A Semantic Representation of Time Intervals in OWL 2

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Abstract: Representing time over the Semantic Web has always been a challenging issue that many scientific works were interested to address. To the best of our knowledge, the most important ones focused on models, whereas Semantic Web and especially OWL 2 offers semantics that can be efficiently used to describe qualitative diachronic information (i.e. information evolving in time and which start and/or end time is unknown). In this work, we show the relationship between the OWL 2 semantics and the representation of time intervals; then we introduce a qualitative representation of temporal information based on a set of SWRL rules, that allows a sound and complete reasoning mechanism.

1 INTRODUCTION

OWL2 (Motik et al., 2009) allows users to write explicit, formal conceptualizations of domains models. It is build upon RDF and RDFS and has the same kind of syntax. As the main primitives of RDF/RDFS are related to the organization of the vocabularies in typed hierarchies using subclass and subproperty relationships, OWL 2 brings more language primitives besides those presented in its previous version to allow richer expressiveness. For example, in addition to the property unqualified cardinality restrictions available in OWL 1, in OWL 2, even the qualified cardinality restrictions are possible. Also, the assertions that an object property is symmetric or transitive provided by OWL 1 was supplemented in OWL 2 by the reflexive, irreflexive and asymmetric object properties assertions. Moreover, the powerful property chain inclusion implemented in OWL 2 allows a property to be defined as the composition of several properties, etc. Formal semantics provided by OWL 2 allows users to describe precisely the meaning of knowledge; they permit to reason about this knowledge, besides.

In the 4D-fluents approach (Welty and Fikes, 2006), any time interval can be related with every other time interval with one basic Allen relation (Allen, 1983), and all the thirteen Allen relations (cf. Figure 2) are thus possible. Therefore, the following Allen operators are all supported: BEFORE, AFTER, MEETS, METBY, OVERLAPS, OVERLAPPEDBY, DURING, CONTAINS, STARTS, STARTEDBY, ENDS, ENDEDBY and EQUALS.

In this work, we introduce a continuity of what was made before by exploiting the semantics provided by OWL 2 to give more precision to time interval representation. We use for this purpose language constructs provided by the OWL-TIME ontology (Cox and Little, 2017) which is a W3C candidate recommendation ontology of concepts of time. The Tbox classes and properties times dimensions will be those introduced in (Batsakis et al., 2017).

The paper is organized as follows. In the next section, we present a motivating example to show the impact of properties characteristics on qualitative information representation. In section 3 we present our approach supported by examples of use and the corresponding sets of SWRL rules. Background and related work on time representation in Semantic Web is discussed in section 4. Finally, we conclude and give some perspectives in section 5.

2 MOTIVATING EXAMPLE

The 4D-Fluents modeling approach allows representing individuals through time slices, i.e. captures of an individual at specific times. And time slices sharing the same relation have the same time interval (cf. Figure 1). Moreover, all time intervals of the same quali-

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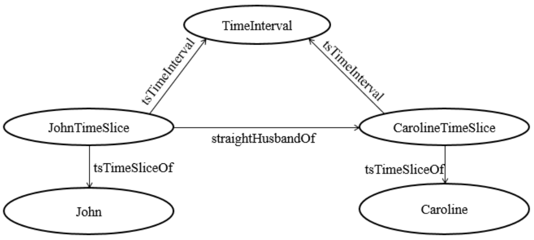

Figure 1: An example of time slices in the 4D-Fluents approach sharing the same time interval.

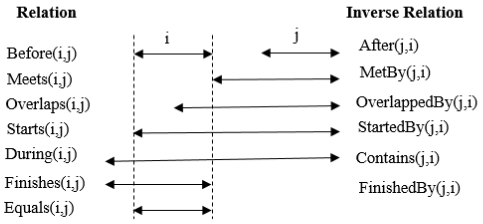

Figure 2: Allen's Relations.

tative relation could be linked to each others with one of the thirteen Allen relations (cf. Figure 2) no matter the relation occurring within this interval. However, this solution creates a significant representation problem. Since the use of Allen's relations between time intervals depends on the semantics of properties as it will be showed in our motivating examples below.

Because time slices could be captures of the same individuals in different time intervals, linking between these time intervals with some Allen's relations could not be possible, since the object property between their time slices could have restrictions, limiting thereby the Allen's relations using possibilities.

We use for expressing our motivating examples, object properties coming from PersonLink[1], an OWL 2 ontology representing family relationships. We chose this ontology due to the rigorous and precise axioms definitions it provides through OWL 2 semantics.

As a motivating example, We consider the following sentences coming from a questionnaire on how does people express their relationships [2]:

(1) John was married to Sarah.
(2) John was married to Nicole.

These two sentences clearly indicate that John was married twice, once to Sarah and the other time to Nicole. Because we have no further information about these relationships, two specific personLink object properties are then possible to express these sentences. If the (1) and (2) relations hold within a monogamous heterosexual marriage, then John has the right to have only one wife at a time interval, and the object property used to express this relationship is "plink:straightHusbandOf" (cf. Figure 3) which is functional (i.e. accepts only one value in its range). That means that the two time intervals of (1) and (2) must be strictly disjoint.

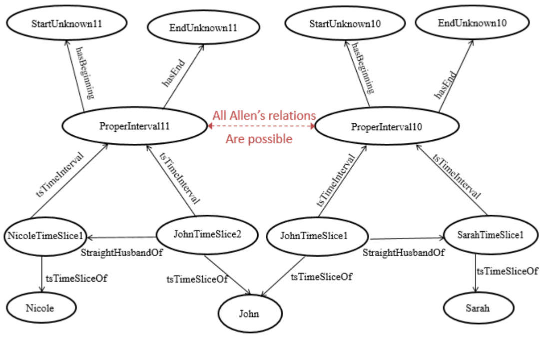

Figure 3: Representation in 4D-Fluents of an example of straight husband relation.

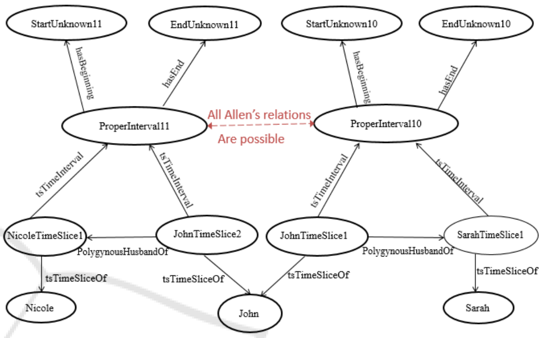

Figure 4: Representation in 4D-Fluents of an example of polygynous husband relation.

But if John is polygynous and his marriages with Sarah and Nicole were within a polygynous heterosexual context, he can have several wives at intersected time intervals (cf. Figure 4). Thus, using personLink, the maximum *n* number of permitted wives will be expressed using the maximal cardinality restriction of the "plink:polygynousHusbandOf" object property, entailing the time intervals *n* intersections possibilities.

More examples are presented with every OWL 2 characteristic of interest in the section 3.

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[1] Available at: `http://cedric.cnam.fr/isid/ontologies/PersonLink.owl`

[2] The names were changed to keep the anonymity of the people questioned

3 APPROACH

In our approach, we consider that relations between time intervals in 4D-Fluents depend on the property used to relate the two time slices having a relationship within the same time interval (i.e. the time interval during which the property holds between two time slices). For our examples, we may use both quantitative relations (i.e. involving known temporal instants or intervals) and qualitative ones (i.e. the exact values of temporal instants or intervals are unknown). Some OWL 2 property restrictions have a direct impact on time intervals, and each property restriction determines the possible Allen relation and thus gives us precisely the possible Allen relation to use to relate between time intervals.

OWL 2 is essentially the description logics $\mathcal{SROIQ}(\mathcal{D})$ (Horrocks et al., 2006) which define concept descriptions inductively by a set of constructors, starting with a set N_C of concept (or class) names, a set N_R of role (or property) names, and a set N_I of individual names. The semantics of the concept descriptions in $\mathcal{SROIQ}(\mathcal{D})$ are defined in terms of an interpretation I such as I=($\triangle^I$, $\cdot^I$) where $\triangle^I$ its domain which consists of a non-empty set of individuals and $\cdot^I$ is its function of interpretation which maps concepts names A $\in N_C$ to a subset $A^I \subseteq \triangle^I$, role names $R \in N_R$ to a binary relation $R^I \subseteq \triangle^I \times \triangle^I$, and each individual name $a \in N_I$ to an individual $a^I \subseteq \triangle^I$. The interpretation of complex concepts and roles follows from the interpretation of the basic entities showed in Table 1.

For the rest of the article, we will use the following notations:

- tsTimeSliceOf $\in N_R$;
- x, y, z, a, b, c individuals from the range of tsTimeSliceOf;
- TimeSlice $\in N_C$;
- TimeInterval $\in N_C$;
- $\forall$ i $\in \mathbb{N}$, TimeSlice(ts_i);
- $\forall$ i $\in \mathbb{N}$, TimeInterval(I_i);
- r $\in N_R$ such as $\exists$ r.$\top \sqsubseteq$ TimeSlice (Domain), $\top \sqsubseteq \forall$ r.TimeSlice (Range);
- s $\in N_R$ such as $\exists$ s.$\top \sqsubseteq$ TimeSlice (Domain), $\top \sqsubseteq \forall$ s.TimeSlice (Range);
- C $\in N_C$;
- D $\in N_C$;

In the next subsections, we will show the result of each OWL 2 object property characteristic having impact on topological (ordering) relations among time intervals. For that purpose, we will use the OWL-TIME ontology[3] temporal concepts.

Reasoning over temporal information is done using a set of DL-safe rules (Motik et al., 2006) expressed in SWRL (Horrocks et al., 2004), as it is the only solution in accordance with current OWL specifications while maintaining decidability. These reasoning rules are based on the basic Allen's relations provided by the OWL-TIME ontology and are specific to each property. SWRL rules were added for all object properties of PersonLink having restrictions, and reasoning was done using Pellet (Sirin et al., 2007) as it is, to the best of our knowledge, one of the reasoners supporting SWRL and the only reasoner supporting date/time comparisons needed for quantitative representations.

3.1 Functional Property

A functional property is a property that can have only one value in its range ($\top \sqsubseteq \leq$ 1r), i.e. each instance x can have only one unique instance y at a time for a given functional property. So, if a property is functional, time slices participating in the relation represented by this property share the same time interval but all time intervals they are sharing outside this relationship with the same functional property must be disjoints with this time interval. Therefore, the relation between this time interval and new time intervals of the same functional property will be one of the following Allen relations: AFTER or BEFORE.

If:
tsTimeInterval(ts_1,I_1), tsTimeInterval(ts_2, I_1),
tsTimeInterval(ts_3,I_2), tsTimeInterval(ts_4, I_2),
tsTimeSliceOf(ts_1,a) and tsTimeSliceOf(ts_3,a)

Then:

$$\begin{aligned}\top \sqsubseteq\ &\text{after}(\text{tsTimeInterval}(ts_1,I_1),\\ &\quad \text{tsTimeInterval}(ts_3,I_2))\\ &\quad \sqcup\ \text{before}(\text{tsTimeInterval}(ts_1,I_1),\\ &\quad \text{tsTimeInterval}(ts_3,I_2))\end{aligned}$$

SWRL:

$$\begin{aligned}&r(?ts_1,?ts_2) \wedge r(?ts_3,?ts_4) \wedge\\ &tsTimesSliceOf(?ts_1,?a) \wedge\\ &tsTimesSliceOf(?ts_3,?a) \wedge\\ &tsTimesSliceOf(?ts_2,?b) \wedge\\ &tsTimesSliceOf(?ts_4,?c) \wedge\end{aligned}$$

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[3] available at: https://www.w3.org/TR/owl-time/

Table 1: The description logic $\mathcal{SROIQ}(\mathcal{D})$ basic Syntax and semantics.

Name	Syntax	Semantics
individual name	a	a^I
atomic role	R	R^I
inverse role	R^-	$\{(x,y) \mid (y,x) \in R^I\}$
universal role	U	$\triangle^I \times \triangle^I$
atomic concept	A	A^I
intersection	C ⊓ D	$C^I \cap D^I$
union	C ⊔ D	$C^I \cup D^I$
complement	¬C	$\triangle^I \setminus C^I$
top concept	⊤	$\triangle^I$
bottom concept	⊥	$\varnothing$
existential restriction	∃ R.C	$\{x \in \triangle^I \mid \exists y \in \triangle^I : (x,y) \in r^I \wedge y \in C^I\}$
universal restriction	∀R.C	$\{x \in \triangle^I \mid \forall y \in \triangle^I : (x,y) \in r^I \wedge y \in C^I\}$
at-least restriction	⩾nR.C	$\{x \in \triangle^I \mid atleastny \in \triangle^I : (x,y) \in r^I \wedge y \in C^I\}$
at-most restriction	⩽	$\{x \in \triangle^I \mid atmostny \in \triangle^I : (x,y) \in r^I \wedge y \in C^I\}$
local reflexivity	∃R.Self	$\{x \mid (x,x) \in R^I\}$
nominal	$\{a\}$	$\{a^I\}$

$$\begin{gathered} tsTimeInterval(?ts_1, ?I_1) \wedge \\ tsTimeInterval(?ts_2, ?I_1) \wedge \\ tsTimeInterval(?ts_3, ?I_2) \wedge \\ tsTimeInterval(?ts_4, ?I_2) \rightarrow \\ intervalDisjoint(?I_1, ?I_2) \end{gathered}$$

Example 1: John is a straightHusbandOf Sarah in a time interval t_1 and a straightHusbandOf Nicole in a time interval t_2, the time intervals t_1 and t_2 are distinct which means that t_1 takes place before or after t_2.

3.2 Inverse Functional Property

In this type of property, the object determines the subject, i.e. the property can accept only one and unique value in its domain at a time for a given object.

Therefore, if a relation $r(x,y)$ of inverse functional type links between two individuals x and y at a time interval t_1, and this same relation r links between x and another individual z at another time interval t_2, this time interval t_2 must be BEFORE or AFTER t_1. This could be written as following:

If:
r(ts_1, ts_2), r(ts_3, ts_4),
tsTimeSliceOf(ts_2, x), tsTimeSliceOf(ts_4, x),
tsTimeInterval(ts_2,I_1) and tsTimeInterval(ts_4,I_2)

Then:

$$\begin{aligned} \top \sqsubseteq\ & \text{after}(\text{tsTimeInterval}(ts_1, I_1), \\ & \text{tsTimeInterval}(ts_3, I_2)) \\ & \sqcup\ \text{before}(\text{tsTimeInterval}(ts_1, I_1), \\ & \text{tsTimeInterval}(ts_3, I_2)) \end{aligned}$$

SWRL:

$$\begin{gathered} r(?ts_1, ?ts_2) \wedge r(?ts_3, ?ts_4) \wedge \\ tsTimesSliceOf(?ts_1, ?a) \wedge \\ tsTimesSliceOf(?ts_2, ?b) \wedge \\ tsTimesSliceOf(?ts_3, ?c) \wedge \\ tsTimesSliceOf(?ts_4, ?b) \wedge \\ tsTimeInterval(?ts_1, ?I_1) \wedge \\ tsTimeInterval(?ts_2, ?I_1) \wedge \\ tsTimeInterval(?ts_3, ?I_2) \wedge \\ tsTimeInterval(?ts_4, ?I_2) \rightarrow \\ intervalDisjoint(?I_1, ?I_2) \end{gathered}$$

Example 2: James is the direct supervisor of Thomas at a period of time t_1, and Carlos is the direct superior of Thomas another period of time t_2. Since the relation hierarchical superior is of type inverse functional, the time intervals t_1 and t_2 must be disjoint, i.e. t_1 happens before or after t_2.

3.3 Symmetric Property

A time slice x connected to another time slice y by a symmetric property at a specific time interval means that the time slice y is linked to the time slice x by the same object property within the same time interval. By definition, the symmetric relations have thus equal time intervals:

Let r ∈ N_R such as r is symmetric r = r^-;

If:
r(ts_1, ts_2), r(ts_3, ts_4),
tsTimeSliceOf(ts_1, x), tsTimeSliceOf(ts_4, x),
tsTimeSliceOf(ts_2, y), tsTimeSliceOf(ts_3, y),
tsTimeInterval(ts_1, I_1) and tsTimeInterval(ts_3, I_2)

Then:
$\top \sqsubseteq$ Equals (I_1, I_2)

SWRL:

$$\begin{gathered} r(?ts_1, ?ts_2) \wedge r(?ts_3, ?ts_4) \wedge \\ tsTimesSliceOf(?ts_1, ?a) \wedge \\ tsTimesSliceOf(?ts_2, ?b) \wedge \\ tsTimesSliceOf(?ts_3, ?b) \wedge \\ tsTimesSliceOf(?ts_4, ?a) \wedge \\ tsTimeInterval(?ts_1, ?I_1) \wedge \\ tsTimeInterval(?ts_2, ?I_1) \wedge \\ tsTimeInterval(?ts_3, ?I_2) \wedge \\ tsTimeInterval(?ts_4, ?I_2) \rightarrow intervalEquals(?I_1, ?I_2) \end{gathered}$$

Example 3: Marta is the partner of Trevor at a time interval t_1. Because the partner of relationship is symmetric, Trevor is also partner of Marta at a time interval t_2 and the time intervals t_1 and t_2 are equal.

3.4 Transitive Property r $\circ$ r $\sqsubseteq$ r

A transitive relation is a relation which binds between a succession of individuals, and which consequently allows to bind the first individual to the last one. In this type of relation, the time interval linking between the first individual and the last one is at least equal to the intersection of the other time intervals of the individuals' succession.

For the transitive diachronic property r :
If:
r(ts_1, ts_2), r(ts_3, ts_4),
tsTimeSliceOf(ts_1, x), tsTimeSliceOf(ts_2, y),
tsTimeSliceOf(ts_3, y), tsTimeSliceOf(ts_4, z),
tsTimeInterval(ts_2, I_1), tsTimeInterval(ts_3, I_2),
TimeInterval(I), during(I,I_1) and during (I,I_2)

Then:

r(ts'_1,ts'_4) with tsTimeInterval(ts'_1,I), tsTimeSliceOf(ts'_1,x), tsTimeSliceOf(ts'_4,z)

This means that the time interval of the deduced relation using transitivity will be at least equal to the period representing the intersection of time intervals of relations from which the relation is deduced. Otherwise, none of Allen relations could be used, because there is no interval intersection.

SWRL:

$$\begin{gathered} r(?ts_1, ?ts'_1) \wedge r(?ts_2, ?ts'_2) \wedge r(?ts_3, ?ts'_3) \wedge \\ tsTimesSliceOf(?ts_1, ?a) \wedge \\ tsTimesSliceOf(?ts'_1, ?b) \wedge \\ tsTimesSliceOf(?ts_2, ?b) \wedge \\ tsTimesSliceOf(?ts'_2, ?c) \wedge \\ tsTimesSliceOf(?ts_3, ?a) \wedge \\ tsTimesSliceOf(?ts'_3, ?z) \wedge \\ tsTimeInterval(?ts_1, ?I_1) \wedge \\ tsTimeInterval(?ts'_1, ?I_1) \wedge \\ tsTimeInterval(?ts_2, ?I_2) \wedge \\ tsTimeInterval(?ts'_2, ?I_2) \wedge \\ tsTimeInterval(?ts_3, ?I_3) \wedge \\ tsTimeInterval(?ts'_3, ?I_3) \wedge \\ intervalDisjoint(?I_3, ?I_1) \wedge \\ intervalDisjoint(?I_3, ?I_2) \rightarrow Nothing \end{gathered}$$

Example 4: Stefan is the hierarchical superior of Monica in a time interval t_1 and Monica is the hierarchical superior of Peter in a time interval t_2. The "hierarchical superior" is a transitive relation, so Stefan is therefore the hierarchical superior of Peter in a time interval t_3, and this time interval is at least equal to the intersection of the t_1 and t_2 time intervals.

3.5 Inverse of Property

An inverse of property is a property that inverses another property, which means that both of these properties concern the same individuals x and y at two time intervals t_1 and t_2. Intuitively, these time intervals are equal:

Let r $\in N_R$ and s $\in N_R$ such as r = s^-;

If:
r(ts_1, ts_2), s(ts_2, ts_1),
tsTimeSliceOf(ts_1, x), tsTimeSliceOf(ts_2, y),
tsTimeInterval(ts_1,I_1)and tsTimeIntervalOf(ts_2, I_2)

Then:
Equals (I_1, I_2)

SWRL:

$$\begin{gathered} r(?ts_1, ?ts_2) \wedge r(?ts_3, ?ts_4) \wedge \\ tsTimesSliceOf(?ts_1, ?a) \wedge \\ tsTimesSliceOf(?ts_2, ?b) \wedge \\ tsTimesSliceOf(?ts_3, ?b) \wedge \\ tsTimesSliceOf(?ts_4, ?a) \wedge \\ tsTimeInterval(?ts_1, ?I_1) \wedge \\ tsTimeInterval(?ts_2, ?I_1) \wedge \\ tsTimeInterval(?ts_3, ?I_2) \wedge \\ tsTimeInterval(?ts_4, ?I_2) \rightarrow intervalEquals(?I_1, ?I_2) \end{gathered}$$

Example 5: John is the straight husband of Sarah in a time interval t_1 and Sarah is the straight wife of John in a time interval t_2. The "husband of" property is the inverse of the "wife of" one thus their time intervals t_1 and t_2 are equal.

3.6 Properties Cardinality Restrictions

OWL 2 allows both qualified and unqualified cardinality restrictions, i.e. it gives the users the ability to put restrictions on the number of instances a property may have. In the sections 3.6.1 and 3.6.2, we will present the repercussions the max and min cardinality restrictions have on the representation of time intervals relations.

3.6.1 Max Cardinality Restriction $\leq$ nr, n $\in \mathbb{N}$

For a property with n maximal cardinality restriction, any new $(n+1)$ relation using this property must have a time interval which has no intersection with the previous (n) time intervals:

Let r(ts_{i1}, ts_{i2}) $\forall$ i $\in$ [1, n+1],

If:
tsTimesSliceOf(ts_{i1}, x) and tsTimeInterval(ts_{i1}, I_i) and TimeInterval(I) $\forall$ i $\in$ [1,n] during (I, I_i)

Then :

$\top \sqsubseteq$ before (I_{n+1}, I) $\sqcup$ after(I_{n+1}, I)

SWRL:

$$\begin{gathered} r(?ts_1, ?ts'_1) \wedge r(?ts_n, ?ts'_n) \wedge \\ tsTimesSliceOf(?ts_1, ?a) \wedge \\ tsTimesSliceOf(?ts_n, ?a) \wedge \\ tsTimesSliceOf(?ts_{n+1}, ?a) \wedge \\ tsTimeInterval(?ts_1, ?I_1) \wedge \\ tsTimeInterval(?ts_n, ?I_n) \wedge \\ tsTimeInterval(?ts_{n+1}, ?I_{n+1}) \wedge \\ notIntervalDisjoint(?I_{n+1}, ?I_1) \wedge \\ notIntervalDisjoint(?I_{n+1}, ?I_n) \rightarrow Nothing \end{gathered}$$

Example 6: Neil is the polygynous husband of Carole, and he is also the polygynous husband of Nadia and Maya in the context of a culture that permits the polygamy and allows to a man to get married to two women at the most. The time interval of one of these three relations is disjoint (i.e. before or after) with the intersection of the two other relations time intervals left.

3.6.2 Min Cardinality Restriction $\geq$ nr, n $\in \mathbb{N}$

In the case of a minimal cardinality restriction, an individual x, participates in a relation with a minimal limitation n in it's range value, witch means that this individual x must have the same relation with at least n other individuals, and that all time intervals concerning each of these relations must be intersected. It seems intuitive when it concerns the natural language. However, this temporal information cannot be introduced because of the Open-World Assumption (Drummond and Shearer, 2006).

4 BACKGROUND AND RELATED WORK

Different approaches have been proposed to represent time evolution in Semantic Web. Some of them like Temporal Description Logics (TDLs) (Artale and Franconi, 2000) relies on the standard Description Logics (Baader et al., 2008) which represent the basics of OWL, they provide further additional constructs and then offer more expressiveness over standard DLs while maintaining DLs decidability. However, they require extending OWL syntax and semantics with the additional temporal concepts. On the other hand, an other work approach (Klein and Fensel, 2001) proposes to make versions of the ontology, whenever a change occurs, even if it is a small one. In this approach, all the versions of the ontology remain independent from each others since there is no relation between evolving concepts.

Reification (Gomez et al., 2000) is also an approach that permits to add the time dimension in OWL, since it allows the representation of n-ary relations. However, this approach doesn't make the predicate characteristics reachable since it's considered as a new object of the reified relation rather than a predicate of the relation. The 4D-Fluents approach and its alternative one (n-ary relations (Noy et al., 2006)) represent time through a 4-Dimensional model, where each concept has its own time slices (i.e. images at specific times), making the changes occur only on the temporal parts and keeping therefore the static part unchanged. The n-ary relations approach is an alternative of the 4D-fluents one since it permits less proliferation of objects than the 4D-fluents approach does. The 4D-Fluents approach (and consequently the n-ary relations) keeps the semantics of all TBOX components and makes available their OWL 2 characteristics and restrictions. All these research activities represented above were made with the aim of creating models and frameworks introducing the temporal dimension into ontologies conception.

(Batsakis et al., 2017) proposes a representation and reasoning over qualitative relations following the 4D-Fluents model and using a set of SWRL rules to represent Allen's relations between time intervals. In this paper, we present OWL 2 properties and characteristics which semantics have direct impact on time intervals representation using appropriate Allen's relations.

5 CONCLUSION AND FUTURE WORK

We have shown in this work through a motivating example that relations between time intervals of 4D-Fluents ontologies depend on OWL 2 semantics, also that Allen's relations linking between qualitative time intervals of the same properties are restricted and are determined by the property's characteristics and semantics. For each OWL 2 property of interest, we defined and made a representation of the impact of its characteristics and restrictions on time interval relations. We have also given examples of use for each of these characteristics, and then we proposed a set of SWRL rules to allow reasoning over time intervals relations while retaining decidability.

We plan to apply this work to two applications: the storage and the retrieval of the entourage of elderly people in the Captain Memo memory prosthesis (Herradi et al., 2015), and the representation and study of prosopography in historical data bases.

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