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► **To cite this version:**

Nassira Achich, Fatma Ghorbel, Fayçal Hamdi, Elisabeth Metais, Faiez Gargouri. Approach to Reasoning about Uncertain Temporal Data in OWL 2. 24th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems (KES), Sep 2020, Verona, Italy. pp.1141-1150, 10.1016/j.procs.2020.09.110 . hal-02893907

**HAL Id: hal-02893907**

**<https://hal.science/hal-02893907>**

Submitted on 4 Jan 2022

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24th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems

## Approach to Reasoning about Uncertain Temporal Data in OWL 2

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### Abstract

In this paper, we propose an ontology-based approach for representing and reasoning about certain and uncertain temporal data. It handles temporal data in terms of quantitative time intervals and points and the qualitative relations between them (e.g., “before”). It includes three parts. (1) We extend the 4D-fluents approach with certain ontological components to represent the handled temporal data in OWL 2. (2) We extend the Allen’s interval algebra to reason about certain and uncertain time intervals. We adapt these relations to allow relating a time interval and a time point, and two time points. All relations can be used for temporal reasoning by means of transitivity tables. (3) The extended Allen’s algebra instantiates the 4D-fluents-based representation. Inferences are based on SWRL rules. Based on this ontology, a prototype is implemented and integrated into an ontology-based memory prosthesis for Alzheimer’s patients to handle certain and uncertain temporal data inputs.

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Peer-review under responsibility of the scientific committee of the KES International.

**Keywords:** Certain Temporal Data; Uncertain Temporal Data; Temporal Representation; Temporal Reasoning; 4D-Fluents Approach; Allen’s Interval Algebra; Certain Ontology

### 1. Introduction

Data entered by Alzheimer’s patients, living in uncertainty, are mostly imperfect. In this context, Captain Memo [18], a memory prosthesis, is proposing to palliate mnemonic problems. Compared to existing solutions, it makes early stage Alzheimer’s patients active in entering data to improve their autonomy. It is based on an OWL 2 ontology, called PersonLink [14], that enables modeling and reasoning about interpersonal relationships (e.g., mother, neighbor) and people description (e.g., lived events).

In a previous work, we proposed a typology of data input imperfection [11]. Regarding this typology, all data entered by Alzheimer’s patients, are considered as uncertain. In this work, we address the problem of representing and reasoning about uncertain temporal data. Indeed, this kind of temporal data imperfection could be numerous in the context of Captain Memo. For example, the patient may enter “I think it was from 1985 to 1990”, “She left

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the university maybe at 09 am” and “I think she got married before university graduation”. PersonLink needs to be extended to represent and reason about not only certain temporal data, but also uncertain ones.

In the Semantic Web field, several approaches have been proposed to represent and reason about certain temporal data. However, most of them handle only time intervals and associated qualitative relations i.e., they are not intended to handle time points and qualitative relations between a time interval and a time point or two time points. Besides, to the best of our knowledge, there is no approach devoted to handle uncertain temporal data in OWL 2.

In this paper, we propose an approach for representing and reasoning about certain and uncertain temporal data in terms of both qualitative relations (e.g., “before”) and quantitative ones (time intervals and points). This approach is based on classical ontology and it does not use probabilistic one. It consists of three parts. (1) The first part is about representing certain and uncertain temporal data in OWL2. Certain time intervals can be modeled in OWL using the 4D-fluents approach [23]. We extend it with new certain ontological components to represent: (1.1) certain and uncertain quantitative temporal data, and (1.2) qualitative temporal relations between time intervals and points. (2) The second part is about reasoning about certain and uncertain temporal data by extending the Allen’s interval algebra [2]. This algebra proposes qualitative relations between time intervals. However, it is not devoted to handle uncertain time intervals. Furthermore, it is not intended to relate a time interval and a time point or even two time points. In this paper, we extend the Allen’s algebra by proposing qualitative temporal relations between uncertain time intervals. They preserve important properties of the original algebra. We adapt the resulting interval relations to propose temporal relations between a time interval and a time point, and two time points. All relations can be used for temporal reasoning by means of transitivity tables. (3) The third part consists of proposing an OWL 2 ontology called “UncertTimeOnto”. It may be integrated in other ontologies to handle certain and uncertain temporal data. It is implemented based on the proposed extensions. Inferences are done using SWRL rules embedded into the ontology.

The rest of the paper is organized as follows. Preliminary concepts and related work are reviewed in Section 2. Section 3 introduce our proposed 4D-fluents approach extension. Section 4 introduce our proposed Allen’s Interval Algebra extension. Section 5 presents the “UncertTimeOnto” ontology. In Section 6, we present some experimentations. Section 7 concludes this work and gives some future directions.

## 2. Preliminaries and Related Work

Temporal data can be certain or uncertain. They are characterized using quantitative or qualitative terms. Certain (classical) quantitative temporal data means certain time intervals and points. Uncertain quantitative temporal data means uncertain time intervals and points. Uncertain time intervals are time intervals characterized by uncertain beginning and/or ending bounds e.g., “Maybe be from 08 am to 10 am”. Uncertain time points are time points that are defined in an uncertain way e.g., “I am not certain if it was in 2006”. Four qualitative temporal relations may exist to relate two time intervals (Interval-Interval), a time interval and a time point (Interval-Point and Point-Interval) or two time points (Point-Point); where time intervals and points may be certain or uncertain. Qualitative temporal data may be also certain or uncertain and can be deduced from quantitative ones.

### 2.1. Representing Temporal Data in Semantic Web

Representing temporal data in ontology is a pressing need. However, ontology languages such as OWL, provide a minimal support since they are all based on binary relations that simply connect two instances and they do not add any temporal data. This explains the emergence of many approaches for representing temporal data in ontology. We classify them into two categories: (1) approaches that extend OWL or RDF syntax by defining new OWL or RDF operators and semantics to incorporate temporal data, and (2) approaches that are implemented directly using OWL or RDF to represent temporal data without extending their syntax.

The first category includes Temporal Description Logics [4], Concrete Domains [17] and Temporal RDF [12]. Temporal Description Logics extends the standard description logics with new temporal semantics such as “until”. This approach retains decidability and does not suffer from data redundancy. However, it is considered as an avoidable solution since it requires extending OWL or RDF, which is a tedious task [11]. Concrete Domains requires introducing additional data types and operators to OWL. Temporal RDF uses only RDF triples. It does not have all the expressive-

Table 1. Allen’s relations between two certain time intervals.

Relation(A, B)	Relations between interval bounds	Inverse(B, A)
Before	$A^+ < B^-$	After
Meets	$A^+ = B^-$	Met-by
Overlaps	$(A^- < B^-) \wedge (A^- < B^+) \wedge (A^+ < B^+)$	Overlapped-by
Starts	$(A^- = B^-) \wedge (A^+ < B^+)$	Started-by
During	$(B^- < A^-) \wedge (A^+ < B^+)$	Contains
Ends	$(B^- < A^-) \wedge (A^+ = B^+)$	Ended-by
Equals	$(A^- = B^-) \wedge (A^+ = B^+)$	Equals

ness of OWL. It cannot also express qualitative relations. A data model to represent temporal data is proposed, which extends RDF, named stRDF.

The second category includes Versioning [16], Reification [7], N-ary Relations [19], 4D-Fluents and Named Graphs [22]. Versioning is described as the ability to handle changes in ontology by creating different variants of it. In this approach, all the versions are independent from each other. This requires exhaustive searches in all of them [24]. Reification is a technique for representing N-ary relations when only binary relations are allowed. Whenever a temporal relation has to be represented, a new object is created. N-ary relations proposes to represent an N-ary relation as two properties each related with a new object. It maintains property semantics. The Named Graphs approach represents each time interval by exactly one named graph, where all triples belonging share the same validity period. The mentioned approaches suffer from data redundancy. The 4D-Fluents approach represents time intervals and their evolution in OWL. Concepts varying in time are represented as 4-dimensional objects with the 4th dimension being the temporal data. It maintains a full OWL expressiveness and reasoning support [5], [3], [13], [20] and [15].

All the reviewed approaches handle only certain temporal data and neglect uncertain ones. They are not intended to handle time points and qualitative temporal relations between a time interval and a time point or even two time points. Our approach should rely on existing OWL constructs. Therefore, we exclude the Temporal Description Logic, Concrete Domain and Temporal RDF approaches. We also exclude the Named Graphs approach as it does not support OWL and it is not a W3C compliant solution. We choose to extend the 4D-fluents approach to represent uncertain quantitative temporal data and associated qualitative temporal relations. Compared to the Reification, N-ary relations and Versioning approaches, the 4D-fluents approach minimizes data redundancy as the changes occur on the temporal parts and keep the static part unchanged. In 4D-fluents approach, two classes, which are “TimeSlice” and “TimeInterval”, are proposed. Four certain properties, which are “tsTimeSliceOf”, “tsTimeIntervalOf” “HasBeginning” and “HasEnd” are introduced. The property “tsTimeInterval” connects an instance of the class “TimeSlice” with an instance of the class “TimeInterval”. “HasBeginning” and “HasEnd” properties relate an instance of the class “TimeInterval” with two time points that specify the beginning and ending bounds of a certain time interval.

## 2.2. Allen’s Interval Algebra: Definition and Extensions

13 qualitative temporal relations between classical time intervals are proposed by Allen. They are defined in terms of the ordering of the beginning and ending bounds of the corresponding intervals. Their definitions are expressed in Table 1. A particularity that the Allen’s algebra holds, is that we can deduce new relations through the composition of other ones (e.g., “Before (A, B)” and “Equals (B, C)” give “Before (A, C)”. Allen’s interval algebra is not dedicated to handle uncertain time intervals. Besides, it does not relate a time point and a time interval, nor two time points.

Many approaches have been extended this algebra such as [8], [19], [23], [22], [21], [6] and [1]. However, these extensions are based on theories related to imperfect data. Therefore, the resulting relations could not be supported in the context of certain ontology. Furthermore, most of these extensions do not preserve all the properties of the original Allen’s algebra. For instance, in [19], the relation “Equals” is not reflexive. However, the compositions of the resulting relations are not studied by the authors. For example, in [9], the authors do not propose the composition table of the proposed temporal relations. In our previous work [1], we extended Allen’s interval algebra to reason about precise and imprecise dates and time clocks in crisp ontology.

### 3. Representing Certain and Uncertain Temporal Data in OWL 2: Extending 4D-Fluents Approach

We extend the 4D-fluents approach with certain ontological components to represent certain and uncertain quantitative temporal data and associated qualitative temporal relations in OWL 2. Fig.1 depicts our extension.

#### 3.1. Representing Quantitative Temporal Data

We extend the 4D-fluents approach to represent uncertain time intervals, and certain and uncertain time points.

##### 3.1.1. Representing Uncertain Time Intervals

Let  $A = [A_a^-, A_a^+]$  be an uncertain time interval.  $A^-$  and  $A^+$  are respectively the beginning and ending bounds; and  $a^-$  and  $a^+$  are, respectively, the associated certainty degrees. We extend the 4D-fluents to represent uncertain time intervals. We introduce two certain datatype properties named “HasBeginnigCertainty” and “HasEndCertainty”. They are associated to the predefined class “TimeInterval”. “HasBeginnigCertainty” and “HasEndCertainty” represent, respectively, the certainty degrees associated to  $a^-$  and  $a^+$ .

##### 3.1.2. Representing Certain and Uncertain Time Points

We extend the 4D-fluents approach to represent certain and uncertain time points. Thus, a certain class “TimePoint” is introduced. Let P be a certain time point. We introduce a datatype property named “HasTimePoint”. It connects the “TimePoint” class and the corresponding value of P. For instance, if we have the following example “Jack moved to his new house in 1992”; “1992” is a certain time point related to the class “TimePoint” using the datatype property “HasTimePoint”.

Let  $Q_q$  be an uncertain time point, where “q” is the associated certainty degree to the corresponding value of Q. We use the datatype property “HasTimePoint” to connect the class “TimePoint” and Q. To represent the certainty degree associated to Q, we propose a certain datatype property named “PointCertainty”. It is associated to the “TimePoint” class.

#### 3.2. Representing Qualitative Temporal Data

To represent certain and uncertain temporal relations between time intervals and time points, we propose four certain object properties. The property “RelationIntervals” connects two instances of the class “TimeInterval” class to represent Interval-Interval relation. “RelationIntervalPoint” property connects an instance of the class “TimeInterval” (domain) and an instance of the class “TimePoint” (range) to represent Interval-Point relation. “RelationPointInterval” property connects an instance of the class “TimePoint” (domain) and an instance of the class “TimeInterval” (range) to represent Point-Interval relation. “RelationPoints” connects two instances of the “TimePoint” class to represent Point-Point relation.

We introduce four object properties to represent the certainty degrees associated to the uncertain qualitative temporal relations named “RelationIntervalsCertainty”, “RelationIntervalPointCertainty”, “RelationPointIntervalCertainty” and “RelationPointsCertainty”, are also proposed to represent the certainty degree associated to a given relation. “RelationIntervalsCertainty” connects two instances of the “TimeInterval” class to represent a certainty degree associated to an Interval-Interval relation. “RelationIntervalPointCertainty” connects an instances of the “TimeInterval” class and an instance of the “TimePoint” class “to represent a certainty degree associated to an Interval-Point relation. “RelationPointIntervalCertainty” connects an instances of the “TimePoint” class and an instance of the “TimeInterval” class “to represent a certainty degree associated to a Point-Interval relation. “RelationPointsCertainty” connects two instances of the “TimePoint” class to represent a certainty degree associated to a Point-Point relation.

### 4. Reasoning about Certain and Uncertain Temporal Data: Extending Allen’s Interval Algebra

We extend the Allen’s interval algebra to: (1) reason about certain and uncertain quantitative temporal data to infer qualitative temporal relations and (2) to reason about the qualitative temporal relations to infer new ones.

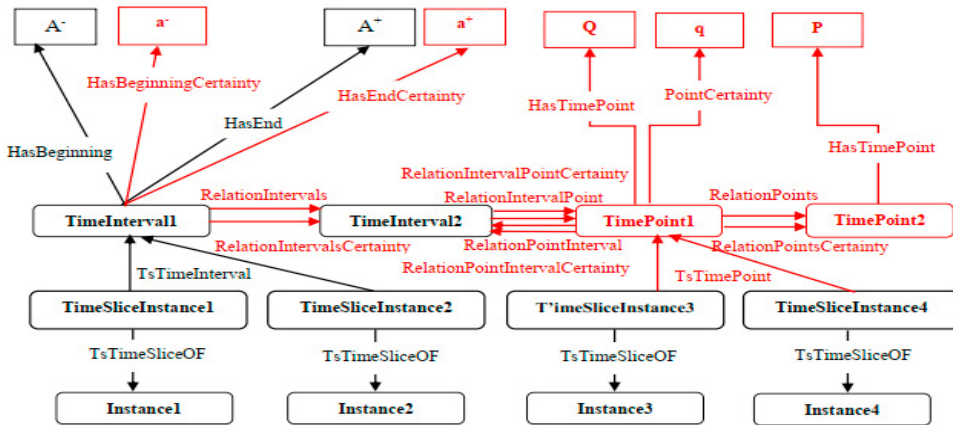


Fig. 1. Our 4D-fluents approach extension.

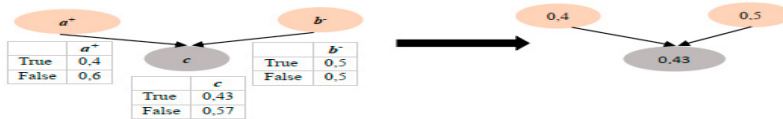


Fig. 2. Bayesian network associated to the relation “before  $c$ ” between two time intervals intervals.

### 4.1. Qualitative Temporal Relations

At the beginning, we propose qualitative temporal relations between uncertain time intervals. Then, we adapt these relations and the original Allen’s relations to relate a time interval and a time point or two time points.

#### 4.1.1. Qualitative Temporal Relations between Time Intervals

When considering certain time intervals, our approach reduces to Allen’s interval algebra. We redefine the 13 Allen’s relations to propose temporal relations between uncertain time intervals. Let  $A = [A_a^-, A_a^+]$  and  $B = [B_b^-, B_b^+]$  be two uncertain time intervals. For instance, we redefine the relation “Before (A, B)” as: “Before $_c$  (A, B)”; where “c” is the certainty degree associated to the relation “Before” between A and B. This means that the uncertain ending bound of the interval A is less than the uncertain beginning bound of B.

$$Before_c(A, B) \Rightarrow A_a^+ < B_b^- \tag{1}$$

The certainty degree “c” is inferred from the certainty degrees  $a^+$  and  $b^-$  using a Bayesian Network. For instance, if we have the certainty degree  $a^+$  is equal to 0,4 and the certainty degree  $b^-$  is equal to 0,5. It holds that “c” is equal to 0,43; as shown in Fig. 2.

We classify the proposed relations into two categories. The first one covers the relations which consists of only one single formula without any conjunction (i.e., “Before $_c$ ”, “after $_c$ ”, “Meet $_c$ ” and “Met-by $_c$ ”). The second one covers the rest of the relations. These one are defined based on a set of conjunctions (e.g., “Overlaps $_c$ ”). Thus, similar to the relation “Before $_c$ ”, we redefine the relation “Meets $_c$ (A, B)”; as shown in Table 2.

We redefine the relation “Overlaps (A, B)” as “Overlaps $_c$  (A, B)”; where “c” is the certainty degree associated to this relation. This means that the uncertain beginning bound of A is less than the uncertain beginning bound of B; the uncertain ending bound of A is greater than the uncertain beginning bound of B; and the uncertain ending bound of

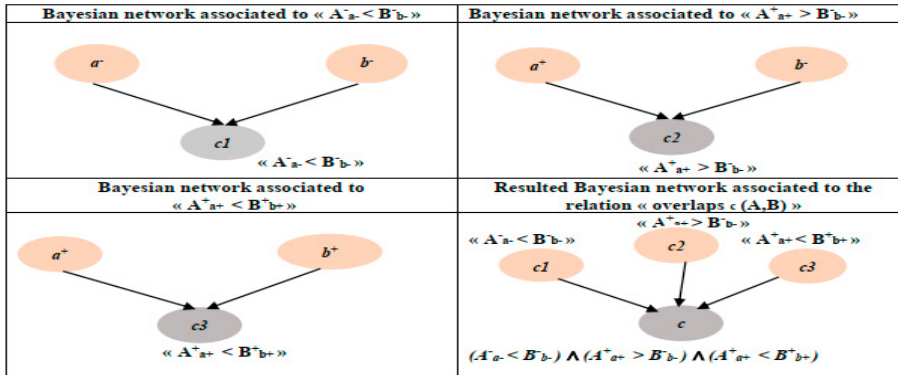


Fig. 3. Bayesian network associated to the relation "Overlaps  $c$ " between two uncertain time intervals.

Table 2. Temporal relations between two uncertain time intervals A and B.

Relation(A, B)	Relations between interval bounds	Inverse(B, A)
Before $c$ (A, B)	$A_a^+ < B_b^-$	After $c$ (B, A)
Meets $c$ (A, B)	$A_a^+ = B_b^-$	Met-by $c$ (B, A)
Overlaps $c$ (A, B)	$(A_a^- < B_b^-) \wedge (A_a^- < B_b^+) \wedge (A_a^+ < B_b^+)$	Overlapped-by $c$ (B, A)
Starts $c$ (A, B)	$(A_a^- = B_b^-) \wedge (A_a^+ < B_b^+)$	Started-by $c$ (B, A)
During $c$ (A, B)	$(B_b^- < A_a^-) \wedge (A_a^+ < B_b^+)$	Contains $c$ (B, A)
Ends $c$ (A, B)	$(B_b^- < A_a^-) \wedge (A_a^+ = B_b^+)$	Ended-by $c$ (B, A)
Equals $c$ (A, B)	$(A_a^- = B_b^-) \wedge (A_a^+ = B_b^+)$	Equals $c$ (B, A)

the interval A is less than the uncertain ending bound of B.

$$Overlaps_c(A, B) \Rightarrow (A_a^- < B_b^-) \wedge (A_a^+ > B_b^-) \wedge (A_a^+ < B_b^+) \tag{2}$$

The certainty degree "c" is inferred from the certainty degrees "c1", "c2" and "c3" associated, respectively, to the conjunctions  $(A_a^- < B_b^-)$ ,  $(A_a^+ > B_b^-)$  and  $(A_a^+ < B_b^+)$ , using four Bayesian Networks. The first one is to define the certainty degree "c1". The second one is to define the certainty degree "c2". The third one is to define the certainty degree "c3". The last one, is to define the certainty degree "c" of the relation from "c1", "c2" and "c3", as depicted by Fig. 3. We redefine the other Allen's relations the same way as the relation "Overlaps  $c$  (A, B)", as shown in Table 2.

*Example 1:* Let  $A = [A_a^-, A_a^+]$  and  $B = [A_b^-, B_b^+]$  be uncertain time intervals where  $A = [1960, 1963]$ ,  $B = [1940, 1963]$ ; and  $a^- = 0,7$ ;  $a^+ = 0,9$ ;  $b^- = 0,2$  and  $b^+ = 0,9$ . It holds that  $Ends_c(A, B) = 1$ ; Where  $(A_a^- > B_b^-) \wedge (A_a^+ = B_b^+) = 1$ ; with a certainty degree "c" equal to 0,66 . This latter is inferred from the certainty degrees "c1" and "c2" of the conjunction of  $(A_a^- > B_b^-)$  and  $(A_a^+ = B_b^+)$  using three Bayesian Networks, as shown in Fig.4.

The proposed temporal relations between uncertain time intervals preserve many properties of the Allen's algebra. We obtain generalizations of the reflexivity/irreflexivity, symmetry/asymmetry and transitivity properties. For example, "Equals" is reflexive. It holds that:  $Equals_c(A, A) = (A_a^- = A_a^-) \wedge (A_a^+ = A_a^+) = 1$ .

#### 4.1.2. Qualitative Temporal Relations between a Time Interval and a Time Point

We adapt the qualitative temporal relations between time intervals to propose relations between a time interval and a time point i.e., Interval-Point and Point-Interval relations, as shown in Table 3.

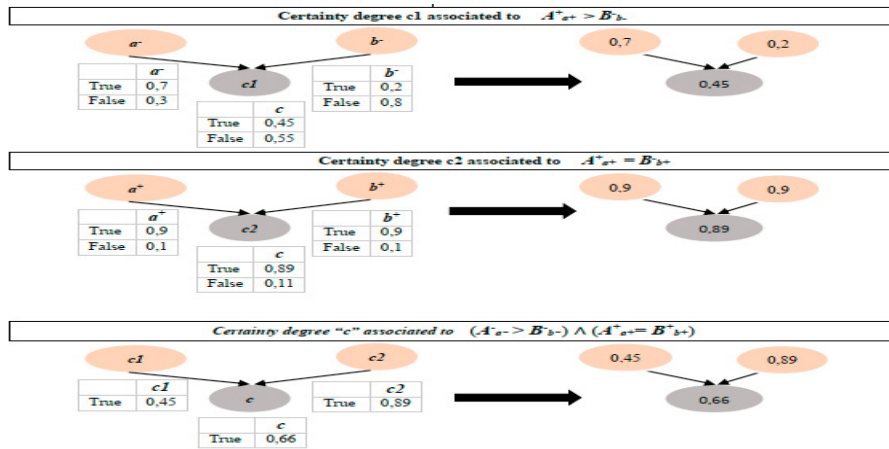


Fig. 4. Bayesian networks associated to Example 1

Table 3. Temporal relations between a time interval A and a time point P.

Relation(P, A)	Definition	Inverse(A, P)
Temporal relations between a certain time interval $A = [A^-, A^+]$ and a certain time point P		
Before (P, A)	$P < A^-$	After (A, P)
After (P, A)	$A^+ < P$	Before (A, P)
Starts (P, A)	$P = A^-$	Stated-by (A, P)
During (P, A)	$(A^- < P) \wedge (P < A^+)$	Contains (A, P)
Ends (P, A)	$P = A^+$	Ended-by(A, P)
Temporal relations between an uncertain time interval $A = [A_a^-, A_a^+]$ and an uncertain time point $P_p$		
Before <sub>c</sub> (P, A)	$P_p < A_a^-$	After <sub>c</sub> (A, P)
After <sub>c</sub> (P, A)	$A_a^+ < P_p$	Before <sub>c</sub> (A, P)
Starts <sub>c</sub> (P, A)	$P_p = A_a^-$	Stated-by <sub>c</sub> (A, P)
During <sub>c</sub> (P, A)	$(A_a^- < P_p) \wedge (P_p < A_a^+)$	Contains <sub>c</sub> (A, P)
Ends <sub>c</sub> (P, A)	$P_p = A_a^+$	Ended-by <sub>c</sub> (A, P)

Table 4. Temporal relations between two time points P and Q.

Relation(P, Q)	Definition	Inverse(Q, P)
Temporal relations between two certain time points P and Q		
Before(P, Q)	$P < Q$	After(Q, P)
Equals(P, Q)	$P = Q$	Equals(Q, P)
Temporal relations between uncertain time points $P_p$ and $Q_q$		
Before <sub>c</sub> (P, Q)	$P_p < Q_q$	After <sub>c</sub> (Q, P)
Equals <sub>c</sub> (P, Q)	$P_p = Q_q$	Equals <sub>c</sub> (Q, P)

#### 4.1.3. Qualitative Temporal Relations between Time Points

The qualitative temporal relations between time intervals are adapted to propose relations between time points, as shown in Table 4.



## 4.2. Transitivity Tables

The Allen's transitivity table lets us obtain from  $R_1(A, B)$  and  $R_2(B, C)$  that  $R_3(A, C)$  holds, where A, B and C are certain time intervals and  $R_1, R_2$  and  $R_3$  are Allen's relations. We generalize such deductions using the three uncertain time intervals  $A = [A^-, A^+]$ ,  $B = [B^-, B^+]$  and  $C = [C^-, C^+]$ . Based on Table 2, "Before<sub>c</sub>(A, K)" can be deduced from "During<sub>c</sub>(A, B)" and "Meet<sub>c</sub>(B, K)". Indeed by "During<sub>c</sub>(A, B)", " $(B_b^- < A_a^-) \wedge (A_a^+ < B_b^+)$ " is deduced, and by "Meet<sub>c</sub>(B, K)", " $(B_b^+ = K_k^-)$ " is deduced. From " $(A_a^+ < B_b^+)$ " and " $(B_b^+ = K_k^-)$ ", it is concluded that " $(A_a^+ < K_k^-)$ " which means that "Before<sub>c</sub>(A, K)" holds. The proposed transitivity table coincides with the Allen's one. We introduce two transitivity tables<sup>1</sup> to reason about the qualitative temporal relations between a time interval and a time point and a transitivity table to reason about time point relations.

## 5. Our "UncertTimeOnto" Ontology to Represent and Reason about Uncertain Temporal Data in OWL2

This section introduces our OWL 2 ontology, called "UncertTimeOnto"<sup>2</sup>. It implements the extended 4D-fluents approach which is instantiated based on the proposed extension of the Allen's algebra. We instantiate the certain object properties {"RelationIntervals", RelationIntervalsCertainty, "RelationIntervalPoint", "RelationIntervalPointCertainty", "RelationPointInterval", "RelationPointIntervalCertainty", "RelationPoints" and "RelationPointsCertainty"} based on our extension of the Allen's algebra. For example, "RelationIntervals" may be one of the Allen's relations. In other words, 13 object properties are associated: {"BeforeIntervals", "MeetsIntervals", "OverlapsIntervals", "StartsIntervals", "DuringIntervals", "EndsIntervals", "AfterIntervals", "Met-byIntervals", "Overlapped-byIntervals", "Started-byIntervals", "ContainsIntervals", "EndedbyIntervals" and "EqualsIntervals" }. Our ontology proposes a set of SWRL rules to infer missing qualitative temporal relations. For each temporal relation, we associate an SWRL rule to deduce it from the quantitative temporal data given by the user. Based on the transitivity tables, we associate an SWRL rule for each transitivity relation. "UncertTimeOnto" contains 2 classes, 6 datatype properties, 64 object properties and 180 SWRL rules. It may be integrated in other certain or probabilistic ontologies to handle certain and uncertain temporal data. In the following, an SWRL rule to infer the object property "EqualsPoints" between two certain time points M and P:

$$\begin{aligned} TimePoint(?m) \wedge TimePoint(?p) \wedge HasTimePoint(?m, ?mt) \wedge HasTimePoint(?p, ?pt) \wedge swrlb : equal(?pt, ?mt) \\ \Rightarrow EqualsPoints(?p, ?m) \end{aligned} \quad (3)$$

## 6. Experimentation

We implement a prototype based on the proposed approach. Then, we integrate it into the Captain Memo prosthesis to manage the temporal dimension in the context of PersonLink.

### 6.1. Our UncertTimeOnto-Based Prototype

We introduce a UncertTimeOnto -based prototype<sup>3</sup>. It uses Netica-J<sup>4</sup> for implementing Bayesian networks, JENA for manipulating ontologies and SPARQL-DL API for querying ontologies. This prototype contains three components: "UncertTimeOnto Population", "Qualitative Temporal Data Inference" and "Querying". First, the user instantiates "UncertTimeOnto" via the user interface shown in Fig. 5. It enables the user to enter certain/uncertain temporal data. After each new temporal data input, the "Qualitative Temporal Data Inference" component is automatically executed

<sup>1</sup> <https://drive.google.com/open?id=1Mwa3T9Vpjb9vgzE4uMoCyFDSpL3I8G5r>

<sup>2</sup> <https://cedric.cnam.fr/isid/ontologies/files/UncertTimeOnto.html>

<sup>3</sup> <https://github.com/Nassira1/Prototype.git>

<sup>4</sup> <https://www.norsys.com/netica-j.html#download>

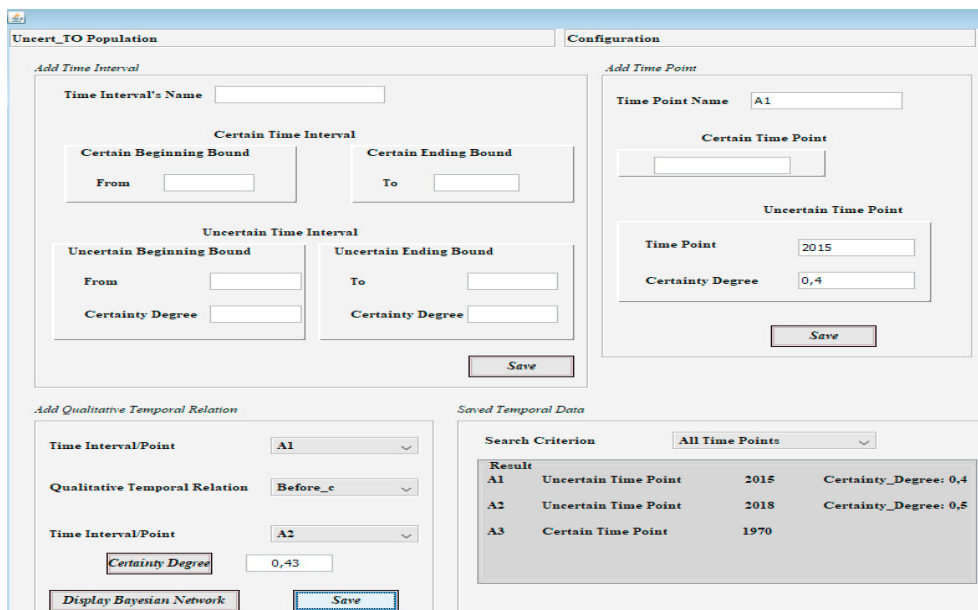


Fig. 5. “UncertTimeOnto Population” user interface.

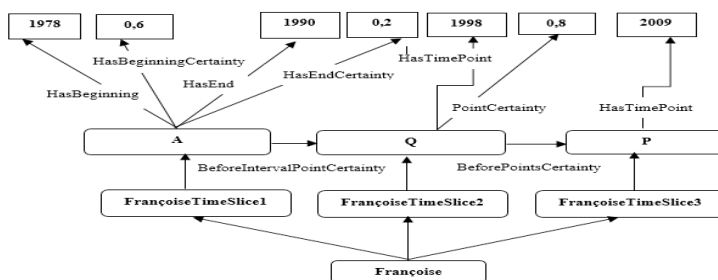


Fig. 6. An example of PersonLink Ontology based on our approach.

to infer missing data and the associated certainty degrees. This component is based on the proposed set of SWRL rules. The third component allows users to query the ontology via SPARQL queries.

### 6.2. Application to the “Captain Memo” Memory Prosthesis

We integrate the UncertTimeOnto-based prototype in the prototype of the Captain Memo memory prosthesis to handle certain and uncertain temporal data inputs in the context of the PersonLink ontology. As an example, if we have: “I think Françoise lived in Paris from 1978 to 1990. Then, she left France for many years and she was back maybe in 1998. She settled down in Toulouse in 2009”. Let  $A = [1978_{0,6}, 1990_{0,2}]$  be an uncertain time interval representing the duration of Françoise’s life in Paris. Let  $Q = 1998_{0,8}$  be an uncertain time point representing the back of Françoise to France. The associated certainty degrees are estimated based on our proposed approach [10]. Let “P = 2009” the certain time point representing the year of Françoise’s life in Toulouse. This example is depicted by Fig.6.

## 7. Conclusion and Future Directions

In this paper, we propose an approach to represent and reason about certain and uncertain temporal data in OWL 2. It is based on three contributions. (1) The first one is about extending the 4D-fluents approach with new certain com-

ponents to represent uncertain time intervals and certain/uncertain time points. It also deals with qualitative temporal relations between time intervals and points. (2) The second one consists of reasoning about the handled temporal data by extending the Allen's interval algebra. We propose 13 temporal relations between uncertain time intervals. Our extension is favored by keeping reflexivity/irreflexivity, symmetry/asymmetry and transitivity. These relations are adapted to relate a time interval and a time point or two time points; where time intervals and points may be certain or uncertain. We introduce four transitivity tables to reason about the resulting temporal relations. (3) The third one consists of proposing the "UncertTimeOnto" ontology that implements both the 4D-fluents approach and Allen's algebra extensions. The main interest of our approach is that it can be implemented with classical certain standards and researchers are not obliged to learn new technologies related to probabilistic ontology. We consider also that classical standards are more mature and have better scaling support. Besides, the proposed extension of the Allen's algebra may be applied to other research fields such as databases.

We plan to extend our approach to handle temporal data which are "uncertain and imprecise" at the same time.

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