensional points sets and has temporal (*CIDOC:P160*) and spatial (*CIDOC:P161*) projections.

Besides this, the CRMgeo extension provides spatial and temporal classes and properties dedicated to formulate declarative information. It also provides links with GeoSPARQL [18]. Indeed, these links with the OGC GeoSPARQL standard are necessary " . . . to make use of the conceptualization and formal definitions that have been developed in the Geoinformation community . . . " [13]. The same remark could be held true in regard to time information. However, CIDOC CRM provides no link to widely used standard like, for instance, OGC OWL-Time [8]. It is important to note that CRMgeo provides no link neither with temporal ontology.

Regarding the use of data types and data properties specifically developed for temporal information, CIDOC CRM offers the possibility to implement individuals type of *E50 Date*. Data types, as *xsd:gYear*, that has a more frequent use in cultural domain, are not yet supported. Currently, in CIDOC-CRM, date types need to register (and thus, to know) the day, the month and the year. Those precisions are rarely present in archaeological data. On another hand, data properties targeting these data types come from *CIDOC CRM:E52 Time Span*. This statement affects the domain of classes that need to be strictly subclasses of E52 entities. At least, for spatial data types, *geo:gmlLiteral* and *geo:wktLiteral* cannot be specifically recognized in CIDOC CRM [17] and CRMgeo therefore encourages the use of GeoSPARQL to this end.

To take advantage of data implemented into the knowledge base, and to be able to run queries or to infer relations, it is necessary, as explained in the spatial representation section 3.1, to have implemented rules and/or reasoning axioms. Such rules do not exist in early stages of CIDOC CRM or in its spatial extension CRMgeo [17]. To formalize these rules, we transcribe logical and topological statements in Semantic Web Rule Language (SWRL). Description logic results ensue then from the asserted rules. For this reason, we choose to use GeoSPARQL and OWL-Time besides CIDOC CRM respectively for storing geometrical and temporal information and to take advantage of their standardized formalization. Following sections explain the different pros and cons to take into account in SWRL.

Commonly, working with GeoSPARQL supposes to structure spatial assertion of geometries as: *geo:Feature geo:hasgeom geo:Geometry* [18]. Some may consider time as a graduated line but GeoSPARQL imposes to formalise geometries in WKT or GML, in which graduation are not supported. OWL-Time provides approximately the same schema with property *owl:Thing time:hastime time:TemporalEntity*, which "... supports the association of temporal information with any temporal entity, such as an activity or event, or other entity... and provides a standard way to attach time information to things, which may be used directly in applications if suitable, or specialized if needed" [8]. This OWL-Time property coming from any domain allows easily linking. *A contrario*, it is not the case with GeoSPARQL where *geo:hasGeometry* relation must have a *geo:Feature* or one of its subclasses as subject. As we do not have "feature" in such, we added another way to link our data with their geometry: *geo:Geometry* are defined as topclass of *SP5 Geometric Place Expression*. Accordingly, *SP5 Place Expression* can be *geo:Point*, *geo:Polygon* ... These entities are linked to correspondent instances of class *SP6 Declarative Place*, the "features", with the existing property *Q10 defines place*. These considerations are depicted in Figure 2 where EPA (Expansion Proposal A) is an extension dedicated to store fuzzy, incomplete, incoherent and imprecise data [25].

On another hand, instead of using *time:hasTime* property between *SP10 Declarative Time Span* and *SP14 Time Expression*, we used the existing and already implemented property *Q14 defines time*. We also created an equivalence between *SP14 Time Expression* and *time:TemporalEntity*. This equivalence allowed us to make *SP14 Time Expression* instances also instances of *time:Instant* or *time:Interval*. Actually *owl:sameAs* relation is mandatory between the considered individuals.

These two mappings bring here the notion of hybrid approach: different top-level ontologies are used to define common semantic concepts. Because of the hierarchy and *owl:equivalentTo* relations, this approach is different from multiples ontologies, where ontologies are used in a common application but without any merging. Ontologies associations are strong and semantic content is widely consolidated.

3.1 Spatial representation

Spatiality is an aspect of the data that is difficult to represent and store. Geospatial topology studies the spatial relationships between connecting or adjacent features (points, polylines and polygons). These features and their compositions are so called geometries within the context of databases. In order to handle spatial representation of the real world, two solutions are proposed: SOWL and GeoSPARQL.

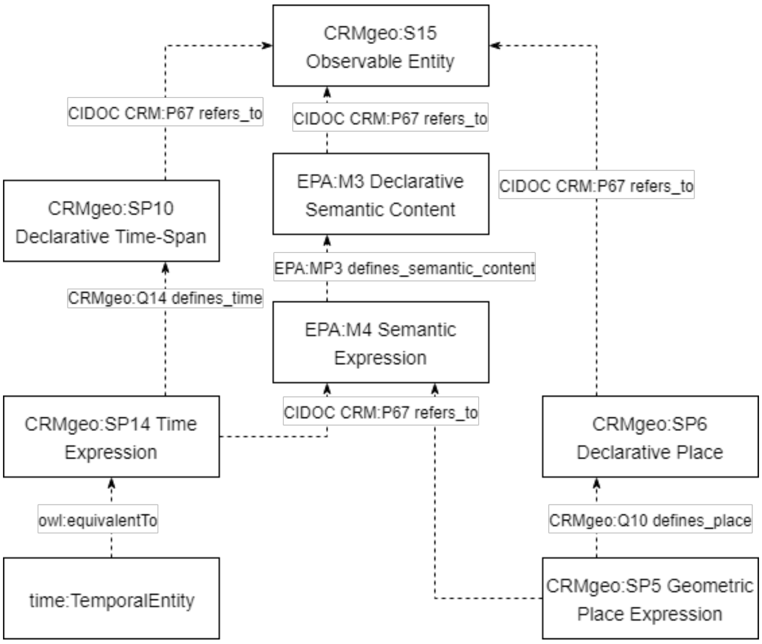

Figure 2 Semantic Expression context

A first example is the approach proposed by SOWL [4], where spatial relations are especially defined using a compass, a cone-based direction representation, and RCC8 relations between entities [19]. Composition tables of these relations can then be translated into rules for reasoning in ontologies.

Composition tables are simple configuration that defines elements as made of elements of the same type. Composition is the result of higher-level rules. For instance, if an Object A contains an Object B and the Object B equals a third Object C, therefore, Object A contains Object C. The composition of all the relations combinations and their results are stored in a table: the composition table. These permit the discovery of knowledge based on asserted relations. This way, relations between concepts can be set but they are not set on objects or their representations but between relations themselves: those entities which are linked are only concepts related to the real objects and do not refer to any proper coordinate or location.

Although topological relations between geometries are indeed well defined and documented in GeoSPARQL (DE-9IM [12] , RCC8 . . .), these are passive. By "passive", we consider here the fact that these relations are not workable by algebraic or logical operations. The semantic content of relations, mostly data type properties, is not workable within the ontology: it is not possible to simply add, multiply, operate . . . their values. Just as it is not possible in SOWL. They need to be processed by other external tools to permit arithmetic, logical or, in a greater dimension, topological computations.

To handle this, frameworks provide plugins, such as GraphDB Java[1], that implement built-in functions for topological and spatial computations in SPARQL queries and spatial indexes. These functions are approved by the OGC Naming Authority and accordingly widely used.

[1] Official documentation : http://graphdb.ontotext.com/documentation/standard/

Thanks to these algorithms, it is possible to compute geometries in a effective way. Topological computations constitute big challenges in databases because of their time-consuming and complexity requirements.

Indexing data following Lucene Apache Spatial[2] indexation methods and extracting them from the graph database, 2D Euclidean/Cartesian geometries can thus be processed through distance and other spatial related math calculations. Lucene only managed WKT-serialised data, which is supported by GeoSPARQL, and improve performances on shapes search. As many *Triple Stores*, GraphDB provides both the predicate-object-subject (POS) index and the predicate-subject-object (PSO) index for triples management. Therefore, because of the use of connectors to these external operations, topological reasoning is achievable. Disadvantages of the method: it needs a complete framework: SPARQL Endpoint, connectors and functions, such as GraphDB provides them. Moreover, the processed elements need to be expressed in a common and well-described spatial reference system to guarantee results consistency.

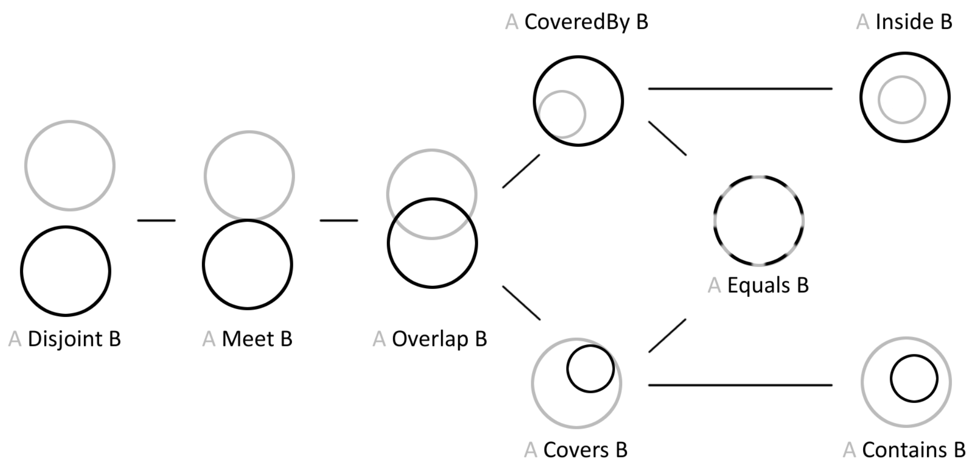

Figure 3 9-Intersection Model

In our study, the choice is made to use second solution GeoSPARQL, defining all data following the Well-Know Text standard (WKT), one of the two standards currently supported by GeoSPARQL. The spatial reference system is set as Belgian Lambert 72. Those data are simply defining the concepts and no topological relations are stored in the database. An example of spatial SPARQL query is provided and explained in the section 5 using the DE-9IM built-in functions, see Figure 3.

3.2 Temporal representation

As it is explained for spatial reasoning, complex reasoning often need external tools to operate data: logical reasoner, built-ins functions ... In our study, spatial information is handled with external plugins. *A contrario*, temporal queries are set up with Semantic Web Rule Language (SWRL). This methodology is a bit different of the previous one because rules

[2] Official website : https://lucene.apache.org/

are formalised within the ontology file but still need a reasoner to be expressive. Pellet [22] is chosen because of its support of SWRL built-in functions. So that, after reasoning, the inferred model consolidates the triples based on the rules. The database can then be updated and avoid further computations or complex queries.

As a reminder, two solutions are proposed in the context of temporal representation: OWL-Time, OGC standard, and SOWL, which introduces SWRL inferred temporal relationships between entities based on OWL-Time definitions.

Defined in OWL-Time, Allen's relationships (see Figure 4) can be used as conditions part in SWRL rules bodies and heads. Differently from the temporal data management of SOWL proposition [4], no composition table is used to build relations on previously asserted relations. In our study, Allen's relationships are results of reasoning and logical computations on dates. Moreover, this proposition makes the links between different temporal entities: intervals (time span between two dates) and instants (a single date). This permit links between different classes and levels in the taxonomy.

Because of this bottom-up approach, the knowledge discovery is considered as wider. One can so discover complex knowledge, for instance relations between intervals from their constituting dates. The former SOWL proposition, which is a top-down approach, decompose the asserted definitions. In a knowledge discovery point of view, it is much better to discover knowledge from data that could be automatically generated than decompose a complex human-made dataset. Possibilities are now open.

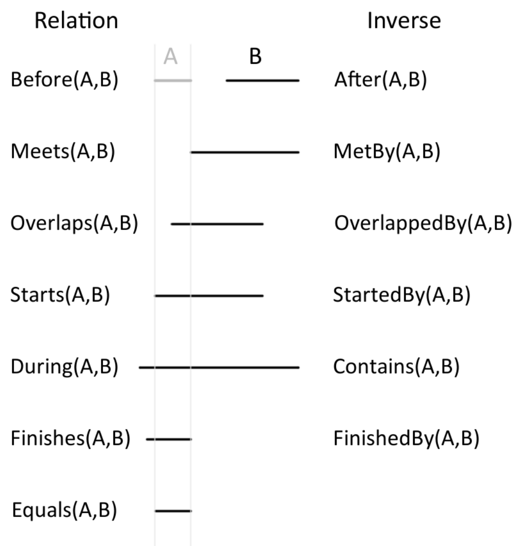

Figure 4 Allen's temporal relationships

About the level of granularity considered in this study, the simplest constituting elements of time is the year. These are so called Instant and refer to the *time:Instant*. At least two *time:Instant* constitute an interval (*time:Interval*). Just like spatial geometries, temporal entities are not workable but needs to be decomposed. Each temporal entity is defined by datatype properties. These properties store year, month, time stamp ... About the time granularity, only the *inXSDgYear* relation, which provides the Gregorian year format of the concept, processed to prove the concept. Because of this constructing relation, SWRL rules are divided in two main sets: top rules, which are based on instants, and Allen's relations based rules, which are based on the top rules.

Top rules are structured around *time:Instant* and a basic inequality between two of them. Time is nothing more than an ordered one-dimension vector of values, which are separated in equal intervals. Therefore, it is possible to determine if one of the value is greater or less than another one. This rule simply expresses this statement and defines the *time:before* relation as a result of two instants when the former is less than the later.

Listing 1 Transcription of before relation rule

```
inXSDgYear(?xInstant, ?xXSD) ^ inXSDgYear(?yInstant, ?yXSD) ^ swrlb:
    lessThan(?xXSD, ?yXSD) -> before(?xInstant, ?yInstant)
```

The inverse rule, *time:after*, is already defined in the initial ontology OWL-Time. A second rule, which expresses equality between two instants, results in an *owl:sameAs* relation. This relation defines that, indeed, both the individuals are two names for a same concept.

Allen's relations based rules are structured on top rules and their results. OWL-Time provides passive semantic definitions. All basic relations and their corollary are written and tested in the scope of this research. However only one relation is depicted and explained in this paper:

Semantic definition of *time:intervalBefore* relation from OWL-Time :

▶ **Theorem 1.** *If a proper interval T1 is intervalBefore another proper interval T2, then the end of T1 is before the beginning of T2.*

Listing 2 Transcription of intervalBefore corollary rule

```
ProperInterval(?T1) ^ ProperInterval(?T2) ^ hasEnd(?T1, ? T1End) ^
    hasBeginning(?T2, ?T2Begin) ^ before(?T1End, ?T2Begin) ->
    intervalBefore(?T1, ?T2)
```

It is important here to pay attention to the fact that *time:before* and *time:intervalBefore* are two different relations with their proper domains and ranges. The former expresses association between two *time:Instant* and the second two *time:ProperInterval*, a hierarchy subclass of *time:Interval*.

One relation is set to link both *time:Instant* and *time:Interval*: *time:inside*. It specifies that an instant is strictly included in an interval. The equality with one of the interval limits results in the previous *owl:sameAs* definition.

Listing 3 Transcription of inside relation rule

```
time:Interval(?i) ^ time:hasBeginning(?i, ?iB) ^ time:hasEnd(?i, ?iE) ^
    time:Instant(?m) ^ time:after(?m, ?iB) ^ time:before(?m, ?iE) -> time:
    inside(?i, ?m)
```

Important advantage of this methodology is that all the rules are computed only one time. It is not an incremental process that involves many steps or complex configuration. The influence of each relation, class or individual is therefore taken into count in all sub-computations. Possible drawback is the computation time needed to achieve a result. An example of temporal SPARQL query is provided and explained in section 5 using the Allen's built-in relations.

4 Assertional box

As explained above, geometries instantiation is rather simple: instances of *geo:Geometry* are subclasses of *CRMgeo:SP5 Geometric Place Expression*. Those are then defined by a data type property *geo:asWKT* that stores the geometry as a *geo:WKTLiteral* (see Figure 5).

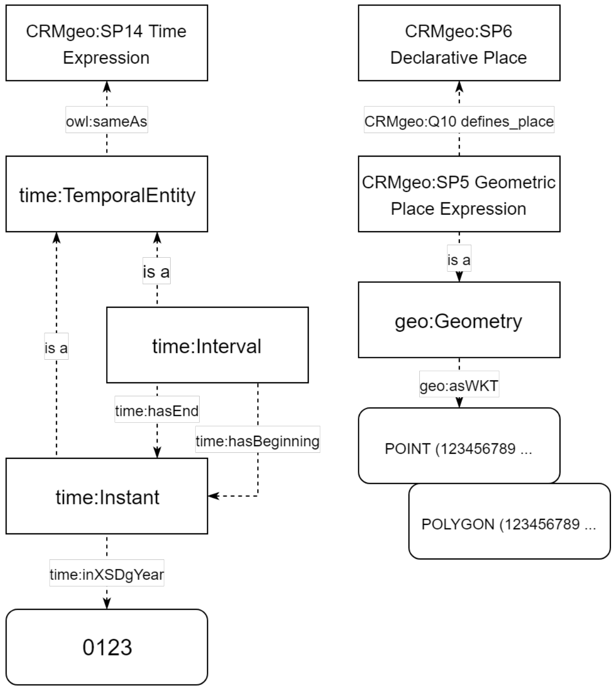

Figure 5 Semantic Expression context

To instantiate temporal data, thanks to the equivalence between *CRMgeo:SP14 Time Expression* and *time:TemporalEntity*, instances of *CRMgeo:SP14 Time Expression* are also *time:Instant* or *time:Interval* (see Figure 5). Since we first had to choose the adequate granularity, where we opted for "year", our instantiated instants are Gregorian years. Commonly, intervals are constituted by a beginning (an instant *time:hasBeginning*) and an end (another instant *time:hasEnd*), but it is also possible to make them begin with a *time:DateTimeInterval* (a day, a month, a year, ...). *Nota bene*, this is the way that PeriodO [21] collection has chosen to implement its intervals' starts and ends.

As explained in OWL-Time ontology, seven properties and their inverse provide alternative ways to describe the temporal relation between two intervals. To store an instant, we choose *time:inXSDgYear* which was the simplest way to allow our temporal reasoning rules to operate.

5 Architecture and spatio-temporal queries

Previous sections was dedicated to theoretical and structural needs to store and/or compute spatial and temporal data in CIDOC. Proposition on theoretical and assertional boxes were defined. This section illustrates possibilities now offered by our architecture especially through complex SPARQL queries.

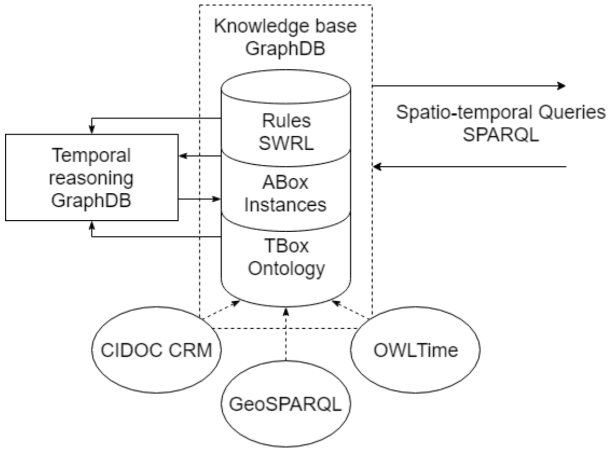

Figure 6 System architecture

The knowledge base is a common GraphDB system architecture (see Figure 6). Temporal reasoning is performed using the integrated reasoner of GraphDB and total materialization assumption (inferences are computed after every modification to the Knowledge Base). GraphDB provides a SPARQL Endpoint with support of GeoSPARQL for querying.

For instance, topological reasoning is also possible to determine which elements are defined by a *geo:Geometry*, a WKT point, which is contained within a study zone, that is also defined by a *geo:Geometry*, a WKT multipolygon. For example:

Listing 4 Which other objects are in Wallonia?

```
PREFIX geosparql: <http://www.opengis.net/ont/geosparql#>
PREFIX geof: <http://www.opengis.net/def/function/geosparql/>
PREFIX CRMGeo: <http://www.ics.forth.gr/isl/CRMgeo/>

select ?DeclarativePlace where {
    :Wallonia_geometry CRMGeo:Q10_defines_place :Wallonia .
    :Wallonia_geometry geosparql:asWKT ?WalWKT .
    ?Geometry CRMGeo:Q10_defines_place ?DeclarativePlace .
    ?Geometry geosparql:asWKT ?GeomWKT .
    FILTER(geof:sfContains(?WalWKT, ?GeomWKT)) .
}
```

Temporal queries are possible over date time but also on date intervals. The different types of relations (instant/instant, instant/interval and interval/interval) may lead to knowledge discovery. Here is an example of temporal query:

Listing 5 What are the intervals that end after 750 and do not have a known beginning date?

```
PREFIX time: <http://www.w3.org/2006/time#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT * WHERE {
```

```
    ?interval time:hasEnd ?end .
    ?end time:inXSDgYear ?xsdE .
    FILTER(?xsdE > "0750"^^xsd:gYear) .
    FILTER ( !EXISTS{ ?interval time:hasBeginning ?beginning })
}
```

These two query examples can be merged into a complex spatio-temporal query. The different aspects, semantic, temporal and spatial, of the query are split here to keep consistency in the reading.

Listing 6 What are the semantic expression that speaks about an entity that existed after 1500 in Wallonia?

```
PREFIX MVR: <http://www.geo.ulg.ac.be/MVR/>
PREFIX geosparql: <http://www.opengis.net/ont/geosparql#>
PREFIX geof: <http://www.opengis.net/def/function/geosparql/>
PREFIX CRM: <http://www.cidoc-crm.org/cidoc-crm/>
PREFIX CRMGeo: <http://www.ics.forth.gr/isl/CRMgeo/>
PREFIX time: <http://www.w3.org/2006/time#>

SELECT ?SemanticExpression ?DeclarativePlace WHERE {
    ?TimeExpression CRM:P67_refers_to ?SemanticExpression .
    ?Geometry CRM:P67_refers_to ?SemanticExpression .

    ?TimeExpression time:hasEnd ?end .
    ?end time:inXSDgYear ?xsdE .
    FILTER(?xsdE > "1500"^^xsd:gYear) .

    :Wallonia_geometry CRMGeo:Q10_defines_place :Wallonia .q<
    :Wallonia_geometry geosparql:asWKT ?WalWKT .
    ?Geometry CRMGeo:Q10_defines_place ?DeclarativePlace .
    ?Geometry geosparql:asWKT ?GeomWKT .
    FILTER(geof:sfContains(?WalWKT, ?GeomWKT)) .
}
```

The computation query needed at most 0.2 seconds on a GraphDB triples store (Free Version), which implements 26000 triples and is hosted on HDD. SSD will be much less computational time.

Such queries also make the comparison possible between different semantic expressions. One of the extensions of this paper will automatise the identification of conflicting declarations. Declarations made from heterogeneous sources may lead to inconsistency in the knowledge base and therefore, errors explanations will help to find antagonist discourse [24]. Are people speaking of the same historical elements? Do people have the same conception of a real-world entity?

6 Conclusion and future work

Cultural heritage information is a field of study since several years. CIDOC CRM defines many extensions to structure information for scientific observation, argumentation, excavation... While spatio-temporal reasoning is at the centre of archaeologists' lifework, its workability in information management, in an automatic way, is not yet supported. GeoSPARQL and OWL-Time fill an important gap. Applications of such a tool can be depicted in all areas of their profession: museums, libraries, archives ... The proposed hybrid ontology allows supporting their efforts and therefore facilitates them.

Knowledge discovery limits are pushed a little further. Archaeological data management is simplified. Machine learning algorithms now have a well-defined structure to build semantic applications that involve spatio-temporal reasoning. Linking such engine with a graph database as DBPedia or Wikidata opens a new horizon.

Future work will, on the basis of the suggested mapping, build consistency analysis and errors detection from heterogeneous sources: concurrent declarative discourse, antagonistic interpretative sequence...

Acknowledgements. The authors would like to thank the anonymous reviewers for their valuable comments and suggestions to improve the quality of the paper.

References

1 J. F. Allen. Towards a general theory of action and time. *Artificial Intelligence*, 23(2):123–154, July 1984. doi:10.1016/0004-3702(84)90008-0.

2 J. F. Allen. Time and time again: The many ways to represent time. *International Journal of Intelligent Systems*, 6(4):341–355, July 1991. doi:10.1002/int.4550060403.

3 Franz Baader, Diego Calvanese, Deborah L. McGuinness, Daniele Nardi, and Peter F. Patel-Schneider. *The Description Logic Handbook: Theory, Implementation and Applications*. Cambridge University Press, New York, NY, USA, 2nd edition, 2010.

4 S. Batsakis and E. G. M. Petrakis. SOWL: A Framework for Handling Spatio-temporal Information in OWL 2.0. In *Rule-Based Reasoning, Programming, and Applications*, Lecture Notes in Computer Science, pages 242–249. Springer, Berlin, Heidelberg, July 2011. doi:10.1007/978-3-642-22546-8_19.

5 C. Bekiari, M. Doerr, P. Le Boeuf, and P. Riva. FRBR object - oriented definition and mapping from FRBRer, FRAD and FRSAD Current version (version 3). Technical report, September 2017.

6 C. Binding, K. May, and D. Tudhope. Semantic Interoperability in Archaeological Datasets: Data Mapping and Extraction Via the CIDOC CRM. In B. Christensen-Dalsgaard, D. Castelli, Bolette Ammitzbøll J., and J. Lippincott, editors, *Research and Advanced Technology for Digital Libraries*, volume 5173, pages 280–290. Springer Berlin Heidelberg, Berlin, Heidelberg, 2008. doi:10.1007/978-3-540-87599-4_30.

7 E. Clementini, P. Di Felice, and P. van Oosterom. A small set of formal topological relationships suitable for end-user interaction. *Advances in Spatial databases LNCS 692*, pages 277–295, 1993.

8 S. Cox and C. Little. Time Ontology in OWL. Technical report, October 2017.

9 N. Croft, I. Dionissadou, M. Doerr, and P. Reed. CIDOC - Conceptual Reference Model - Information Groups. Technical Report version 1, September 1998.

10 M. Doerr, A. Felicetti, S. Hermon, G. Hiebel, A. Kritsotaki, A. Masur, K. May, P. Ronzino, W. Schmidle, M. Theodoridou, D. Tsiafaki, and E. Christaki. Definition of the CRMarchaeo. An extension of CIDOC CRM to support the archaeological process. version 1.4.5 April 2018. Technical report, April 2018.

11 M. Doerr, A. Kritsotaki, Y. Rousakis, G. Hiebel, and M. Theodoridou. CRMsci: Scientific observation model. Definition of the CRMsci. An extension of CIDOC-CRM to support scientific observation. proposal for approval by CIDOC CRM-SIG. Version 1.2.5 September 2017. Technical report, May 2018.

12 M. Egenhofer and R. Franzosa. Point-set topological spatial relations. *International Journal of Geographical Information Systems*, 5(2):161–174, 1991.

13 G. Hiebel, M. Doerr, Ø. Eide, and M. Theodoridou. CRMgeo: a Spatiotemporal Model. An Extension of CIDOC-CRM to link the CIDOC CRM to GeoSPARQL through a Spatiotemporal Refinement. Proposal for approval by CIDOC CRM-SIG Version 1.2. September 2015. Technical report, September 2015.

14 P. Le Boeuf, M. Doerr, C. E. Ore, and St. Stead. Definition of the CIDOC Conceptual Reference Model. Produced by the ICOM/CIDOC Documentation Standards Group, Continued by the CIDOC CRM Special Interest Group. Version 6.2.3 Mai 2018. Technical report, May 2018.

15 E. Le Goff, O. Marlet, X. Rodier, S. Curet, and P. Husi. Interoperability of the ArSol (Archives du Sol) Database based on the CIDOC-CRM Ontology. In *Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology CAA 2014 - 21st Century Archaeology*, pages 179 – 186, Paris, 2015. Giligny F., Djindjian F., Costa L., Moscati P., Robert S.

16 O. Marlet, S. Curet, X. Rodier, and B. Bouchou-Markhoff. Using CIDOC CRM for Dynamically Querying ArSol, a Relational Database, from the Semantic Web. In *Proceedings of the 43rd annual conference on computer applications and quantitative methods in archaeology. CAA2015 - Keep the Revolution going*, pages 241 – 249, Sienne, 2016. S. Campana, R. Scopigno, G. Carpentiero, M. Cirillo.

17 S. Migliorini and P. Grossi. Towards the Extraction of Semantics from Incomplete Archaeological Records. In *Proceedings of Workshops and Posters at the 13th International Conference on Spatial Information Theory (COSIT 2017)*, Lecture Notes in Geoinformation and Cartography, pages 349–358. Springer, Cham, September 2017. `doi:10.1007/978-3-319-63946-8_52`.

18 M. Perry and J. Herring. GeoSPARQL - A Geographic Query Language for RDF Data | OGC, September 2012.

19 D. A. Randell, Z. Cui, and A. G. Cohn. A spatial logic based on regions and connection. *Proc. 3rd Int. Conf. on Knowledge Representation and Reasoning*, page 165–176, 1992.

20 P. Ronzino, F. Niccolucci, A. Felicetti, and M. Doerr. Definition of the CRMba. An extension of CIDOC CRM to support buildings archaeology documentation. Proposal for approval by CIDOC CRM-SIG, Version 1.4, April 2016. Technical report, 2016.

21 Ryan Shaw, Adam Rabinowitz, Patrick Golden, and Eric Kansa. A sharing-oriented design strategy for networked knowledge organization systems. *International Journal on Digital Libraries*, 17(1):49–61, March 2016. doi:10.1007/s00799-015-0164-0.

22 E. Sirin, B. Parsia, B. C. Grau, A. Kalyanpur, and Y. Katz. Pellet: A practical OWL-DL reasoner. *Web Semantics: Science, Services and Agents on the World Wide Web*, 5(2):51–53, June 2007. doi:10.1016/j.websem.2007.03.004.

23 S. Stead, D. Oldman, and J. W. Cloud. Exploring Time ans Space in the Annotation of Museum Catalogues: The Sloane Virtual Exhibition Experience. In *Proceedings of the 42nd Annual Conference on Computer Applications and Quantitative Methods in Archaeology CAA 2014 - 21st Century Archaeology*, pages 221 – 225, Paris, 2015. Giligny F., Djindjian F., Costa L., Moscati P., Robert S.

24 Mehdi Teymourlouie, Ahmad Zaeri, Mohammadali Nematbakhsh, Matthias Thimm, and Steffen Staab. Detecting hidden errors in an ontology using contextual knowledge. *Expert Systems with Applications*, 95:312–323, April 2018. doi:10.1016/j.eswa.2017.11.034.

25 M. Van Ruymbeke, P. Hallot, G.-A. Nys, and R. Billen. Implementation of multiple interpretation data model concepts in CIDOC CRM and compatible models. *Virtual Archaeology Review*. doi:10.4995/var.2018.8884.