A Semantic Analysis of Moving Objects Using as a Case Study Maritime Voyages from Eighteenth and Nineteenth Centuries

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***Abstract*—In this paper, we present a spatial model designed to extract knowledge from the tracks of moving objects. The model uses a *perdurantism* approach, implemented using Semantic Web technologies. In order to show the capabilities of the model, we employ it to handle a large dataset composed of historic maritime records. By using Semantic Web tools, we are able to implement rules and identify user defined patterns. Although there are limitations due to currently available tools, our results are promising.**

Keywords–spatial modeling; moving objects; semantics.

I. INTRODUCTION

The two main philosophical theories for the representation of objects evolving along time are: *endurantism* and *perdurantism*. The first one, *endurantism*, considers objects as three dimensional entities that exist wholly at any given point of their life. On the other hand, *perdurantism*, also known as the four dimensional view, considers that entities have temporal parts, *timeslices* [1]. Each *timeslice* is a partial representation of the object, valid only for a specific period or point of time. A complete representation of the object along time is the result of aggregating all its *timeslices*. From a designer point of view, the *perdurantism* approach offers advantages over the *endurantism* one, by allowing richer representations of real world phenomena [2].

Most of current Geographic Information Systems (GIS) tools use a *snapshot* approach to study spatial systems. With this type of tools, it is difficult to analyse dynamic phenomena with spatial-temporal dimensions. An alternative to traditional data management approaches is the Semantic Web. This is a set of standards that enable sharing data and semantics of the data on the web. Using Semantic Web related technologies, it is possible to develop data models called ontologies specifically designed for reasoning and inference with software mechanisms. Ontologies allow for any given domain, the representation of relevant high level concepts as well as their properties and the relationships between concepts and entities. In this research, we use Semantic Web technologies to develop the “continuum model”, an ontology that allows us to represent diverse dynamic entities and analyse their relationships along time. Traditionally, ontologies are static in the sense that the information represented in them does not change in time or space. However, previous research such as [1] [3] [4] and [5] aim to fill this gap, by developing ontologies that use a *perdurantism* approach to handle dynamic entities. The focus of [4] and [5] is on evolving entities represented in space as areas. In this paper, we propose an extension of the previous research, changing the focus to moving entities. In this paper, we use historical maritime records as a test bed. In Section II, we identify other works in this field. Section III provides a description of the dataset we use. We describe our model and how we implement it in Section IV. Finally, in Section V, we present our conclusions and indicate our future research in this field.

II. RELATED RESEARCH

Currently, new datasets containing large amounts of tracking data are becoming available. These datasets contain the recorded position of a travel entity while it moves in space. In order to extract knowledge from this information, a new set of tools and algorithms are being developed in the research world. In Parent et al., 2013, the authors present a survey on current approaches and techniques for the definition of *semantic trajectories* within the field of *data mining*. This paper describes techniques to create trajectories from raw data, to add semantics to the trajectories and to extract knowledge [6].

A raw *trajectory* comprises the record of the position of a moving entity, during a time interval, in which this entity moves for some meaningful purpose. In some domains, the identification of the begin and end of the trajectory is evident, while in others this might require some domain specific criteria. The positions and intervals allow us to identify possible *stops* along the trajectory. Additional information can be obtained by linking the trajectory to external datasources. For instance, comparing the track record of a person with a set of places of interest of a city, could tell us what places has the person visited [6].

By analyzing the trajectory, it is possible to identify stops and elements on the route. Then, we can add *annotations* creating in this way a *semantic trajectory*. An analysis of the trajectory can also lead to the identification of a particular behaviour of the moving entity. For instance, by analyzing the elements on the route of a tracked person, we could distinguish a tourist from a pizza delivery service [6].

An implementation of the previously described concepts is presented in Spaccapietra et al., 2008 [7]. Here, the authors implement their approach with a relational Database Management System (DBMS), using as a case study data from the annual migrations of white storks *(Ciconia ciconia)*.

An approach that puts more focus on Description Logics (DL) based tools is presented in Yan et al., 2008. Here, the authors propose the use of three different ontologies to address the study of moving entities. The first one is caled *Geometric Trajectory Ontology*. This ontology defines the basic concepts for the spatio-temporal definition of the trajectory. Using the elements defined in this ontology, we can specify temporal points, areas, lines etc. The second one is called *Geography ontology*. In this ontology, the authors describe natural and artificial features of interest for the specific domain. Finally, the third one is called *Application Domain Ontology*. In this ontology, the authors define higher level concepts for specific domains. In Yan et al., 2008, the authors test their ideas using data from cars equipped with GPS devices. The data is loaded into a commercial relational DBMS with support for ontological data [8].

In Yan et al., 2011, the authors introduce the Semantic Middleware for Trajectories (SeMiTri). This software is designed to create *annotations* by analyzing the geometric properties of the trajectory and linking it to background geographic and application specific data. The proposed system has three parts: 1) *Trajectory computation layer*, here the raw GPS data is cleaned, raw trajectories are identified and each trajectory is divided into trajectory episodes. 2) *Semantic annotation layer*, to link the trajectory to areas it crosses, road networks. It also estimates probabilities of association between *stops* and geographic features using a Markov model algorithm. 3) *Semantic trajectory analytics layer*, here are the components of the system that compute statistics, and store obtained information. An additional component is the Web Interface, designed to allow the user to define queries and visualize results [9].

An example of a *perdurantism* approach for spatial dynamics is presented in Harbelot, Arenas & Cruz, 2013b. In this research, the authors introduce the *continuum* model, a methodology that can successfully represent the changes of entities in space and property values along time [5]. However, this approach focuses on entities represented as areas, making the approach not well suited for moving entities represented as points. In this paper, we further define the *continuum* model to represent traveling entities. In the next sections, we will describe the datasets and the model we propose.

III. DATASETS

In this paper, we present a methodology to model spatial moving objects using a Semantic Web approach. Our moving objects are ships from the eighteenth and nineteenth centuries, whose positions have been recorded in logbooks. Between 2001 and 2003 the European Union funded the project: Climatological Database for the World's Oceans (CLIWOC). A product of this project is the digitized version of logbooks of pre 1854 voyages of English, Spanish, Dutch and French ships [10][11].

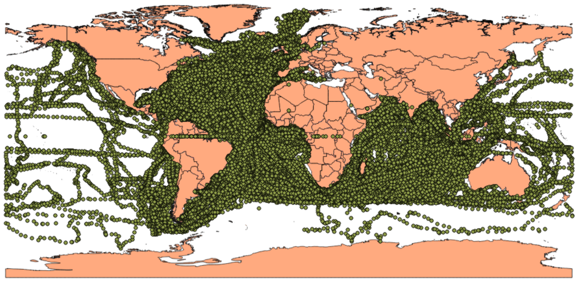

Figure 1. CLIWOC dataset, points represent logbook records.

The CLIWOC datasets became available online in 2003 [12]. The dataset contains 280280 records. Each record on the logbooks contains the position of the ship, as well as meteorological observations (temperature, wind speed, atmospheric pressure, etc.). Figure 1 depicts a map with the recorded logbook observations. Due to technological limitations, some of the positions recorded might have spatial errors, as can be noted by observing the positions recorded within land masses.

The creators of CLIWOC processed more than 3000 logbooks that represent more than 5000 voyages through world's oceans. Entries in the logbooks were done at noon. For each entry, the officer in charge registered the observed climatic conditions at the time. The CLIWOC dataset allows scientists to study weather patterns in the eighteenth and nineteenth centuries. By analyzing the records, it is possible to infer the evolution of phenomena such as the Nino Southern Oscillation or the North Atlantic Oscillation. Surprisingly, the dataset represent less than 10% of data available from original documents [12].

The climatic measurements in the logbooks were taken using archaic methodologies. For instance, in the case of the wind force, the measurements were recorded using old terms no longer in use. It is therefore necessary to translate them to modern units for study purposes. This problem was solved by the CLIWOC team with a dictionary that allows the translation from each archaic language vocabulary into Beaufort scale terms [12].

The CLIWOC dataset has been previously used to study climatic patterns. However, as noted by [13], the dataset can be used to other fields. For instance, it is possible to study the spread of technology. Maritime chronometers were popular on ships of the East Indian Company before they became common on Royal Navy vessels. With better location techniques, sailors were able to modify their routes and take advantage of more favourable wind patterns, which meant a modification on the routes. Using the logbooks, it is also possible to study the evolution of the crew health at ships of different countries, along time. From the end of XVIII century, improvements in

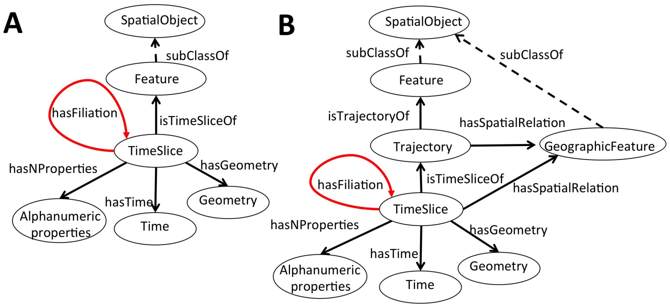

Figure 2. A)The *Continuum* model as introduced in [5]. B) Modified version of the *Continuum* model adapted for moving objects.

ventilation, diet and hygiene reduced the amount of diseases in maritime travels. Health information was recorded in logbooks of all the countries in the study, allowing scientist to make comparable studies. Another possible research topic is the influence of seasonal weather patterns on travels. For instance, British and Dutch ships were strongly affected by seasonal weather patterns when travelling to the Indian Ocean. Because of this, it was very unusual to see ships of these nationalities sailing in the South Atlantic around November and December [13].

In order to enhance the knowledge we can extract from the CLIWOC dataset, we created a *Geography Ontology* following the approach suggested by [8]. The geographic entities in this ontology are the seas and oceans of the world. We obtained this information from a high resolution dataset introduced in [14]. The creators of this dataset based their work on the document S-23, titled *Limits of Oceans and Seas* published by the International Hydrographic Organization (IHO) in 1953 [15]. The vector dataset, although based on an official document, it is not an official document itself. The vector dataset has a very high resolution coastline that is not necessary in our research. In order to facilitate our spatial operations, we simplified it using GeoTools.

IV. PROPOSED MODEL

In Harbelot et al., 2013a and Harbelot et al., 2013b [4] [5], the authors introduced the *continuum* model, an approach well suited to represent dynamic entities represented spatially as areas. Figure 2A depicts the continuum model as described in [5]. This model follows a *perdurantism* approach. It creates multiple ephemeral representations (*timeslices*) to depict a dynamic entity. Each *timeslice* is valid for a determined time interval. A *timeslice* has four components: 1) An identity, linking it to the object it represent. 2) A set of properties with alphanumeric values, representing different characteristics of the object. 3) A time component that indicates the valid period of time for the *timeslice* and 4) A geometric component, the ephemeral spatial representation of the entity. The model creates a new *timeslice* everytime there is a change in the geomety, the identity or in the alphanumeric properties. It is then possible to establish a filiation relationships between a newly created *timeslice* and the one that originated it.

The *continuum* model needs to be modified in order to deal with tracking information of travelling entities. Figure 2B depicts our upgraded version of the *continuum* model. In the new model, we have the moving objects as instances of the class *Feature*. We split the movements of the objects into *Trajectories*, which are semantic units with a defined *start* and *end* spatio-temporal points. The *Trajectory* itself is composed of a set of *timeslices*, with the same components as in the original version of the *continuum* model.

Following the approach suggested by [8] we developed a *Geographic Ontology* composed of *GeographicFeatures*. This ontology allows us to extract new knowledge from the tracking information.

A. Model Specification

In our model, we define the following concepts:

- *Temporal Points* We can think of the temporal domain as a linear structure $\mathcal{T}$ composed of a set of temporal points $\mathcal{P}$. The components of $\mathcal{P}$ follow a strict order $<$, which forces all points between two temporal points t_1 and t_2 to be ordered [16].

$$\mathcal{P} \sqsubseteq \top \tag{1}$$

- *Geometries* A set of coordinates that define points, lines, curves, surfaces and polygons.

$$\mathcal{G} \sqsubseteq \top \tag{2}$$

- *Spatial Objects* This class represents any entity with geometric representation.

$$\mathcal{O} \equiv \exists hasGeometry.\mathcal{G} \tag{3}$$

- *Spatio-Temporal Point* We use this class to define points with a spatial and temporal representations.

$$\mathcal{TP} \equiv \exists hasGeometry.\mathcal{G} \sqcap \exists hasTime.\mathcal{P} \tag{4}$$

- *Moving Features* This class is used to represent entities that change their positions along time.

$$\mathcal{MF} \sqsubseteq \mathcal{O} \tag{5}$$

  The movement of the feature is divided into semantical units called trajectories.

$$\mathcal{MF} \equiv \exists hasTrajectory.\mathcal{TR} \tag{6}$$

- *Trajectories* This class is used to represent semantical units of movement, with a defined start and end spatio-temporal points.

$$\begin{aligned} \mathcal{TR} \equiv & \exists hasTimeSlice.\mathcal{TS} \sqcap \exists isTrajectoryOf.\mathcal{MF} \\ & \sqcap \exists hasStart.\mathcal{TP} \sqcap \exists hasEnd.\mathcal{TP} \end{aligned} \tag{7}$$

- *TimeSlice* This class is used to depict a partial representation of a moving entity. Each *timeslice* has a defined geometric and temporal representations. It also has an identity component that links it to a specific *trajectory* and a set of alphanumeric properties $(\overline{\mathcal{TS}})$ that represent diverse characteristics of the entity at the specific point of time defined by its temporal dimension.

$$\begin{aligned} \mathcal{TS} \equiv & \exists hasGeometry.\mathcal{G} \sqcap \exists hasTime.\mathcal{P} \\ & \sqcap \exists \overline{\mathcal{TS}} \sqcap \exists isTimeSliceOf.\mathcal{TR} \end{aligned} \tag{8}$$

- *Geographic Entity* Following the approach suggested by [8], we implement a external ontology, composed of geographical entities GE. By combining the track of moving objects with these external geographic entities, we can improve the knowledge extraction. In our test study, we use a seas and oceans dataset based on a document published by International Hydrographic Organization (IHO) in 1953 [14].

$$\mathcal{GE} \sqsubseteq \mathcal{O} \tag{9}$$

Then, we can create individuals for each of the classes/concepts. For instance, $\mathcal{TS}(ts)$ indicates that ts is an individual of type *timeslice* ((TS)). Following the definition of the class TS, we know that the individual ts has a geometric component ts_g which is an instance of the class $\mathcal{G}$, then $\mathcal{G}(ts_g)$. The temporal dimension of ts is represented by ts_t, which is an instance of the class Temporal Points ($\mathcal{P}(ts_t)$). The individual ts is linked to a trajectory (ts_{tr}), and through the *trajectory* to a specific individual of the type *Feature* , and in this way it has a defined identity. We represent the alphanumeric properties that describe the characteristics of the timeslice $ts1$ as $ts1_{\overline{ts}}$.

Using the temporal and identity components of the *timeslices*, it is possible to identify a sequence, and in this way establish a *filiation* relationship between two *timeslices*. For the relationship to exist, both *timeslices* must belong to the same trajectory, and there should no exist other *timeslice* of the same trajectory occurring in between.

$$\begin{aligned} & after(ts1_t, ts2_t) \\ \wedge\neg\exists(ts \in \mathcal{TS})|(ts1_t < ts_t < ts2_t) \wedge & (ts1_{tr} = ts2_{tr} = ts_{tr}) \\ & \rightarrow hasFiliation(ts1, ts2) \end{aligned} \tag{10}$$

Then, we can compare *timeslices* that hold *filiation* relationships. For instance, we can calculate the speed of the moving entity for the interval defined between them as the following:

$$\begin{aligned} speed(ts1, ts2) \equiv & \left(\frac{distance(ts1_g, ts2_g)}{timeDiff(ts1_t, ts2_t)}\right) \\ & |hasFiliation(ts1, ts2) \end{aligned} \tag{11}$$

Using the *filiation* relationships and the *speed* calculation, we can identify episodes with unusual behaviours. For instance, a very low speed between two timeslices might suggest a *stop*. On the other hand, an unusually high speed might suggest errors in the geometric component of one of the timeslices, requiring further attention by the researcher. To identify unusually high speeds, we can calculate the statistics of the speeds of a *trajectory*.

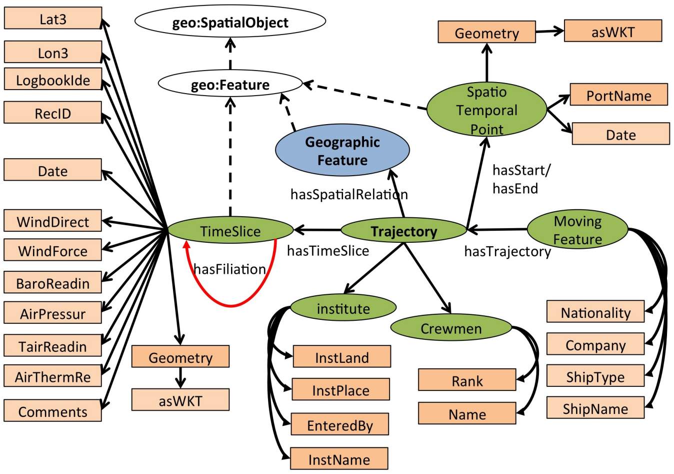

Figure 3. Classes and properties defined to model the CLIWOC dataset using the *Continuum* model

$$\begin{aligned} (speed(ts1, ts2) - mean(tr_{speed})) > \lambda(\sigma(tr_{speed})) \\ \wedge(hasFiliation(ts1, ts2)) \\ \rightarrow suspiciousFiliation(ts1, ts2) \end{aligned} \tag{12}$$

Where tr is a given trajectory, $mean(tr_{speed})$ depicts the average speed of the trajectory tr. The standard deviation of speed values is represented by $\sigma(tr_{speed})$, while λ represents a scalar value, by default 3.

We can later identify specific timeslices with geometries that require further attention by the researcher.

$$\begin{aligned} \exists suspiciousFiliation(ts1, ts) \\ \wedge\exists suspiciousFiliation(ts, ts2) \\ \rightarrow suspiciousTimeSlice(ts) \end{aligned} \tag{13}$$

A suspicious timeslice only indicates that the speed required to reach this point is unusually high. However, it does not prove that the position of the timeslice is incorrect.

We can extract knowledge by establishing spatial relationships between trajectories with an external geographic entities

$$\begin{aligned} \exists ts|hasTimeSlice(tr, ts) \wedge (Intersect(geo_g, ts_g)) \\ \vee(Within(geo_g, ts_g)) \vee (DistanceWithin(geo_g, ts_g, d))) \\ \rightarrow hasSpatialRelation(tr, geo) \end{aligned} \tag{14}$$

where ts is a timeslice ($TS(ts)$), tr is a trajectory ($\mathcal{TR}(tr)$) and geo is an geographic entity ($\mathcal{GE}(geo)$).

Figure 3 depicts a detailed representation of the continuum model with the CLIWOC dataset. The classes are represented as ellipses, while the values for the various properties are represented as squares.

TABLE I. SUMMARY OF THE ENTITIES UPLOADED INTO THE TRIPLESTORE

Count	Ontology Class	Description
280280	$\mathcal{TS}$	Records from logbooks, each record is represented as a timeslice and has a 0 dimensional spatial representation (point). Each timeslice has a link to a trajectory. Each timeslice has also climatic observations and a date entry property.
5198	$\mathcal{TR}$	Voyages, as identified in the original CLIWOC dataset. Each voyage has a departure and end spatio-temporal point. Each voyage is linked to the ship it corresponds.
1261	$\mathcal{MF}$	Ships, are the moving features in the ontology. Each ship has the properties : hasShipName, hasNationality, hasCompany and hasShipType. In some cases, the value property was not available on the dataset.
105	$\mathcal{GE}$	Oceans/Seas, represented as polygons. The dataset covers the whole world. It required a simplification process before being uploaded. We simplified the coastlines and removed the islands.

B. Implementation of the model using the CLIWOC dataset

The knowledge in the Semantic Web is represented using standards such as the Resource Description Framework (RDF) [17] and Web Ontology Language (OWL) [18], while the traditional ontology query language is the Protocol and RDF Query Language (SPARQL) [19]. It is possible to query spatial information stored in an ontology, using GeoSPARQL [20]. This is a set of standards from the Open Geospatial Consortium (OGC). In our research, we decided to implement our model and store it in a Parliament triplestore. We opted for Parliament due to its support for GeoSPARQL. In order to upload the datasets to the triplestore, we developed a program in Java using the Jena and GeoTools libraries. Table I contains a summary of the entities uploaded to the triplestore.

Due to performance reasons, we opted to perform certain operations outside the triplestore, using a Java application instead. For instance, the CLIWOC dataset uses geographic coordinates, therefore distance calculation is not a trivial task. We decided to perform this operation with Java, because we could have better control over the results. It was also possible to test different formulas and make performance comparisons.

Once the data was uploaded into the triplestore, it was possible to identify the *filiation* relationship as defined in equation 10. The following query is a SPARQL translation of equation 10. It detects the filiation relationships between timeslices corresponding to the trajectory $abc:trajectory\_5198$.

```
INSERT
{?tsParent abc:hasFiliation ?tsChild.}
WHERE {
abc:trajectory_5198 abc:hasTimeSlice ?tsParent.
abc:trajectory_5198 abc:hasTimeSlice ?tsChild.
?tsParent abc:hasDate ?ParentDate.
?tsChild abc:hasDate ?ChildDate.
NOT EXISTS{
abc:trajectory_5198 abc:hasTimeSlice ?tsX.
?tsX abc:hasDate ?XDate.
FILTER
((?ParentDate <?XDate) &&
(?XDate <?ChildDate))}
FILTER
((?tsParent!=?tsChild) &&
(?ParentDate<?ChildDate))}
```

According to [13], *British* and *Dutch* vessels on route to the Indian Ocean were affected by seasonal wind patterns. Because of this, vessels of these nationalities were not seen in the Southern Atlantic in the months of November and December. Using the model we can identify these unusual voyages of *British* ships as:

$$\begin{aligned}
\mathcal{GE}(geo), \mathcal{TR}(tr), \mathcal{TS}(ts)\\
|(geo_{name} = `SouthAtlantic')\wedge\\
(\exists ts|hasTimeSlice(tr, ts))\\
\wedge(Within(ts_g, geo_g))\\
\wedge(hasMonth(ts_t, `November')\vee\\
hasMonth(ts_t, `December'))\\
\rightarrow UnusualTrajectory(tr)
\end{aligned} \tag{15}$$

Equation 15 can be translated in SPARQL as:

```
INSERT
{?t a abc:UnusualTrajectory}}
WHERE {
?t a abc:Trajectory.
?m a abc:MovingFeature.
?m abc:hasShipNationality "British".
?m abc:hasTrajectory ?t.
?t abc:hasTimeSlice ?ts.
?ts abc:hasDate ?tDate.
?tDate xsd:Month(?tDate)
?ts geo:hasGeometry ?tsGeo.
?tsGeo geo:AsWKT ?tsWKT.
?g a abc:GeographicFeature.
?g abc:hasGeographicName "South Atlantic".
?g geo:hasGeometry ?gGeo.
?gGeo geo:AsWKT ?gWKT.
FILTER((geof:sfIntersects(?gWKT,?tsWKT))&&
((str(month(?tsDate))="11")||
(str(month(?tsDate))="12")))}
```

The result of this query allows us to identify trajectories of ships of *British* nationality that in the opinion of an expert on the field, follow an unusual trajectory pattern [13].

By using an ontology, we are able to easily identify specific patterns on the data, enabling scientist to better understand large datasets containing records of moving entities.

V. CONCLUSION

In this paper, we present an approach to analyse historical maritime records. Our approach allows the knowledge discovery in large datasets, enabling scientist to identify patterns that might be hidden due to the large size of the dataset.

Our starting point is very basic raw data, from which we produce more sophisticated constructions that allow a better understanding of the events depicted in the dataset.

Currently, we use a state of the art triplestore as our data repository, which gives us several advantages: 1) We can maintain formal defined relationships between objects. 2) It allows us flexibility, we can easily define new properties and relations between entities and concepts, and 3) It allows us to operate in large datasets in triple format.

At the moment, we use Parliament, a triplestore that supports GeoSPARQL, allowing us to perform spatial analysis without additional software. GeoSPARQL is an OGC standard that comprises a set of functions that extend SPARQL. Thanks to using OGC standards, our approach can be deployed in alternative OGC compliant environments.

We plan to continue our research in the field of semantic modelling of dynamic entities. An interesting field of research is the definition of semantic rules. At the moment, there are two submissions to the World Wide Web Consortium (W3C) [21] that aim to work in this field: SPARQL Inference Notation (SPIN) [22] and Semantic Web Rule Language (SWRL) [23]. However, none of them is yet an official W3C standard. In the future, we plan to explore the rule definition option, sticking to accepted standards, securing in this way the extensibility of our work.

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