Applying the Closed World Assumption to SUMO-Based FOL Ontologies for Effective Commonsense Reasoning

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Abstract. Most commonly, the Open World Assumption is adopted as a standard strategy for the design, construction and use of ontologies. This strategy limits the inferencing capabilities of any system because non-asserted statements (missing knowledge) could be assumed to be alternatively true or false. As we will demonstrate, this is especially the case of first-order logic (FOL) ontologies where non-asserted statements are nowadays one of the main obstacles to its practical application in automated commonsense reasoning tasks. In this paper, we investigate the application of the Closed World Assumption (CWA) to enable a better exploitation of FOL ontologies by using state-of-the-art automated theorem provers. To that end, we explore different CWA formulations for the structural knowledge encoded in a FOL translation of the SUMO ontology, discovering that almost 30% of the structural knowledge is missing. We evaluate these formulations on a practical experimentation using a very large commonsense benchmark obtained from WordNet through its mapping to SUMO. The results show that the competency of the ontology improves more than 50% when reasoning under the CWA. Thus, applying the CWA automatically to FOL ontologies reduces their ambiguity and more commonsense questions can be answered.

1 Introduction

Large knowledge-bases and complex ontologies are being used in a wide range of knowledge based systems [7] that require practical commonsense reasoning [8, 28, 39, 10, 43]. To represent this knowledge, the most prominent and fundamental logical formalism is the first-order predicate calculus, or first-order logic (FOL) for short. The semantics of FOL, and thus also of Description Logics (DL), operates under the Open World Assumption (OWA) allowing monotonic reasoning [11]. OWA considers that statements which are not logical consequences of a given knowledge base are not necessarily considered false but possible. Therefore, statements that are false or impossible must be clearly stated as so in the ontology. The OWA presumes incomplete knowledge about the domain being modelled. Thus, ontologies basically encode positive information about the modelled world since the number of negative facts vastly exceeds the number of positive ones. In fact, under the OWA, it is totally unfeasible to explicitly represent all such negative information in the ontology.

Otherwise, the Closed World Assumption (CWA) presumes perfect knowledge about the domain being modelled. CWA is a common non-monotonic technique that allows to deal with negative information in knowledge bases and data bases [34]. In fact, commonsense reasoning is non-monotonic: the addition of new knowledge can invalidate conclusions drawn before the addition [17].

There is a considerable computational and representational advantage to reason under the CWA since negative information should be inferred by default [35]. The Careful CWA (CCWA) is an extension of the CWA [15]. It allows us to restrict the effects of closing the world by specifying the predicates which may be affected by the CWA rule in indefinite databases.

Nowadays OWL 2 [44] is currently one of the most common formal knowledge representation formalism, but it is unable to fully cope with general upper ontologies like Cyc [24], DOLCE [14] or SUMO [26] since full FOL expressivity or higher is required. Further, CWA cannot be entirely applied to DL ontologies, but some approximations have been proposed in the literature [12, 25, 22].

In order to provide advanced reasoning support to FOL conversions of expressive ontologies [33, 20, 30, 4] state-of-the-art automated theorem provers (ATP) for FOL such as Vampire [21] or E [36] have proven its efficiency by implementing many sophisticated techniques like axiom selection [19]. However, the semi-decidability of FOL and the poor scalability of the known decision procedures have been usually identified as the main drawbacks for the practical use of FOL ontologies.

In this paper, we report on our empirical research applying the Careful CWA, that was originally conceived for indefinite databases, to the structural knowledge of a FOL ontology. In particular, we propose two complementary strategies for the application of the CCWA to the structural knowledge about classes represented in a FOL conversion of the top levels of SUMO [26]. To the best of our knowledge, this is the first attempt of applying the CWA to FOL ontologies since up to now the research on SUMO has been developed under the OWA.

Figure 1. An example of competency question for SUMO obtained from WordNet

We test the original and the resulting versions of SUMO by using the knowledge in WordNet [13] as gold standard. For this pur-
pose, we build a benchmark by automatically deriving a very large set of competency questions (CQs) from WordNet and its mapping to SUMO [27] on the basis of 7 manually created question patterns (QPs) [5]. These QPs focus on the main structural relations of WordNet, which are hyponymy and antonymy. The results show that applying carefully the CWA to the structural knowledge about classes in SUMO improves the competency of the ontology more than 50% when reasoning on the same commonsense benchmark.

For instance, in Figure 1 we describe the CQ “Drinking water is a beverage” that results from the hyponymy pair of WordNet synsets drinking_water (the hyponym) and beverage (the hyperonym), which are respectively connected to the SUMO concepts Water and Beverage. From this CQ, we obtain two conjectures: the first one states that some instances of Water can be instance of Beverage, and the second one is its negation. None of these conjectures are solved using SUMO, but one of them is entailed depending on the strategy for the application of the CWA to SUMO, concretely the CCWA to subclass and disjoint predicates. From now on, we will refer to CCWA as CWA.

Our research empirically demonstrates the existence of large knowledge gaps in SUMO and that the missing knowledge in SUMO-based FOL ontologies is nowadays one of the main obstacles for its practical application in automated commonsense reasoning tasks. Anyway, our proposal is not intended to provide that missing knowledge but, nevertheless, it could help ontologists to complete the knowledge in the ontology.

The contributions of this paper are fourfold. First, we propose an effective method to apply automatically the CWA to the structural knowledge of SUMO, which enables a really compact formalization. Second, we perform a detailed analysis of the empirical results obtained when comparing the resulting versions of SUMO with the original one on a very large commonsense benchmark with more than 14,000 CQs. This analysis demonstrates that the competency of the ontology can improve more than 50% when reasoning under the CWA. Third, we provide a quantitative analysis of the structural knowledge about classes that still needs to be encoded in the top levels of SUMO. Fourth, we discuss some suitable design criteria that enable the automated application of the CWA in FOL ontologies.

Outline of the paper. In Section 2 we present SUMO and its translations into FOL; in Section 3, we describe our approaches for the application of the CWA to subclass and disjoint; in Section 4 we report on the experimental results that we discuss in Section 5; and we conclude in Section 6 by outlining the future work.

2 SUMO and its FOL versions

SUMO\(^4\) [26] is a well-known upper level ontology proposed as a starter document by the IEEE Standard Upper Ontology Working Group. SUMO is expressed in SUO-KIF (Standard Upper Ontology Knowledge Interchange Format [29]), which is a dialect of KIF (Knowledge Interchange Format [16]). The syntax of both KIF and SUO-KIF goes beyond FOL and, therefore, SUMO axioms cannot be directly used by FOL ATPs without a suitable transformation.

To the best of our knowledge, there are two main proposals for the translation of the two upper levels of SUMO into FOL formulas that are described in [30, 31] and [4] respectively. Both proposals have been developed under the OWA and are currently included in the Thousands of Problems for Theorem Provers (TPTP) problem library\(^5\) [40].

The knowledge of SUMO, and therefore of its translations into FOL, is organized around the notions of classes and particulars. The main structural knowledge about classes is provided by the predicates i) subclass, which is defined as a partial order relation (reflexive, transitive and anti-symmetric), and ii) disjoint, which is defined as symmetric and irreflexive. The predicate subclass provides the classical concept of relation inclusion between classes, while the predicate disjoint relates incompatible classes: in Adimen-SUMO, incompatible classes cannot share any common instance or subclass. In SUMO, particulars are introduced by the predicate instance.

From the axiomatization of SUMO, particulars are inherited by superclasses (inheritance of instance via subclass). Additionally, every pair of disjoint classes do not share any instance and are not subclass of each other. Further, SUMO includes some additional predicates that provide structural knowledge about disjoint classes: specifically, partition and disjointDecomposition.

In the experiments, we will use Adimen-SUMO the FOL version of SUMO that has proved to be more competent [1, 6, 37]. Currently, Adimen-SUMO consists of 8,291 formulas, out of them 5,255 are atomic, and defines 2,169 classes.

Since Adimen-SUMO has been developed under the OWA, sometimes missing knowledge is not inferable. For example, although considering both the explicit and implicit knowledge in Adimen-SUMO, it is not possible to infer whether SentientAgent (“An agent that has rights but may or may not have responsibilities and the ability to reason”) and Sandwich (“Any food which consists of two or more pieces of bread and some sort of filling between the two pieces of bread”) are related by subclass/disjoint or not. From now on, we say that pairs of classes are non-asserted pairs (or missing knowledge) if Adimen-SUMO cannot entail whether they are related or not by subclass/disjoint. We have obtained an upper-bound of the amount of missing structural knowledge in Adimen-SUMO. For this purpose, we have considered both the explicit and implicit knowledge in Adimen-SUMO as follows: first, we have used ad hoc tools by focusing on the structural knowledge from Adimen-SUMO; second, we have used ATPs with the whole knowledge of Adimen-SUMO. Among the total of 4,704, 561 (2, 169\(^6\)) different pairs of classes, it is possible to infer that a) 18, 374 (0.39 %) pairs of classes are related by subclass (thus, not related by disjoint), b) 3, 304, 246 (70.23 %) pairs of classes are related by disjoint (thus, not related by subclass) and c) 62, 069 (1.32 %) pairs of classes are not related by disjoint (because those pairs of classes share some instance/subclass). Consequently, there are at most 1, 381, 941\(^7\) non-asserted subclass pairs (29.37 %) and 1, 338, 246\(^7\) non-asserted disjoint pairs (28.45 %). In other words, in the worst case scenario almost 30% of the structural knowledge about classes is missing in Adimen-SUMO.

3 Completing Adimen-SUMO

In this section, we describe different applications of the CWA to the structural knowledge about classes in Adimen-SUMO in order to reduce missing knowledge. We also provide the amount of new formulas that are required in each case. Concretely, we focus on the predicates subclass and disjoint. In the case of subclass, we apply a single strategy in which every non-asserted subclass pairs in Adimen-SUMO are assumed to not be related by subclass (see Subsection 3.1). With respect to disjoint, we apply two complementary strategies by assuming disjointness/non-disjointness to non-asserted pairs (see Subsections 3.2 and 3.3 respectively).

\(^4\) http://www.ontologyportal.org
\(^5\) http://www.tptp.org
\(^6\) 1, 381, 941 = 4, 704, 561 − (18, 374 + 3, 304, 246)
\(^7\) 1, 338, 246 = 4, 704, 561 − (3, 304, 246 + 62, 069)
3.1 Applying the CWA to subclass

In this subsection, we describe our proposal for the application of the CWA to subclass by assuming that the non-asserted subclass pairs are not related by subclass.

The application of the CWA to subclass is based on the set of class pairs that are explicitly related by subclass: direct subclasses. From now on, we denote by all_direct_subclasses_of(c) the set of all the Adimen-SUMO classes that are explicitly defined to be direct subclasses of an Adimen-SUMO class c.

In order to apply the CWA to subclass, we conveniently adapt the data base completion method proposed in [9]. For this adaptation, we implicitly adopt the Domain Closure Assumption (DCA) (that is, closed domain of classes) and assume that the domain of classes is finite: the domain only includes the classes that are explicitly introduced by the ontology.

Our adaptation of the data base completion relies on the fact that subclass is defined as a partial order relation in SUMO. This implies that given two classes c and c' such that c' is direct subclass of c (that is, c' ∈ all_direct_subclasses_of(c)), every subclass of c' is also subclass of c (by transitivity) and c is subclass of itself (by reflexivity):

\[ \forall x \forall y \forall z \ ( \text{subclass}(x,y) \land \text{subclass}(y,z) \rightarrow (\text{subclass}(x,z)) \]

Further, we also know that any superclass of c (except of c itself) is not subclass of c (by asymmetry):

\[ \forall x \forall y \ ( \text{subclass}(x,y) \land \text{subclass}(y,x) \rightarrow x = y ) \]

Consequently, the completed set of subclasses of an Adimen-SUMO class c can be defined as

\[ \forall x \ ( \text{subclass}(x,c) \leftrightarrow (x = c \lor \lor_{i=1}^{n} \text{subclass}(x,c_i)) \]

where all_direct_subclasses_of(c) = \{c_1, ..., c_n\}. The reverse implication is already given by the ontology. In particular, by axioms (1-3).

Thus, we only have to augment Adimen-SUMO by including the direct implication. For example, BloodCell have two direct subclasses in Adimen-SUMO, which are RedBloodCell and WhiteBloodCell:

\[ \text{subclass}(\text{RedBloodCell}, \text{BloodCell}) \]

\[ \text{subclass}(\text{WhiteBloodCell}, \text{BloodCell}) \]

Therefore, we have that all_direct_subclasses_of(BloodCell) = \{RedBloodCell, WhiteBloodCell\} and the formula that results from (4) to complete the information about the subclasses of BloodCell in Adimen-SUMO:

\[ \forall x \ ( \text{subclass}(x, \text{BloodCell}) \rightarrow (x = \text{BloodCell} \lor \text{subclass}(x, \text{RedBloodCell}) \lor \text{subclass}(x, \text{WhiteBloodCell}) ) \]

It is worth noting that, although the transitive closure of a binary relation cannot—in general—be expressed in first-order logic, all the formulas involved in the proposed application of the DCA to Adimen-SUMO classes (axioms (1-3) and (5-7) in the case of BloodCell) are pure FOL formulas.

In total, since Adimen-SUMO inherits 2, 169 classes from SUMO we have automatically augmented Adimen-SUMO by including 2, 169 new formulas as the one above (one per SUMO class), where we have used 4, 705 subclass atoms.

In this approach every non-asserted subclass pairs in Adimen-SUMO are assumed not to be related by subclass. It is worth noting that the complementary strategy—that is, assuming that every non-asserted subclass pairs in Adimen-SUMO are related by subclass—turns most of the classes into equal by antisymmetry.

3.2 Applying the CWA to disjoint by assuming disjointness

In this subsection, we describe our proposal for the application of the CWA to disjoint by assuming that the non-asserted disjoint pairs of classes are disjoint.

Formally, the application of the CWA by assuming disjointness can be described as follows: for any pair of non-asserted disjoint classes c_1 and c_2, we augment Adimen-SUMO by stating that c_1 and c_2 are disjoint. For example, in Figure 2 we show some of the subclasses of Beverage and CompoundSubstance, where all the depicted subclasses of Beverage are non-asserted disjoint with all the depicted subclasses of CompoundSubstance. Hence, the above described application of the CWA to disjoint by assuming disjointness introduces, among others, the following formulas in Adimen-SUMO:

\[ \text{disjoint}(\text{Beverage}, \text{CompoundSubstance}) \]

\[ \text{disjoint}(\text{Beverage}, \text{Water}) \]

It is obvious that the second conjecture obtained from “Drinking water is a beverage” is entailed by the augmented version of Adimen-SUMO, because Beverage and Water do not have any common instance/subclass if they are disjoint (see formula (9)).

In practice, most of the formulas that results from the application of the above method are redundant because of the axiomatization of disjoint in SUMO and can be easily omitted. More specifically, two classes are related by disjoint iff there is no common instance or subclass. Hence, given a pair of disjoint classes c_1 and c_2, every subclass c'_1 of c_1 (resp. c'_2 of c_2) is disjoint with c_2 (resp. c_1) by the inheritance of instance via subclass and the transitivity of subclass since all the instances/subclasses of c'_1 (resp. c'_2) are also instance/subclass of c_1 (resp. c_2). Therefore, disjointness is inherited by subclasses. For example, the classes Beverage and Water are still inferred to be disjoint although augmenting Adimen-SUMO by only formula (8) (and not formula (9)), because Water is defined as subclass of CompoundSubstance in Adimen-SUMO.

This way, we have augmented Adimen-SUMO by adding 20, 896 non-redundant atomic formulas.
3.3 Applying the CWA to disjoint by assuming non-disjointness

Conversely, next we describe the application of the CWA to disjoint by assuming that the non-asserted disjoint pairs of classes are non-disjoint.

For this purpose, we proceed similar to our previous strategy: for any pair of non-asserted disjoint classes \( c_1 \) and \( c_2 \), augment Adimen-SUMO by stating that \( c_1 \) and \( c_2 \) are non-disjoint. Coming back to the example about the non-asserted disjoint classes in Figure 2, above, the application of the CWA to disjoint by assuming non-disjointness would introduce, among others, the following formulas:

\[
\neg \text{disjoint}(\text{Beverage, Compound Substance}) \quad (10)
\]
\[
\neg \text{disjoint}(\text{Beverage, Water}) \quad (11)
\]
\[
\neg \text{disjoint}(\text{Coffee, Water}) \quad (12)
\]

This time, the first conjecture that results from “Drinking water is a beverage” is entailed by the augmented version of Adimen-SUMO due to formula (11), since pairs of non-disjoint subclasses necessarily have some common instance/subclass. However, this way we would obtain, as before, many redundant formulas: given a pair of non-disjoint classes \( c_1 \) and \( c_2 \), it can be inferred in Adimen-SUMO that all the superclasses \( c_2 \) of \( c_1 \) (resp. \( c_1 \) of \( c_2 \)) are non-disjoint with \( c_2 \) (resp. \( c_1 \)) by the inheritance of instance via subclass and the transitivity of subclass. That is, non-disjointness is inherited upwards. However, it is not easy to omit the redundant formulas in this case: for this purpose, we have to introduce non-disjoint pairs only between classes that do not have subclasses. This generates a very high number of new formulas. In addition, we need to check whether the classes are defined as disjoint. To verify this, two strategies can be followed: 1) stating for each pair if it is disjoint, for which it is necessary to use a lot of memory; 2) checking the hierarchy of classes. In this last case, there are two other options:

- By following a top-down strategy: given a branch, it is necessary to check all other non-disjoint ones, with many repetitions.
- By following a bottom-up strategy: for each pair that is non-disjoint, it is necessary to check the whole branch from the leaves to the root, which is computationally expensive.

In order to minimize the number of atomic formulas that are required to apply the CWA to disjoint by assuming non-disjointness, we introduce a new predicate — nonDisjoint — that states the downwards inheritance of non-disjointness. This new predicate is axiomatized as follows:

\[
\forall x_1 \forall y_1 \forall x_2 \forall y_2 \forall y_2 \left( ( \neg \text{disjoint}(x_1, x_2) \land \text{subclass}(y_1, x_1) \land \text{subclass}(y_2, x_2) ) \rightarrow \neg \text{disjoint}(y_1, y_2) \right)
\]

By means of this new predicate, we can proceed as follows: for any pair of classes \( c_1 \) and \( c_2 \) such that

- the pair \( c_1 \) and \( c_2 \) is non-asserted disjoint,
- any subclasses \( c_1' \) and \( c_2' \) of \( c_1 \) and \( c_2 \) respectively are either non-asserted disjoint or not related by disjoint

then we augment Adimen-SUMO by stating that \( c_1 \) and \( c_2 \) are related by nonDisjoint. By proceeding this way, non-disjointness is inherited both upwards and downwards, which enables a very compact formalization. In the above example, Beverage and Water are non-asserted disjoint (condition a) and, additionally, all the subclasses of Beverage (Coffee, Milk and Tea, among others) are non-asserted disjoint or not related with all the subclasses of Water (condition b). Consequently, we augment Adimen-SUMO as follows by the application of the CWA to disjoint assuming non-disjointness:

\[
\text{nonDisjoint}(\text{Beverage, Water})
\]

By formula (14), Beverage and Water are directly asserted to be non-disjoint, as given by formula (11). Further, all the pairs obtained from the super-classes of Beverage and Water respectively are asserted to be non-disjoint by upwards inheritance: for example, Beverage and Compound Substance (as given by formula (10)). Additionally, all the pairs obtained from the subclasses of Beverage and Water respectively are asserted to be non-disjoint by downwards inheritance: for example, Beverage and Coffee (as given by formula (12)), Beverage and Milk, etc. Consequently, formulas (10-12) (and many others) can be replaced with formulas (13-14) while preserving logical equivalence. It is worth noting that condition b prevents the introduction of inconsistencies caused by the downwards inheritance of non-disjoint, since all the involved pairs of subclasses are restricted to be non-asserted disjoint or not related by disjoint.

In total, we have augmented Adimen-SUMO by adding 29,643 atomic formulas and 1 general formula.

4 Experimental Results

In this section, we present the experiments with the different versions of Adimen-SUMO under the OWA and CWA as introduced in Section 3.
First of all, we have validated the completed versions of Adimen-SUMO using white-box testing techniques [3], and we have not found any inconsistency. Next, we have evaluated the efficiency and competency of each FOL version of Adimen-SUMO. For this purpose, we have used the framework for the evaluation of the competency of SUMO-based ontologies introduced in Álvez et al. [6]. The interested reader can find a detailed analysis in Álvez et al. [2]. This framework uses competency questions (CQs) [18] derived from several predefined question patterns (QPs) and three main knowledge resources: 1) the lexical database WordNet [13], where lexical concepts encoded in synonym sets or synsets are semantically related by different types of semantic relations such as hyponymy, antonymy, meronymy, etc. 2) a FOL translation of SUMO like Adimen-SUMO and 3) the semantic mapping between WordNet and SUMO [27]. Specifically, our benchmark is composed of 14,324 commonsense CQs obtained from 4 QPs based on hyponymy —2 QPs for nouns and 2 QPs for verbs—and 3 QPs based on antonymy. Each CQ consists of two conjectures: the first is called the truth-test, which is expected to be entailed by the ontology and describes the CQ; the second is called falsity-test, which is obtained as the negation of the truth-test and is expected not to be entailed by the ontology. Next, we briefly describe our QPs and provide some examples of the resulting CQs. Given a hyponym pair of nouns or verbs, the semantics of the hyponym is subsumed by the semantics of the hyperonym, and our QPs simply state the same property in terms of Adimen-SUMO, as proposed in [6] and obtain a CQ consisting of the truth-test

$$\forall x \forall y (\text{instance}(x, \text{Melting}) \land \text{instance}(y, \text{Freezing}) \rightarrow \neg x = y)$$ (16)

and its negation.

Given a benchmark, two dual tests are performed for each CQ using FOL ATPs: the first test is to check whether, as expected, the truth-test is entailed by the ontology; the second one is to check if the falsity-test is entailed. If ATPs find a proof for either the truth- or the falsity-test, then the CQ is classified as solved (or resolved). In particular, the CQ is passing/non-passing if ATPs find a proof for the truth-test/falsity-test. Otherwise (that is, if no proof is found), the CQ is classified as unresolved or unknown. For example, the CQ described by "Drinking water is a beverage", which consists of truth-test (15) and its negation, is classified as unknown by using the original version of Adimen-SUMO, as non-passing by using Adimen-SUMO augmented by the application of the CQA to subclass and disjoint assuming disjointness, and as passing by using Adimen-SUMO augmented by the application of the CQA to subclass and disjoint assuming non-disjointness.

Our experimentation has been performed by using Vampire v4.2.2—which is theCADE ATP System Competition (CASC) FOF division winner in 2017 [32, 41] and the latest available stable release[8] of Vampire at the time of our experimentation—in a Intel® Xeon® CPU ES-2640v3@2.60GHz with 2GB of RAM memory per processor. For each test, we have set an execution-time limit of 300 seconds and a memory limit of 2GB. [2] Totally, the experimentation has required almost 300 days/processor of computation effort: 3 ontologies, 14,324 CQs, 2 tests per CQ and 300 seconds per test. All the required knowledge resources—the original ontology Adimen-SUMO and its versions under the CWA, the set of CQs and conjectures, the mapping between SUMO and WordNet v3.0, WordNet v3.0 relation pairs—and the resulting execution reports are available at https://adimen.si.ehu.es/web/AdimenSUMO.

| Competency Questions | Passing | Non-passing |
|----------------------|---------|-------------|
|                       | CWA-D   | CWA-n-D     | CWA-D   | CWA-n-D     |
| noun #1 (3,386)       | 1,151 s | 1,111 s     | 115 s   | 111 s       |
| noun #2 (657)         | 3,300 s | 3,250 s     | 300 s   | 300 s       |
| verb #1 (1,103)       | 1,103 s | 1,063 s     | 103 s   | 103 s       |
| verb #2 (155)         | 155 s   | 151 s       | 5 s     | 5 s         |
| antonym #1 (29)       | 29 s    | 25 s        | 5 s     | 5 s         |
| antonym #2 (352)      | 352 s   | 342 s       | 32 s    | 32 s        |
| antonym #3 (1,357)    | 1,357 s | 1,347 s     | 137 s   | 137 s       |
| Total (7,039)         | 7,039 s | 6,999 s     | 399 s   | 399 s       |

We summarize our experimental results in Table 1, where CQs are organized by QP. In the first column (Competency Questions column), we provide the QP type and the number of CQs (between brackets). In the next 9 columns, we provide the number (columns...
mented by applying the CW A to assuming disjointness (CW A-D, 3 columns), and Adimen-SUMO augmented by applying the CWA to subclass and disjoint assuming non-disjointness (CW A-n-D, 3 columns).

From our results, it is easy to see that the CWA surpasses the OWA in our benchmark in terms of competency: the two augmented versions of Adimen-SUMO outperform the original version in terms of solved CQs that are solved by using each version of Adimen-SUMO: the original version of Adimen-SUMO (OW A, 3 columns), Adimen-SUMO augmented by applying the CWA to subclass and disjoint assuming disjointness (CW A-D, 3 columns), and Adimen-SUMO augmented by applying the CWA to subclass and disjoint assuming non-disjointness (CW A-n-D, 3 columns).

In our benchmark in terms of competency: the two augmented versions of Adimen-SUMO outperform the original version in terms of solved CQs (9, 781 and 9, 498 against 7, 285 solved CQs) and that the total number of solved CQs increases more than 50 % (10, 970 against 7, 285 solved CQs). Further, for each QP the number of solved CQs also increases up to 136 % (1, 502 against 637 solved CQs from verb #1). However, in the case of the CQs that result from antonym #1, the original version of Adimen-SUMO outperforms the augmented ones (36 against 29 and 27 solved CQs). This is because when using the augmented versions of Adimen-SUMO the ATP runs out of resources (mainly time) at trying to solve some of the CQs that were already solved by using the original version of the ontology. In total, 359 CQs (4.93 %) that are solved by using the original version of Adimen-SUMO remain unresolved when trying one of the augmented versions of Adimen-SUMO in our experimentation. However, for each QP many new CQs are solved only when using one of the augmented versions of Adimen-SUMO. Moreover, even improving the competency, the augmented versions of Adimen-SUMO also outperform the original one in terms of efficiency (55.12 s. and 58.75 s. against 61.30 s.), mainly because of the efficiency improvement at solving the CQs obtained from verb #1 and antonym #3. This implies that the new added knowledge has not a deep negative impact in the efficiency of the augmented ontologies. Further, we have checked that the newly added axioms sometimes serve as shortcuts in the proof of problems that were already solved using the original version of Adimen-SUMO.

Additionally, in Table 2 we provide some figures about the CQs that remain unresolved when using the original version of Adimen-SUMO. In the first column (Competency Questions column), we provide the QP from which CQs have been obtained and the number of CQs that remain unresolving when using the original version of Adimen-SUMO (between brackets). The last 12 columns are organized into groups of 3 columns. In each group, we provide the number (# columns), percentage of CQs (% columns) and average runtime (T columns) that are respectively classified as passing/non-passing by using each augmented version of Adimen-SUMO: Adimen-SUMO augmented by applying the CWA to subclass and disjoint assuming disjointness (CWA-D), and Adimen-SUMO augmented by applying the CWA to subclass and disjoint assuming non-disjointness (CWA-n-D).

According to the reported results, the classification of the newly solved CQs strongly depends on the given assumption that we adopt in order to apply the CWA: 2, 684 CQs (38.13 %) are classified as passing if assuming non-disjointness, while 2, 724 CQs (38.70 %) are classified as non-passing if assuming disjointness. Among them, 732 CQs are solved only when applying the CWA to subclass and disjoint by assuming disjointness. On the contrary, 527 CQs are solved only when applying the CWA to subclass and disjoint by assuming non-disjointness. Further, the chosen assumption also influences the kind of CQs that are most frequently solved: the largest amount of CQs obtained from hyponymy are solved when assuming disjointness (2, 773 against 2, 179 solved CQs obtained from noun #1, noun #2, verb #1 and verb #2), although the largest number of CQs obtained from antonymy-based QPs are solved when assuming non-disjointness (638 against 363 solved CQs obtained from antonym #1, antonym #2 and antonym #3). Regarding average runtimes, it seems that assuming disjointness at applying the CWA to disjoint yields to a more efficient augmented version of Adimen-SUMO.

5 Discussion

In this section, we discuss the experimental results reported in the above section.

The experimental results reported in Section 4 can be further improved. First, we think that the ATP runs out of resources (especially time) when trying to prove conjectures that are entailed by some of the augmented versions of Adimen-SUMO. Actually, we have experimentally checked that the ATP runs out of resources using the augmented versions of Adimen-SUMO when trying to solve 359 CQs that are solved by the original version of Adimen-SUMO (less than 5 %). Thus, it is very likely that there are more solvable CQs. Second, we also think that our results are penalized by the poor mapping of adjectives sets as pointed out by [2], since the worst results reported in Table 1 correspond to the CQs obtained from the QPs based on pairs of antonym adjectives. Third, we have manually inspected some cases and detected that some knowledge is still under-specified, despite of the application of the CWA. For example, it is not possible to infer from the augmented versions of Adimen-SUMO whether Animal and LinguisticExpression are disjoint or not. Another example of missing knowledge is the axiomatization of many attributes. We have discovered this problem by analysing the most frequent concepts involved in the unknown CQs e.g. SubjectiveAssessmentAttribute.

Regarding non-asserted subclass pairs, our assumption is that those pairs are not related by subclass, since otherwise most of the involved classes would become equal by anti-symmetry as discussed in Section 3. Interestingly, the impact of augmenting Adimen-SUMO by applying the CWA only to subclass as described in Subsection 3.1 is really small. On the contrary, the impact of the application of the CWA to subclass in combination with the application of the CWA to disjoint is much higher. This is especially the case when applying the CWA by assuming disjointness, mainly because the DCA is also applied in the proposal described in Subsection 3.1.

With respect to non-asserted disjoint pairs, we have assumed that those pairs are either disjoint (in Subsection 3.2) or non-disjoint (in Subsection 3.3). As described in Section 4, the classification of most of the newly solved CQs depends strongly on the chosen assumption: if assuming disjointness, 2, 724 newly solved CQs are classified as non-passing, while 3, 136 newly solved CQs are classified as passing when assuming non-disjointness (see Table 2). An example of this is the CQ described in the introduction: “Drinking water is a beverage”, see truth-test (15). This fact confirms the lack of structural knowledge about classes in Adimen-SUMO.

We have, therefore, proved that structural knowledge is missing and it will be necessary to augment the ontology. We foresee that the classification of the newly solved CQs can guide the application of the CWA to disjoint using WordNet as a reliable knowledge source. Let us explain this proposal with two examples. On the one hand, by assuming that Melting and Freezing are disjoint, the CQ described by “the adjectives liqueescent and frozen are antonym”, consisting of truth-test (16) and its negation, is passing, but if non-disjointness is assumed, it is non-passing. So, using the knowledge in the ontology and the combination of both augmented versions we can conclude
that Melting and Freezing must be disjoint. On the other hand, the CQ described by “Drinking water is a beverage” is non-passing when assuming that Beverage and CompoundSubstance are disjoint but passing when assuming non-disjointness. Thus, these classes should be non-disjoint. In sum, the combination of assuming disjointness in cases such as Melting and Freezing and non-disjointness in cases such as Beverage and CompoundSubstance seems to be appropriate to obtain the correct disjoint/non-disjoint axioms if using WordNet as a reliable knowledge source. In any case, the above described solutions for disjoint require the addition of many new axioms. We have proved that the source Adimen-SUMO and its completed versions are comparable in terms of efficiency according to the experimentation reported in Section 4, even though we have added many axioms. However, if we follow suitable structural design criteria, it is not necessary to include additional axioms in a FOL ontology for the application of the CWA to disjoint.

One of these possible criteria is linked to the the application of the CWA to subclass: Organizing the knowledge around the notion of classes will implicitly provide a solution for disjoint. If we define two classes as disjoint iff they do not share any common subclass, the completion of subclass itself (see Subsection 3.1) enables deciding whether two classes are disjoint or not. However, at this time, this is not possible because the notion of disjointness in SUMO inappropriately states that two classes are disjoint iff they do not share any common instance

\[ \forall x_1 \forall x_2 \forall y \left( \text{disjoint}(x_1, x_2) \implies \neg \left( \text{subclass}(y, x_1) \wedge \text{subclass}(y, x_2) \right) \right) \]  

(17)

and not subclasses as we propose:

\[ \forall x_1 \forall x_2 \forall y \left( \text{disjoint}(x_1, x_2) \implies \neg \left( \text{subclass}(y, x_1) \wedge \text{subclass}(y, x_2) \right) \right) \]  

(18)

Further, the inappropriate use of instance is extended to most parts of SUMO and makes it possible to infer that many pairs of classes that do not share any common subclass do have common instances. This fact makes it really difficult to correct the axiomatization of disjoint in SUMO without reconstructing all the knowledge from almost scratch and, consequently, it prevents the easy application of CWA to disjoint in SUMO.

In sum, we consider that the best choice for the practical application of the CWA in a FOL ontology is to follow the suitable design criteria such as the one explained above.

6 Conclusions and Future Work

To the best of our knowledge, up to now the research and evaluation of SUMO-based FOL ontologies have been developed exclusively under the Open World Assumption. This paper reports on the first investigation on the application of the Closed World Assumption to SUMO-based FOL ontologies. Concretely, we have applied the Careful CWA introduced by [15] to the subclass and disjoint relations of a FOL version of SUMO. We have checked two CWA formulations for disjoint: i) by assuming disjointness and ii) by assuming non-disjointness. We have tested these two formulations on a very large benchmark of 14,324 commonsense competency questions extracted from WordNet and its mapping to SUMO. Summing up, although the size of the ontologies has been increased, the resulting ontologies are far more compact and keep their efficiency. Regardless of the CWA strategy applied to disjoint, our research empirically demonstrates that the competency of the ontology can improve more than 50% when reasoning under the CWA. As a side effect, we have also discovered that the missing structural knowledge in SUMO is nowadays one of the main obstacles for its practical application in automated commonsense reasoning tasks. In fact, almost 30% of the structural knowledge about classes is missing in Adimen-SUMO. Further, our proposal can help ontologists to complete the missing knowledge, for example, by using WordNet. Thus, the practical utility of our proposal in tasks that require commonsense reasoning is clear.

Although the approach assuming disjointness obtains the best results, a combination of both approaches should be further investigated. For example, using WordNet as reliable source of knowledge, a possible approach is to weigh each new pair according to the number of solutions in which it is used and its kind (passing/non-passing), and then proceed to choose the most relevant ones while keeping consistency. Similar approaches could be taken into account by considering other sources of knowledge. Additionally, as discussed, suitable design criteria can facilitate the application of the CWA to FOL ontologies. Future work will focus on implementing the proposed strategies. It will also involve experimenting with other knowledge representation strategies such as the Unique Name Assumption (UNA) [23] and testing augmented versions of the ontology with other datasets such as the ones created in the Webchild project [42] and ConceptNet [38].

ACKNOWLEDGEMENTS

We would like to thank the reviewers for their comments, which helped improve this paper considerably.

This work has been partially funded by the the project Deep-Reading (RTI2018-096846-B-C21) supported by the Ministry of Science, Innovation and Universities of the Spanish Government, and GRAMM (TIN2017-86727-C2-2-R) supported by the Ministry of Economy, Industry and Competitiveness of the Spanish Government, the Basque Project LoRea (GIU18/182), Ixa Group-consolidated group type A by the Basque Government (IT1343-19) and Big-Knowledge – Ayudas Fundación BBVA a Equipos de Investigación Científica 2018.

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