

Praedixi, Redegi, Cogitavi: Adaptive Knowledge for Resource-aware Semantic Reasoning

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Abstract

Representing knowledge with ontologies and performing reasoning with semantic reasoners is important in many intelligent applications. However, existing reasoners do not take into account the available resources of the device where they run, which can be important in many scenarios such as reasoning with very large ontologies or reasoning on resource-constrained mobile devices.

In this paper, we propose a novel approach to adapt the size of knowledge managed by applications, taking into account several criteria about resources available (such as time, memory, and battery consumption), at the same time. Thus, rather than giving no answer due to the lack of resources needed to deal with a full ontology, we propose a novel architecture to compute a subontology to provide an incomplete answer at least. Our approach makes use of existing approaches to predict the performance of semantic reasoners and to compute ontology modularisation and ontology partition, but taking into account the associated resource consumption. We also propose a novel measure to estimate the semantic loss when replacing the original ontology by a subontology. Finally, we present an implementation and evaluation of the whole pipeline, showing that the semantic loss incurred in the process is acceptable.

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1. Introduction

One of the key reasons behind the success of intelligent applications is the exploitation of knowledge. From old knowledge-based systems or expert systems, it has been clear that knowledge representation is a crucial task. Modern intelligent applications usually represent the relevant explicit knowledge using ontologies (see for example (Allemang et al., 2020)), which are formal and shared specifications of the vocabulary of a domain of interest. Ontologies are usually formalised using Description Logics (DLs) (Baader et al., 2003), which have many advantages, including the possibility of using *semantic reasoners* (Khamparia and Pandey, 2017) to answer questions regarding an ontology, compute new knowledge which is not implicitly represented in the ontology, etc. Ontology reasoners solve one or several reasoning tasks. Popular reasoning tasks include *consistency checking* (verifying that an ontology does not have logical contradictions), *instance retrieval* (computing all the instances of a given concept), *classification* (computing a concept hierarchy and a property hierarchy based on the subsumption relationships), and *ontology materialisation* (precomputing some inferences, such as indirect subclass axioms).

Unfortunately, the algorithms currently implemented by the semantic reasoners do not take into account the resources available for the running environment. Let us discuss some examples where resources are important:

- Reasoners do not take into account the memory of computers where they are executed: if the input ontology is very large, the reasoner might abort its execution returning an “out of memory error” and therefore the user would not receive any answer. For example, let us consider GALEN medical ontology, which has been used as a reference terminology for surgical procedures in France, for oral hygienists and dietitians in the Netherlands, and for drugs in the UK (Rogers et al., 2001). When trying to reason with the 20.1 MB GALEN on a desktop computer with an Intel Core i7-6700K@4.00 GHz CPU and 24GB of RAM,

28 HermiT (Glimm et al., 2014) reasoner did not finish in 400 s and, after extending
29 the timeout to 3600 s, it ran out of memory. Indeed, in order to support GALEN,
30 people had to manually identify, extract, and use fragments of the ontology. Over
31 the years, different authors identified different fragments of the ontology, with
32 different expressivities and sizes, suitable for their particular hardware resources
33 and information needs. Ideally, such a process should be automatised and gener-
34 alised so that it can adapt to the user device resources.

35 MMD ontology, used at Aibel company (Norway), is another example where
36 modularisation is critical to perform efficient reasoning (Skjæveland et al., 2012).
37 In fact, requirements and specifications are represented using generic ontologies,
38 ontologies describing generic concepts in the engineering domain, and domain
39 ontologies. However, existing modules cannot be dynamically adapted to the
40 user device resources.

- 41 • In ontology visualisation (which requires using a reasoner to deal with the im-
42 plicit knowledge) (Dudáš et al., 2018), the ontology could be too large to be
43 displayed completely, so it is a good idea to take hardware resources and user
44 preferences into account. On the one hand, ontology visualisation tools should
45 adapt to the running environment, taking into account, for example, the size of
46 the screen. On the other hand, even if the ontology has a large number of nodes,
47 it is not necessary to display all of them (no user will be able to see the details of
48 thousands of nodes at the same time) but rather limit itself to showing a subset
49 of nodes that are interesting for the user or the most relevant concepts to get a
50 global view.
- 51 • Mobile devices typically have limited resources (at least when compared to desk-
52 top/server counterparts) in terms of CPU processing, available memory, remain-
53 ing battery charge, and connectivity (wireless communications are, in general,
54 less reliable than wired ones). This also applies to the Internet of Things (IoT),
55 where the devices deployed to perform so called *edge-computing* would be also
56 limited by their hardware resources. For example, let us consider an emergency-
57 assistance app for mobile devices, such as the one implemented in the SHER-

LOCK system (Yus and Mena, 2015). In order to assist the health staff to find a proper treatment for a particular patient, it should be able to avoid medication errors by automatically checking that there is no incompatibility between the medicines and the allergies of the patient (according to the knowledge in a certain ontology). Being able to reason locally on such devices is important when connectivity is not guaranteed (Huitzil et al., 2020). This is the case not only for smartphones, but also tablets, laptops, wearable devices, etc. However, due to its limited resources, significantly fewer reasoning tasks are completed on a mobile device than on a desktop computer, as illustrated in the example in Figure 1, adapted from (Bobed et al., 2015), where in 61 out of the 572 evaluated tasks, the reasoning did not end successfully on the mobile device. Another example is the beer recommender system GimmeHop, that required to compute manually a fragment of the ontology to reason on a local mobile device (Huitzil et al., 2020).

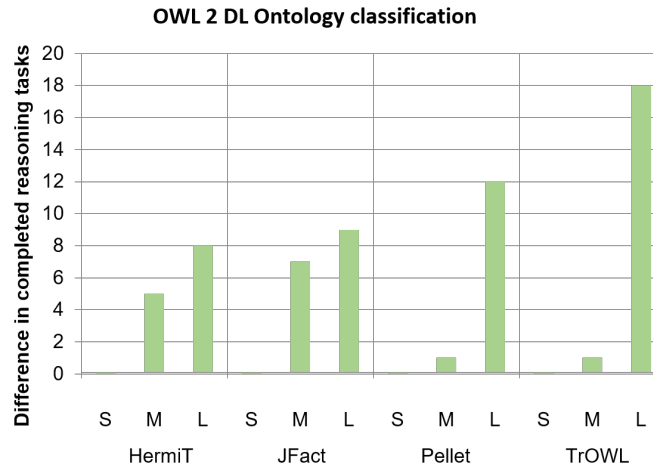


Figure 1: Difference in the number of tasks that finished on a desktop computer but did not finish on an Android device, for different reasoners and ontology sizes: *S*(*mall*, <500 axiomas), *M*(*edium*, [500,5000) axiomas) and *L*(*arge*, ≥5000 axioms).

We claim that an intelligent application cannot really be called “intelligent” if it does not work when available resources are not optimal. For example, coming back to

73 our emergency-assistance app, it should not assume that a stable wireless connection
74 will always exist in a remote mountainous area or inside a tunnel: in such critical
75 cases, the application should implement strategies to guarantee that there will be an
76 acceptable behaviour, such as working with the local knowledge, finding alternative
77 ways to communicate (e.g., an ad-hoc network), etc.

78 Current ontology tools, such as semantic reasoners (e.g., Pellet (Sirin et al., 2007),
79 HermiT (Glimm et al., 2014), TwOWL (Thomas et al., 2010), or MORE (Armas-
80 Romero et al., 2012)) or ontology editors (e.g., Protégé (Musen, 2015)) start to solve a
81 reasoning task without taking into account whether they will finish such a task or not.
82 If reasoning cannot be finished under the existing resources, current tools just abort
83 their execution and throw an exception (typically, “out of memory” error).

84 A first solution would be to adapt existing reasoning algorithms to different re-
85 source limitations, but this is complex as resource management is heterogeneous and
86 can be contradictory; e.g., to minimise reasoning time, semantic reasoners typically
87 use auxiliary data structures, which increases the memory use.

88 In this paper, instead, we propose a novel approach to promote *resource-aware se-*
89 *mantic reasoning*, deciding at run-time how much knowledge can be processed by the
90 device. As a consequence, it will improve the semantic capabilities of resource-limited
91 devices. In particular, we will mainly focus on adapting the available knowledge to
92 a size that a device is able to handle, to avoid aborting reasoning tasks due to a lack
93 of resources. Ideally, one would like to take into account all the available knowledge,
94 but limited capabilities might force us to restrict to a (as large as possible) subset. Fur-
95 thermore, our approach will make it possible for applications to detail the percentage of
96 knowledge that is being handled and to explain to the user that the answer of the reason-
97 ing is incomplete and its estimated loss of information. To do so, we propose (i) to first
98 estimate the needed resources for a given reasoning task on a given ontology, building
99 on previous approaches to predict the resource consumption of DL reasoners (Guclu
100 et al., 2016b; Kang et al., 2012; Pan et al., 2018), (ii) if needed, considering to the
101 specified limitations for the device, to compute a subset of knowledge to work with,
102 and (iii) to run a semantic reasoner to solve the given reasoning task on the (computed

103 subset of knowledge¹.

104 This context leads to two important research questions:

- 105 1. On the one hand, which size of knowledge are we able to manage in a given
106 device? As the resources of the devices are fixed, we turned our attention to the
107 knowledge to be processed, which can be selected somehow.
- 108 2. On the other hand, even if we had a general framework to predict the cost in
109 terms of different criteria, how do we measure the consequences of dealing with
110 a subset of available knowledge only? In particular, given an ontology and an
111 extracted subontology, is it possible to measure, for a given reasoning task, the
112 semantic loss we will incur when working only with the latter one? As we will
113 discuss in Section 2.3, existing approaches are not directly applicable.

114 The main contributions of this paper are the following ones:

- 115 • We firstly propose a general architecture based on a combination of ontology
116 modularisation strategies (Del Vescovo et al., 2013) and prediction of the cost of
117 a given reasoning task.
- 118 • Then, for the sake of concrete illustration, we implement a prototype which fo-
119 cuses on a single resource: it adapts the reasoning to the specified maximum
120 running time, using a particular choice of prediction and modularisation tech-
121 niques.
- 122 • We propose and evaluate a measure to estimate the semantic loss incurred, given
123 that our proposal advocate working with subontologies instead of full (but un-
124 manageable) ontologies.
- 125 • We empirically demonstrate the feasibility of our approach by studying the ac-
126 curacy of the prediction when computing the adapted subontologies and the es-
127 timated semantic loss.

¹In Latin, “Praedixi, Redegi, Cogitavi” means “I predicted, I reduced, I reasoned.”

128 The rest of the paper is organised as follows. First, in Section 2 we present an
129 overview of the related work. Section 3 describes the proposed architecture, and its
130 possible use in a mobile computing scenario. Section 4 presents some possible knowl-
131 edge extraction strategies, implemented in a prototype. Then, Section 5 presents our
132 proposal to measure the semantic loss of a module. In Section 6, we perform an exper-
133 imental evaluation of our prototype. Finally, we draw some conclusions and present
134 the future work in Section 7.

135 2. Related Work

136 In this section we will overview some related work on computing ontology subsets
137 (Section 2.1), adapting ontology reasoning to the resources (Section 2.2), and measur-
138 ing semantic loss (Section 2.3). Finally, we identify some open issues (Section 2.4).

139 2.1. Computing ontology subsets

140 Several years ago Stuckenschmidt and Klein asserted that the realisation of the Se-
141 mantic Web depended on the ability to reuse ontologies (Stuckenschmidt and Klein,
142 2004). They proposed that problems arising from the monolithic nature and size of
143 ontologies could be solved by an automatic *partitioning mechanism*. Ontology par-
144 titioning consists of dividing an ontology into several subontologies such that every
145 axiom of the original ontology belongs to exactly one subontology. However, auto-
146 matic partitioning strategies so far do not take into account either the target environ-
147 ment where the extracted knowledge is going to be deployed or the actual tasks such
148 knowledge is going to be used for. For example, when dealing with SNOMED CT on-
149 tology (BioPortal, 2023), automatic partitioning strategies, such as SWOOP (Cuenca
150 Grau et al., 2006), or PATO (Schlicht and Stuckenschmidt, 2006), either produced one
151 very big subontology (due to the inner links between concepts), or one subontology
152 which takes into account parameters that were hardly related to the available resources
153 of our devices, such as *number of partitions*. Other approaches, such as Prompt (Noy
154 and Musen, 2004), rely on *manual partitioning* strategies which require some param-
155 eters (again not related to resource consumption) set by the user/developer such as *depth*
156 *of traversal*, *relationships to be included*, and *a starter concept*.

157 Apart from ontology partitioning, ontology *modularisation* consists of computing
 158 a subset of an original ontology such that the inferences related to some terms (a seed
 159 signature) are preserved. Some approaches have been proposed for which the ontol-
 160 ogy conforms an *conservative extension* for a given signature, such as (Armas-Romero
 161 et al., 2016; Cuenca Grau et al., 2008; Gatens et al., 2013; Konev et al., 2013). For ex-
 162 ample, *syntactic locality-based module extraction* (Cuenca Grau et al., 2008; Jiménez-
 163 Ruiz et al., 2008) proposes six different types of modules for an ontology with different
 164 assumptions and expectations from a module. A comparison of three logically sound
 165 notions of a module (i.e., MEX modules, semantic locality, and syntactic locality) con-
 166 cluded that syntactic locality, which is computationally cheaper to find, can be a good
 167 approximation of semantic locality, and that “*in general* there appears to be no or little
 168 difference between semantic and syntactic locality” (Del Vescovo et al., 2013). AMEX
 169 modules have been generated by implementing a depletion approach on acyclic ontolo-
 170 gies using provided signatures (Gatens et al., 2013). However, despite the benefits of
 171 their logical grounding, these approaches focus only on the logical properties that the
 172 logical modules must satisfy, but they do not consider the resource consumption.

173 Using partitioning or modularisation techniques to obtain better performance re-
 174 sults can be seen in MORE (Armas-Romero et al., 2012), a meta-reasoner which tries
 175 to divide the ontology into different modules according to their expressivity and for-
 176 wards them to the appropriate underlying reasoner. For example, MORE would split a
 177 given ontology and use two reasoners, one efficient \mathcal{EL} reasoner (i.e., ELK (Kazakov
 178 et al., 2014)) for processing axioms that have the expressivity of the OWL 2 EL profile
 179 in the fastest way possible, and a DL reasoner (e.g., HermiT (Glimm et al., 2014)) for
 180 processing axioms with higher expressivity. This approach, while similar to the nature
 181 of our proposal, does not take into account the available resources.

182 2.2. Adapting to resources

183 The mobile reasoner mTableaux implements a weighted partial matching approach
 184 that would terminate the process when it reaches a given RAM threshold, and would
 185 provide the results according to matching conditions provided by the user (Steller et al.,
 186 2009). However, why should we deplete all the device resources if we could just work

187 with a specifically task-tailored piece of knowledge? This is specially more important
188 in these scarce-resources scenarios, where we have to optimise everything as much
189 as possible. Besides, this approach expects the user/developer to provide *successful*
190 *matching conditions* and weights for matching conditions to give priority in their depth-
191 first checking algorithm.

192 In order to guide the extraction taking into account the resource consumption,
193 we also need to be able to predict the resource consumption of reasoners. In this
194 regard, there have been several different proposals mainly oriented to predict execu-
195 tion times (Guclu et al., 2016a; Kang et al., 2012, 2014; Pan et al., 2018; Sazonau
196 et al., 2014; Zhang et al., 2010) in desktop computers. Other works proposed differ-
197 ent set of ontology metrics mainly at TBox reasoning level to predict the reasoning
198 time using classification and regression models (Zhang et al., 2010; Kang et al., 2012,
199 2014). (Pan et al., 2018) explored their capabilities when trying to predict reasoning
200 times with big ABoxes, proposing an extension of the metrics which allowed to im-
201 prove the time processing prediction. Instead of building global models such as these
202 methods do, (Sazonau et al., 2014) proposed a local prediction method that involves
203 selecting a *suitable* small subset of the ontology and use extrapolation to predict total
204 time consumption of ontology reasoning using the data generated by the processing
205 of such a small subset. We think that using both of them together will be a starting
206 point to get enough information to guide the resource aware knowledge adaptation our
207 proposal requires.

208 Beyond the semantic reasoning application, (Hutter et al., 2014) showed that it
209 is possible to predict the performance of algorithms for hard problems, in particular
210 propositional satisfiability (SAT), travelling sales person (TSP), and mixed integer pro-
211 gramming (MIP) problems. Prediction approaches based on random forests showed
212 the best performance. Identifying metrics for the prediction is problem-dependent: the
213 authors identified 138, 121, and 64 features for SAT, TSP, and MIP, respectively. The
214 prediction of the performance of other discrete problems (such as the travelling thief
215 problem, the quadratic assignment problem, or solving quantified Boolean formulae)
216 but also continuous problems (in particular, both unconstrained and constrained single-
217 objective optimisation problems) has also been investigated (Kerschke et al., 2019).

218 Regarding reasoning specifically on mobile devices, reasoners can be native (Ruta
 219 et al., 2022, 2019; Steller et al., 2009; Van Woensel and Abidi, 2019) (implemented
 220 for a specific mobile device or an edge-computing device) or ported (to reuse existing
 221 semantic reasoners (Bobed et al., 2015)). (Bobed et al., 2015) adapted some existing
 222 reasoners to Android and presented a thorough evaluation of the time performance
 223 of DL reasoners, showing that it is feasible to use them up to “medium-size” ontolo-
 224 gies. While there have been some approaches that have adapted semantic reasoners to
 225 constrained-resource devices (Ruta et al., 2022, 2019; Steller et al., 2009; Van Woensel
 226 and Abidi, 2019); none of them is able to adapt the reasoning to the resources of a
 227 particular device. In particular, (Van Woensel and Abidi, 2019) proposes to optimise
 228 mobile reasoning by de-activating inference rules (for the OWL 2 RL profile) to de-
 229 crease the running time. However, specific resources are not taken into account, so
 230 it could de-activate more rules than needed, and even after de-activating some rules,
 231 the resource limit could still be reached. Furthermore, (Kleemann, 2006) discussed re-
 232 source restrictions (computing power, memory, and energy) from the point of view of
 233 reasoner development, but the implementation cannot adapt to the resources. Finally,
 234 it is worth to mention the only previous work predicting the resource consumption on
 235 mobile devices, which presented a battery consumption prediction module for Android
 236 devices (Guclu et al., 2016b).

237 2.3. *Semantic loss*

238 While there are some works that compute the semantic loss when a query expres-
 239 sion is rewritten, such as the OBSERVER system (Mena et al., 2001), computing the
 240 semantic loss when replacing an ontology with another one is not always considered.
 241 The main reason is that, as already mentioned, ontology modularisation computes a
 242 subset of an original ontology such that the inferences related to the seed signature are
 243 preserved, so there is no semantic loss (with respect to the seed signature).

244 (Gobin-Rahimbux, 2022) overviews the metrics to evaluate ontology modules and
 245 classifies them into eight categories: naming convention, syntax, module character-
 246 isation and distribution, module structure, module richness, logical criteria, module
 247 relatedness, and module quality. Module quality includes precision and recall, but they

are restricted to taxonomical relations (disregarding other axioms) and do not consider the consequences of the axioms.

In the context of *ontology alignment*, (Euzenat, 2007) proposed the definitions of semantic precision and semantic recall. The idea is that the true and false positives do not only consider the explicit alignments but also their consequences (i.e., implicit alignments). In our scenario, semantic precision would be 1 by definition, as all the axioms in the subontology are part of the original ontology. However, we will consider a similar notion of semantic recall.

While we are interested in computing the semantic loss between an original ontology and a subontology, the notion of *semantic difference* is more general, as it is asymmetric and is thus concerned with both axioms that belong to O_1 and not to O_2 , and axioms that belong to O_2 and not to O_1 . Measures to compute the semantic difference are also typically based on the percentage of consequences which change with respect to another ontology (Pernisch et al., 2021).

2.4. Open issues

Thus, after analysing the available approaches, we have identified two main points that hinder the adoption of semantic reasoning where resources are constrained:

1. *Lack of interaction and collaboration* between reasoning and knowledge extraction for a better optimisation of knowledge processing on resource constrained scenarios. The MORE approach indicates that it is promising to explore such a possible interaction for other purposes such as mobile devices.
2. *Lack of generalisation*, because previous works on the subject are *embedded* in various research prototype implementations and cannot be easily generalised. For example, the weighted matching algorithm (Steller et al., 2009) is embedded in mTableaux DL reasoner and it would essentially require a complete reimplementation if it is expected to be used in an \mathcal{EL} reasoner.

We aim at proposing a *flexible architecture* that can adopt any particular reasoner and knowledge extraction technique. Furthermore, previous approaches to measure the semantic loss must be adapted to our framework.

277 3. Adaptive Reasoning

278 In this section, we firstly propose an architecture that evaluates whether a partic-
279 ular device can process an ontology under some resource constraints, and, if it is not
280 the case, adapts the reasoning task to support as much knowledge as possible. Then,
281 we discuss strategies for the prediction of the resources consumption and a possible
282 integration in a more general case, an intelligent framework selecting among local rea-
283 soning, global reasoning, or a hybrid approach following (Bobed et al., 2017).

284 3.1. Architecture of the Proposal

285 Our resource-aware system is flexible and can receive a wide plethora of con-
286 straints. For the sake of concrete illustrations, we will provide a non-exhaustive list
287 of examples:

- 288 • Hardware constraints such as CPU capacity, memory, battery consumption, con-
289 nectivity and bandwidth, or screen size. In some cases, such as memory and
290 battery, this includes not only the maximum value but also the available one.
- 291 • User preferences, such as a maximum running time.
- 292 • Non-functional properties, such as a required user privacy level.
- 293 • Feedback from the system, such as a prediction of the cost to reason with the
294 current subontology or the semantic loss with respect to the original one.
- 295 • The input ontology (size, expressivity ...) and the particular reasoning task, as
296 they affect the cost of the reasoning.

297 Figure 2 shows the main high-level components and steps of our architecture, which
298 we are going to discuss in detail:

- 299 1. First, the Constraint Evaluation Module receives the ontology and the constraints,
300 and evaluates the constraints according to the features of the ontology and the re-
301 sources of the device. If the ontology fulfils them, it is forwarded to the reasoner
302 (step 4); otherwise, the ontology as well as the constraints are passed to the
303 Knowledge Extraction Module.

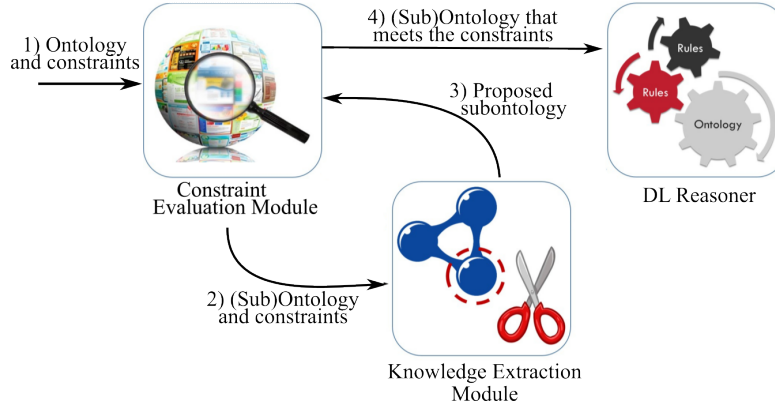


Figure 2: High-level architecture for the knowledge adaptor module.

2. The Knowledge Extraction Module tailors the knowledge according to the given constraints in an iterative way. In particular, it computes a subontology of the input ontology, taking into account the constraints, trying to keep the most important knowledge to solve the reasoning task, and trying to minimise the semantic loss. This flexible architecture will be instantiated on Section 4.
3. Once extracted, the subontology is returned for its evaluation to the Constraint Evaluation Module. Therefore, we repeat the loop *predict* cost of the reasoning - *evaluate* constraints - *extract* subontology - *predict* again as many times as needed, until obtaining a subontology which has been estimated to be manageable by the semantic reasoner².
4. Finally, once the knowledge has been estimated to be manageable by the semantic reasoner, the execution of the reasoning task is performed over the original ontology or a subontology that meets all the constraints.

The proposed architecture assumes that reasoning is performed locally on the user device. However, the resource-aware reasoning module could be integrated in a broader

²If the subontology is finally empty (in fact, it would include at least the signature), it means that there was no way to fulfil all the given constraints.

319 framework, where reasoning does not need to be performed locally. (Bobed et al.,
320 2017) proposed three main strategies to be adopted in a mobile scenario, but they can
321 actually be considered in any scenario with limited resources. Briefly, those strategies
322 are:

- 323 • Server-side External Reasoner: External powerful servers perform all the calcu-
324 lations. However, the application might need to send a lot of data through the
325 network, which can be a serious limitation in mobile computing environments,
326 and user privacy can be compromised as the user's data would be sent to an
327 external server.
- 328 • Device-side Local Reasoner: Calculations are computed on a local device, which
329 is the best choice to keep privacy or when network communications are not re-
330 liable. As limitations, reasoning becomes challenging in devices with limited
331 resources. For instance, there is some evidence that reasoning in mobile devices
332 might be affordable only for small or not very expressive ontologies when using
333 ported reasoners (Bobed et al., 2015).
- 334 • Hybrid-reasoning Approach: In this last strategy, some parts can be computed
335 locally and others can be computed on an external server, depending on the re-
336 source available in runtime.

337 The objective would be to automatically determine which one is the best option to
338 use a semantic reasoner. The optimal (or maybe Pareto-optimal) choice depends on the
339 application or, more specifically, on several factors, and is left as future work.

340 In the following, we detail an important part of our architecture: how resource
341 consumption can be predicted.

342 3.2. Predicting Resources Consumption

343 To perform the resource consumption prediction, we could use a model to predict
344 each single resource. One problem of this approach is that we do not have any feedback
345 about which features might be interesting to modify in order to make the ontology fit
346 in the device. This might lead to a blind search, having to apply different extraction

347 heuristics in a blind way. However, the works (Ribeiro et al., 2016, 2018) suggest that
348 we could obtain some explanations in the feature space which could be used to guide
349 the extraction as well. Moreover, some works such as (Sazonau et al., 2014) suggest
350 that some features are strongly correlated and could at least give us some clues about
351 how to proceed (in that example, the number of axioms was one of the most relevant
352 features to predict OWL 2 DL reasoning time)³.

353 On the other hand, to be able to act on the source ontology and know which pa-
354 rameters to focus on in order to meet the criteria, we considered having models that,
355 given a (predicted) resource limit, return which feature/s should be modified and how
356 to meet the criteria. We aimed at exploiting the strong correlations that exists between
357 the number of axioms and the predicted values (Sazonau et al., 2014); however, the
358 initial tests about the accuracy were not good, so further analysis using explainabil-
359 ity techniques in the feature space must be carried out before considering this option.
360 Thus, as a strategy to reduce the resource consumption, we have adopted an axiom size
361 reduction heuristic, leaving the exploration of these techniques as future work.

362 Besides, given the heterogeneity of the devices, we might need to train a model for
363 each family of devices: the ontology features do only depend on the input ontology,
364 but the actual resource consumption is dependent on the actual characteristics of the
365 device, thus requiring a model for each group of them (trained once, and shared among
366 all of them). In order to simplify the extraction of training data for new devices, it could
367 be interesting to use Antutu (in mobile devices) or PassMark (in desktop computers)
368 values to scale the values obtained for other devices. Note as well that the prediction
369 depends on the concrete reasoning task, but this will be explained in detail in Section 4.

370 We are aware that the resource-constrained device might have to reason with in-
371 complete information (depending on the knowledge extraction technique used), but it
372 is important to stress that, since semantic reasoners implement monotonic reasoning,
373 the results would be correct always (although may be incomplete). This approximate

³In order to show the feasibility of our approach, in the prototype described in Section 4, we adopted time as our main limiting resource and use the already studied ontology features (Kang et al., 2012; Pan et al., 2018) to predict the reasoning time.

reasoning is not the optimal option, but, when resources are not enough, it is preferable than providing no result at all. Furthermore, one of the novelties of our current proposal is how to measure the semantic loss incurred.

4. Instantiating the Architecture

In this section, we firstly analyse some strategies to instantiate the architecture proposed in the previous section (Section 4.1), and then report our prototype implementation for a particular choice of those strategies (Section 4.2).

4.1. Design of the Solution

First of all, we have to note that it is not possible to apply directly “classical” modularisation or partitioning methods, as they do not take the resources into account.

Moreover, in the previous section we have omitted the requested reasoning task (i.e., what is the knowledge being used for) on purpose. Indeed, the knowledge adaptation module must take into account the nature of this target task. In fact, as we will see in the following, the nature of the target task will give us a starting point to guide the extraction.

Figure 3 shows an instantiation of our proposal, highlighting the different works that could be applied to each stage. It takes as input an ontology, a list of the resource constraints, and the reasoning task that has to be performed. Note that the approach might take several iterations: if after computing a subset of the original ontology, the subset is still too big for the device resources, another round of knowledge extraction is performed. The main components are as follows:

1. **Resource Predictor Model/s:** As discussed in Section 2, several metrics to predict the reasoning time (on desktop computers) and the battery consumption (on mobile devices) have been proposed in the literature. These metrics can be considered in our approach as a starting point, building a model for each of the resources that whose consumption we want to predict.
2. **Constraint Evaluation Module:** The predictions obtained by the models for each resource would be taken into account in a multicriteria decision problem

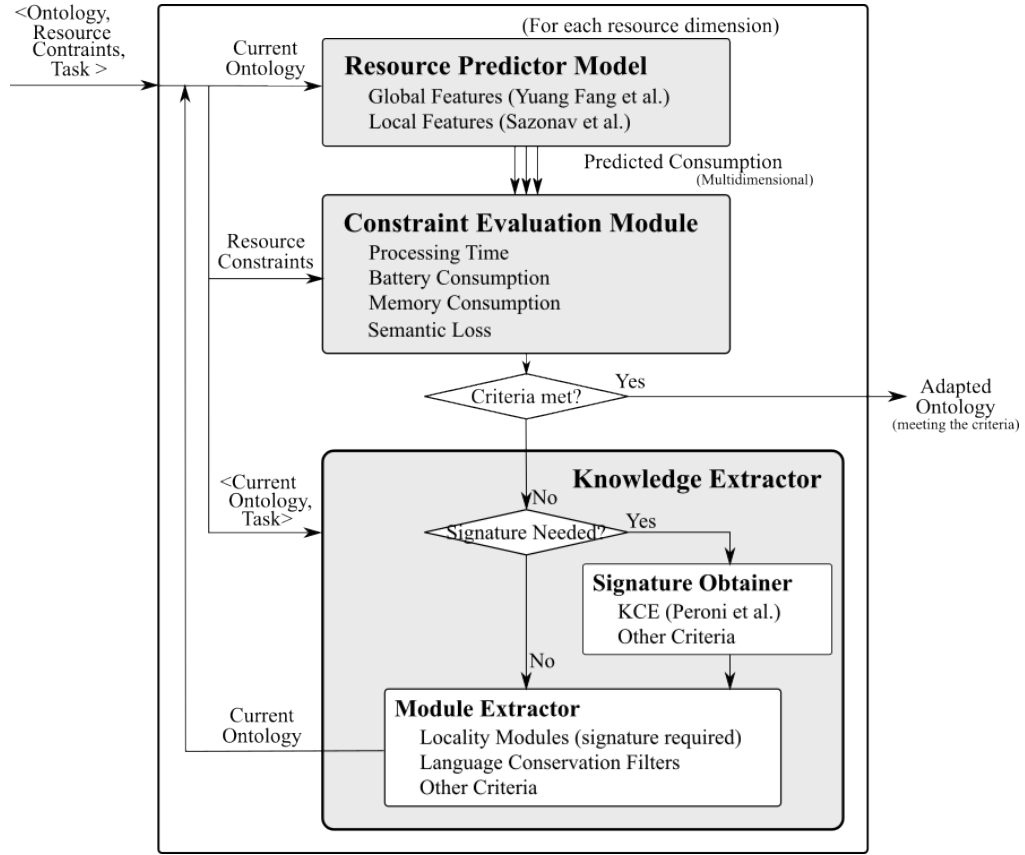


Figure 3: Possible implementation of the knowledge adaptor module.

deciding whether reasoning is feasible or not. In the latter case, it would be necessary to further reduce the amount of knowledge until it is feasible. In principle, the system could interpret all constraints in a conjunctive way and ensure that all of them are satisfied. However, more sophisticated solutions are possible: the user could define the most important constraints and the system could go on if some of the less important constraints are satisfied, there could be an interval of values (for example, for the maximum running time) rather than a strict value, etc.

3. **Knowledge Extractor:** Its purpose is to compute a subontology of the input ontology according to the resource constraints and reasoning task. Firstly, it

might invoke the Signature Obtainer, described below, to get a seed signature. Secondly, it invokes the Module Extractor and returns the computed subontology. At this point, the output ontology could be empty if all the constraints cannot be met given the available resources.

4. **Signature Obtainer:** The reasoning task to solve might require a *signature seed* (i.e., a set of atomic concepts, individuals, object properties and datatype properties to start with) or not. An example with signature is an instance retrieval query, where the user wants to retrieve books that have been written in English. The signature seed would be {Book, writtenIn, english}. An example without signature is ontology graphical representation, where the user just wants to browse the available knowledge.

To compute the subontology, there are several possible choices about which knowledge to keep and which to discard. If the task imposes a signature seed, then it should guide the extraction procedure. However, when the target task does not impose a signature or we cannot derive an useful signature from the context of the application, we have two options: trying to find a signature seed, or not using a signature seed. In this latter case, we can use different strategies such as the following ones (the list is by no means complete):

- To restrict to some OWL 2 profile discarding the other axioms, or a less expressive DL language.
- To approximate the ontology to some OWL 2 profile, e.g., as in the syntactic-based approximation of TrOWL.
- To keep just the subclass taxonomy of the ontology.

More generally, we could define our *preservation language*, defining the axioms and complex concepts to be kept. This is similar to the proposal of (Cuenca Grau et al., 2012). Although in their approach there is no control over the particular values of the ontological features we would like to change, we could act further in the extraction by limiting the applicability of different grammar rules (e.g., limiting the depth of the parsing trees).

If we consider it relevant, we can obtain a seed signature attending to general criteria (Signature Obtainer in Figure 3). For this purpose, we could apply, for example, the detection of Key Concepts proposed by (Peroni et al., 2008). These concepts would comprise the signature seed in the absence of such for the task. In fact, they could be added as metadata (OWL 2 annotation) in the ontology to compute them offline and just once, as it is an expensive task.

5. **Module Extractor:** Apart from restricting the expressivity, if the target task provides somehow a signature to exploit (or we have been able to define a relevant one), we can follow several strategies (again, we do not intend to be exhaustive):

- Incremental approaches: given an initial signature seed, add more axioms corresponding to the seed signature. After that first step, one could also add axioms corresponding to the new signature introduced by the previous axioms.
- Pruning approaches: given an initial ontology, remove axioms. Following the spirit of the extraction with no signature, a possible approach could be to limit the “locality” of the axioms up to a certain depth. This would imply to apply the syntactic rules for the acceptance of the different axioms in (Cuenca Grau et al., 2008) parameterised to limit the activations/depth to which a particular rule can be applied.
- Hybrid approaches or variants of the above approaches.

In the case of multiple criteria, it is necessary to decide an order for the criteria to be relaxed (for example, we could go first for the most restrictive constraint, but other strategies could be studied in the future).

4.2. A Prototype Implementation

As a first step towards our objectives, we have implemented a prototype to show the feasibility of the whole pipeline, with a specific choice of the multiple alternatives discussed in the previous section. Our prototype takes an input ontology and computes a subontology, considering a maximum reasoning time as the only limited resource, on a desktop computer. As we have seen in Section 2.2, there are only prediction models

470 for the reasoning time on desktop computers and for battery consumption on mobile
471 devices. We advocate building our prototype for desktop computers because reasoning
472 on mobile devices is limited to small and medium ontologies (Bobed et al., 2015), so it
473 is not possible to process a meaningful benchmark. The only supported reasoning task
474 is ontology materialisation using the OWLAPI (method `precomputeInferences`).

475 The prototype uses OWLAPI 3.5.7⁴(Horridge and Bechhofer, 2011) as program-
476 ming API and is able to use any semantic reasoner implementing the `OWLReasoner`
477 interface. In particular, we used HermiT 1.3.8 (Glimm et al., 2014) to gather the data
478 for training the models and to perform all the materialisations required. The reason
479 is that HermiT has already been successfully used to predict the reasoning time (Pan
480 et al., 2018).

481 **Definition 1.** *Let O be an ontology. The materialisation of O , denoted $mat(O)$, is the*
482 *set of consequences that can be derived from O by using the types of `InferredAxiom-`*
483 *Generator supported in OWLAPI 3.5.7⁵, namely*

- 484 • *`InferredClassAssertionAxiomGenerator`,*
- 485 • *`InferredDataPropertyCharacteristicAxiomGenerator`,*
- 486 • *`InferredDisjointClassesAxiomGenerator`,*
- 487 • *`InferredEquivalentClassAxiomGenerator`,*
- 488 • *`InferredEquivalentDataPropertiesAxiomGenerator`,*
- 489 • *`InferredEquivalentObjectPropertyAxiomGenerator`,*
- 490 • *`InferredInverseObjectPropertiesAxiomGenerator`,*
- 491 • *`InferredObjectPropertyCharacteristicAxiomGenerator`,*

⁴We kept this version as the original prediction features(Kang et al., 2012; Pan et al., 2018) were developed with such one.

⁵<https://javadoc.io/doc/net.sourceforge.owlapi/owlapi-distribution/3.5.7/index.html>

- 492 • *InferredPropertyAssertionGenerator*,
- 493 • *InferredSubClassAxiomGenerator*,
- 494 • *InferredSubDataPropertyAxiomGenerator*, and
- 495 • *InferredSubObjectPropertyAxiomGenerator*.

496 In the following, we will discuss each step of the prototype in detail.

497 *Resource Predictor Model.* In order to train the model, we used the whole set of
 498 metrics used in (Pan et al., 2018) to predict the reasoning time, which included the
 499 metrics proposed by (Kang et al., 2012). The models have been trained using *scikit-*
 500 *learn 1.2*, which allows to export the models to PMML (Predictive Model Markup
 501 Language) (Guazzelli et al., 2009) to import them afterwards in other applications.

502 The values of those metrics only depend on the input ontology and not on the de-
 503 vice. Therefore, in order to train several devices, such values can be computed just
 504 once, and possibly on a faster external server. However, recall that each family of de-
 505 vices will require to have their own prediction model. Besides, when actually using
 506 the system, it is important that those metrics can be efficiently computed on a limited-
 507 resource device or, alternatively, we can assume that the input ontology has been an-
 508 notated with them (as this is not standard) or the existence of an external service to
 509 compute them (as we will need to assume that there is some connectivity).

510 *Constraint Evaluation Module.* As above mentioned, our current implementation is
 511 focused on time as resource. This module uses the model trained to predict the time
 512 and decide, given a timeout, between whether the criteria is met or not, and if not,
 513 whether there are more actions (i.e., reduce the size of the ontology) that we can apply
 514 to try to meet the requirements.

515 As reduction criteria, we currently reduce the number of axioms by a 25%⁶ at each
 516 prediction step iteratively until the criteria is predicted to be met (i.e., we repeat the

⁶As we will see in Example 2, we also tried a 12.5% reduction with GALEN-Full-Union.ALCHOI(*D*) ontology and obtained the same results of the reasoning, but higher materialisation times.

517 loop *predict* - *evaluate* constraints - *extract* knowledge - *predict* again as many times
518 as needed).

519 *Signature Obtainer.* We have integrated Key Concept Extraction (KCE) technique (Per-
520 oni et al., 2008) to find the top most important k concepts. To compute them, we
521 adapted the implementation provided by (Peroni et al., 2008): when KCE API retrieved
522 more than the demanded k concepts, we just selected the first k ones, as they are equally
523 important (according to our own source code inspection). The value k could depend on
524 the available resources.

525 We noticed that KCE implementation is not efficient enough, and it usually does
526 not finish on an average mobile device with medium-size ontologies. Therefore, we
527 assume that KCEs have been computed offline (for example, on a desktop computer or
528 a remote server) and that they are represented as metadata attached to the ontology via
529 an OWL 2 annotation property `keyConcepts`.

530 *Module Extractor.* The extraction technique we have implemented to compute the sub-
531 ontology while having control over its size proceeds as follows:

- 532 1. Starting from the given signature, it extracts all the subclass hierarchical infor-
533 mation of its entities, obtaining a minimal skeleton⁷. That, it assumes a preser-
534 vation language built using axioms of type *A SubclassOf B*, with A and B being
535 atomic concepts. Then, it updates the signature with all the terms included in the
536 skeleton.
- 537 2. It iteratively adds logical axioms related to the updated signature, expanding the
538 covered part of the original ontology in a breadth-first way, until reaching the
539 maximum number of axioms computed by the Constraint evaluation module.
540 Those logical axioms can be OWL 2 axioms of any type. In each step, the
541 signature is also updated and expanded with the newly added terms.

542 While pretty straight-forward, this approach allows us to reduce the size of the on-
543 tology while keeping the information that we have deemed important. In fact, keeping

⁷This skeleton can also be built in an incremental way to avoid running out of resources

544 the hierarchical skeleton could be substituted by any conservation language.

545 Note that, as we reduce knowledge in an iterative way, we cannot recover knowl-
546 edge discarded in previous iterations. Therefore, knowledge extraction should not be
547 too aggressive in discarding axioms, as a more conservative extraction could be re-
548 fined in next iterations. An alternative strategy could be, for example, if the computed
549 subontology is not satisfactory, to find a subset of the signature which tries to max-
550 imise the amount of knowledge that the module extracts and which is still within the
551 limits. After that, we could add progressively the information available in the module
552 obtained: 1) adding more axioms corresponding to the seed signature, or 2) adding ax-
553 ioms not corresponding to the seed signature. However, we consider the exploration of
554 the different strategies as future work.

555 5. Measuring the Semantic Loss

556 Apart from leading to a lower resource consumption (due to the simplification and
557 reduction of the size of the processed ontologies), these potential approximations will
558 have an associated *semantic loss* which has to be measured (and possibly be predicted)
559 to be part of the decision process and to provide users with a confidence degree on the
560 system answer.

561 We advocate to adapt the notion of *semantic recall* proposed by Euzenat ([Euzenat,](#)
562 [2007](#)) in the context of *ontology alignment*.

563 **Definition 2.** *Given an ontology O , let $Cons(O)$ be the set of consequences that follow*
564 *from O .*

565 The *syntactic recall* is defined as the proportion of axioms that had been extracted
566 from the original ontology.

Definition 3. *Let two ontologies O and O' , where O' is the result of any extraction
process over O (i.e., $O' \subseteq O$ syntactically). The syntactic recall of O' w.r.t. O is given
by:*

$$SynRecall(O', O) = \frac{|O'|}{|O|}$$

567 While syntactic recall compares original axioms, semantic recall compares conse-
 568 quences.

Definition 4. *Let two ontologies O and O' , where O' is the result of any extraction process over O (i.e., $O' \subseteq O$ syntactically). The theoretic semantic recall of O' w.r.t. O is given by:*

$$SemRecall_T(O', O) = \frac{|Cons(O')|}{|Cons(O)|}$$

569 Potentially, $Cons(O)$ and $Cons(O')$ can be infinite, so we have to restrict it to the
 570 set of axioms that we can materialise from the extracted module:

Definition 5. *Let O and O' be two ontologies, where O' is the result of any extraction process over O (i.e., $O' \subseteq O$ syntactically). The practical semantic recall of O' w.r.t. O is given by:*

$$SemRecall(O', O) = \frac{|mat(O')|}{|mat(O)|}$$

571 where $mat(O) \subseteq Cons(O)$ is the ontology containing all the axioms that can be materi-
 572 alised by a reasoner from O .

573 The definition of the ontology that can be materialised by a reasoner from an in-
 574 put ontology $mat(O)$ could be defined in many different ways, depending on the axiom
 575 types that the reasoner takes into account. In this paper, we use the strategy imple-
 576 mented in our prototype, presented in Definition 1.

577 Note that, following Definition 5, we can work with different versions of the ontolo-
 578 gies. In particular, we could choose to work under different materialisation regimes,
 579 where we could choose to have different kinds of inferences materialised in order to
 580 improve the semantic loss analysis⁸.

581 Depending on the particular task, it can be convenient to extend further the defini-
 582 tion to take the signature of the extracted subontology into account:

583 **Definition 6.** *Let O and O' be two ontologies, where O' is the result of any extraction
 584 process over O (i.e., $O' \subseteq O$ syntactically). The signature-aware practical semantic*

⁸Of course, this requires the cost of materialising the different ontologies, so it has to be defined carefully.

585 recall of \mathcal{O}' w.r.t. \mathcal{O} is given by:

$$SemRecall_{SIG}(\mathcal{O}', \mathcal{O}) = \frac{mat(\mathcal{O}')}{restrictSig(mat(\mathcal{O}), Sig(\mathcal{O}'))}$$

586 where $restrictSig(\mathcal{O}, S)$ is the set of axioms in \mathcal{O} which refer to any element in the
587 signature S , and $Sig(\mathcal{O}')$ is the signature of \mathcal{O}' .

588 The signature of the extracted ontology must not be confused with the *seed signa-*
589 *ture* of the subontology, i.e., the signature used as starting point for the subontology
590 extraction. This leads, for the sake of completeness, to define the generalisation of the
591 definition to work with any particular signature externally defined:

592 **Definition 7.** Let \mathcal{O} and \mathcal{O}' be two ontologies, where \mathcal{O}' is the result of any extraction
593 process over \mathcal{O} (i.e., $\mathcal{O}' \subseteq \mathcal{O}$ syntactically). The externally defined signature-aware
594 practical semantic recall of \mathcal{O}' w.r.t. \mathcal{O} is given by:

$$SemRecall_{SIG}^E(\mathcal{O}', \mathcal{O}, S) = \frac{restrictSig(mat(\mathcal{O}'), S)}{restrictSig(mat(\mathcal{O}), S)}$$

595 It follows that $SemRecall_{SIG}(\mathcal{O}', \mathcal{O}) = SemRecall_{SIG}^E(\mathcal{O}', \mathcal{O}, Sig(\mathcal{O}'))$.

596 Finally, note that we could use the above definitions to compare two different sub-
597 ontologies \mathcal{O}' and \mathcal{O}'' extracted from the same original ontology \mathcal{O} by relaxing the
598 condition of syntactical inclusion (as they might extract different parts of the original
599 ontology). In this case, the precision would be always 1, as all the axioms comes from
600 the same source, but we would be calculating the *Syntactic* and *Semantic Overlap*:

Definition 8. Let two ontologies \mathcal{O}' and \mathcal{O}'' , where both \mathcal{O}' and \mathcal{O}'' are the result of
any extraction process over \mathcal{O} (i.e., $\mathcal{O}' \subseteq \mathcal{O}$ and $\mathcal{O}'' \subseteq \mathcal{O}$ syntactically). The syntactic
overlap of \mathcal{O}' and \mathcal{O}'' is given by:

$$SynOverlap(\mathcal{O}', \mathcal{O}'') = \frac{|\mathcal{O}' \cap \mathcal{O}''|}{|\mathcal{O}' \cup \mathcal{O}''|}$$

Definition 9. Let two ontologies \mathcal{O}' and \mathcal{O}'' , where both \mathcal{O}' and \mathcal{O}'' are the result of
any extraction process over \mathcal{O} (i.e., $\mathcal{O}' \subseteq \mathcal{O}$ and $\mathcal{O}'' \subseteq \mathcal{O}$ syntactically). The semantic
overlap of \mathcal{O}' and \mathcal{O}'' is given by:

$$SemOverlap(\mathcal{O}', \mathcal{O}'') = \frac{|mat(\mathcal{O}') \cap mat(\mathcal{O}'')|}{|mat(\mathcal{O}') \cup mat(\mathcal{O}'')|}$$

601 Note that we have considered the semantic loss between a pair of ontologies, but
602 one could also define semantic loss for specific reasoning tasks.

603 In the following section, we will apply these measures in order to evaluate how
604 our initial implementation of the pipeline behaves in terms of semantic loss. As a
605 baseline, we will consider the syntactic recall and the relaxed definitions (*Overlaps*)
606 in order to evaluate our proposed technique to a safe-module extraction one (locality-
607 based modularisation (Cuenca Grau et al., 2008)).

608 6. Evaluation

609 In order to show the feasibility of our approach, we have focused our experiments
610 on several particular aspects: 1) we first test how accurate the prediction of the exe-
611 cution time was with our dataset (Section 6.1), 2) then, we evaluate how such accu-
612 racy affects our approach regarding materialising ontologies within a restricted timeout
613 (Section 6.2), 3) we evaluate the extraction technique regarding the semantic loss in-
614 curred when compared to the original ontologies and safe-modules (Section 6.3), and
615 4) we discuss some detailed examples involving particular ontologies (Section 6.4).

616 *Experimental Setup.* For the experiments, we used the ORE 2015 dataset (Parsia et al.,
617 2016), composed of 16,555 independent ontologies (many of them, real ontologies).
618 The dataset was developed by independent researchers and was not designed for this
619 task, so there is not any bias. We adopted Random Forests as a machine learning model,
620 using 500 trees as hyperparameter. We explored other models such as Multilayer Per-
621 ceptron and Linear Regression, but Random Forests were the best ones out of the shelf
622 providing results that were good enough for our purposes, and we chose them for the
623 sake of simplicity. (Hutter et al., 2014) also found that random forest models showed
624 the best results to predict the performance of some algorithms to solve combinatorial
625 problems (SAT, TSP, and MIP). We used Hermit 1.3.8 as reasoner and established a
626 maximum timeout of 300 seconds for materialising the ontologies. Figure 4 shows the
627 distribution of the execution times for the ontologies that were materialised under such
628 a timeout: around 95% of ontologies are materialised before 100 seconds, around 98%
629 before 200 seconds. The reasoning task to solve was to compute all the inferences

630 available using the OWLAPI (we materialised all the inferences OWLAPI allows for,
631 adding all the axioms to both the TBox and ABox). Finally, all the experiments were
632 run on a desktop computer with an Intel Core i7-6700K processor (4 cores, 8 threads,
633 although no parallelism was applied) at 4.00 GHz and 32 GB of RAM memory.

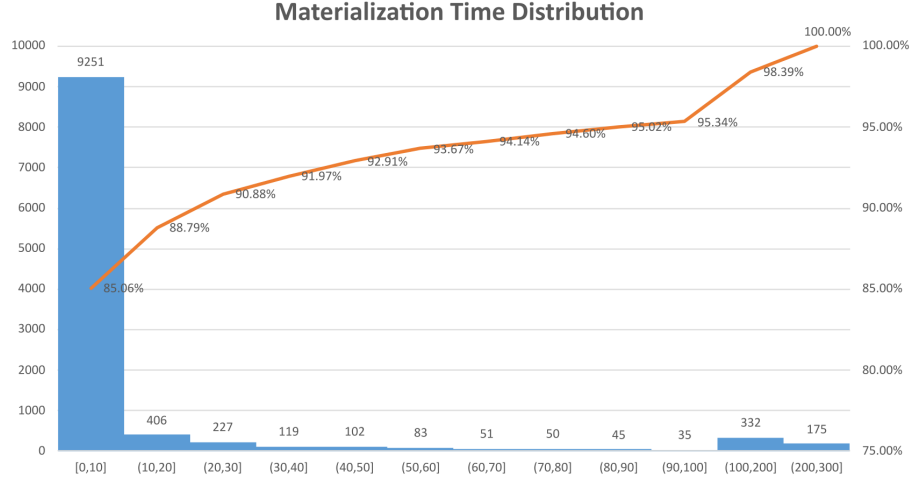


Figure 4: Distribution of ontology materialisation time. Axis-x shows materialisation time intervals, in seconds. Axis-y shows number of ontologies analysed (left) and percentage of materialised ontologies (right).

634 Our extraction method provides us with the capability of establishing a size for
635 the module in number of axioms, but we needed to assess its semantic conserva-
636 tion capabilities. Thus, as a baseline to compare it in the semantic loss experiments,
637 we have considered locality-based modularisation, using the Locality Module Extrac-
638 tor (Cuenca Grau et al., 2008)⁹, which also has a Protégé plug-in called ProSÉ (Jiménez-
639 Ruiz et al., 2008): Starting from a signature, we extract the Upper Modules (UMs) from
640 \perp -locality (as suggested for the authors to reuse terminologies). Because UMs does not
641 take into account the device resources, we needed to fix the number of axioms consid-
642 ered for the sake of comparability: the number of axioms to be extracted by our method
643 is given by the size of the correspondent UM module, and we set $k \in \{5, 10, 15, 20\}$.

⁹<http://www.cs.ox.ac.uk/isg/tools/ModuleExtractor>

6.1. Precision of the Resource Prediction

First of all, we double checked that the 143 ontology features proposed in (Kang et al., 2012) and (Pan et al., 2018) were appropriate for our purposes. For this, we first materialised the whole dataset. Establishing the timeout of 300 s, we managed to obtain the materialisation time for 10,932 ontologies.

With such data, we adopted a 10-fold cross-validation approach and two setups: 1) using just the data (ontological features + materialisation time) for the ontologies materialised to train the models, and 2) augmenting the data with subontologies obtained from the original ontologies and materialised under the same conditions (i.e., the training test contains the original ontologies plus a set of subontologies). The rationale was to check whether giving further insight about intermediate points for the ontologies provided the models with relevant information, as suggested in (Sazonau et al., 2014). In particular, the data augmentation was carried out using the locality-based modularisation (UM) and our extraction method with 5, 10, 15 and 20 concepts as signature (obtained with KCE).

Table 1 shows the R^2 score, MAE (Mean Average Error), and RMSE (Root Mean Square Error) obtained for both setups. Split size states the training and the test sizes for each case. Recall that $R^2 \in [0, 1]$, whereas MAE and RMSE are measured in seconds.

| | Original data | Augmented data |
|------------|---------------|----------------|
| Split size | 9839/1093 | 86113/9575 |
| R^2 | 0.904 | 0.848 |
| MAE | 3.118 | 0.801 |
| RMSE | 12.690 | 6.709 |

Table 1: R^2 , MAE and RMSE values for both setups using Random Forests with 500 trees. The splits for CV including the modules were done splitting the ontologies and then selecting the modules to avoid data leaking.

We can see that the high R^2 values show that the features used are informative

664 enough to predict the time for materialisation¹⁰. Observe that although augmented data
665 have a smaller R^2 score, MAE and RMSE values suggest that the model trained on this
666 dataset is more accurate. However, given that the data augmentation technique might
667 be computationally expensive, we will use original data to avoid such a cost. The errors
668 for the original data are low as well, and we will check that their precision is enough
669 for our purposes in the next section.

670 6.2. *Adjusting the Available Knowledge to the Resources*

671 We now turn our attention to whether the previous precision is good enough for
672 our proposal. In this case, we use the model trained with just the ontologies (modules
673 are not used), and fix the signature size to 10 concepts (the most important concepts
674 according to KCE signature extraction) and a timeout of 10 seconds (which seems a
675 reasonable time for a final user to wait). We split the results into two different sets:
676 the 10876 ontologies that were materialised within the 300 s timeout (those used in
677 the previous section), and the 5,679 other ones which were not handled within such a
678 timeout.

679 Table 2 shows two confusion matrices for the ontologies within the timeout. The
680 left matrix shows the contrast between the predicted time and the real one for the orig-
681 inal ontologies. In this matrix, the worst situation would be the false positives (41
682 ontologies were predicted to be under the 10 seconds limit, but actually required more
683 time, which is a 0.38% of the whole dataset). The right matrix shows the results after
684 iterating to reduce the size of the ontologies, as explained in Section 4.2 (i.e., reducing
685 iteratively the size of the ontology a 25% at each step, until the prediction consumption
686 met the criteria).

687 We can see how, for the final results (after having predicted and extracted the mod-
688 ules), summing up the “ ≤ 10 ” column of the right matrix, we would have 10,654
689 ontologies which we estimated that will be processed under 10 seconds (97.9% of the

¹⁰As already mentioned, we explored as well the possibility of training a model to predict the number of axioms, but it was not accurate enough to do the way back for the prediction and the iterative approach was deemed to be more suitable for showing the feasibility of the approach.

| | | Real Time | | | | Final Time | |
|----------------|-----------|------------------|------------------|--|--|------------------|----------------|
| | | ≤ 10 | > 10 | | | ≤ 10 | > 10 |
| Predicted Time | ≤ 10 | 8943 (82.23%) | 41 (0.38%) | | | 8969 (82.47%) | 15 (0.14%) |
| | > 10 | 308 (2.83%) | 1584 (14.46%) | | | 1685 (15.49%) | 207 (1.90%) |

(a) Predicted Time: Initial prediction (b) Predicted Time: Final results

Table 2: Confusion matrices for the 10,876 ontologies that were materialised within the timeout of 300 s.

set of materialised ontologies). Note that this success ratio includes both the ontologies predicted correctly from the beginning (8969), and those processed and which ended taking less than 10 s (1685).

For the ontologies that were not processed within 300 s (5,679 ontologies, 34.30% of the dataset), we checked how many were predicted to be out of the 300 s timeout and of our 10 s limit. None was predicted to be above the 300 s timeout, showing a limitation of our selected machine learning model (we leave the use of better generalising models as future work). On the other hand, 899 ontologies (5.43%) were predicted to be within the 10 s. limit which was obviously wrong, but curiously they all were ontologies that HerMiT could not process¹¹. Nevertheless, assuming that all of them were above the 10 s timeout, we managed to reduce and process 3,465 (20.93%) out of 4,490 ontologies (27.12%) with our approach within the established time out (the rest of the ontologies, 1,189 (7.18%), were not handled by that version of HerMiT).

6.3. Evaluation of the Semantic Loss

Once we tested the feasibility of the knowledge extraction pipeline, we focused on measuring the semantic loss of: 1) our extraction technique when compared to logic-based module techniques, and 2) the actual application of our pipeline when compared to using the full ontologies.

¹¹Mainly due to inconsistencies, malformed literals, and unsupported characteristics.

708 Comparison to Locality-based Modules

709 As commented in the experimental setup, in order to check if our extraction method
 710 was good enough for our purposes, we compared the overlap of our extracted partitions
 711 to locality-based modularisation (Cuenca Grau et al., 2008) extracting the Upper Mod-
 712 ules (UM). In particular, out of the 16,555 ontologies, we were able to extract and
 713 materialise both modules (ours and UM) for 14,255 of them. Figure 5 shows the com-
 714 parison in terms of *syntactic* and *semantic overlap* as defined in Section 5. We add the
 715 *reduction* percentage as we noticed that, even though we established the size of UM
 716 modules as an upper bound for our extraction procedure, in general UM modules were
 717 still bigger than ours as ours exhausted the extraction earlier.

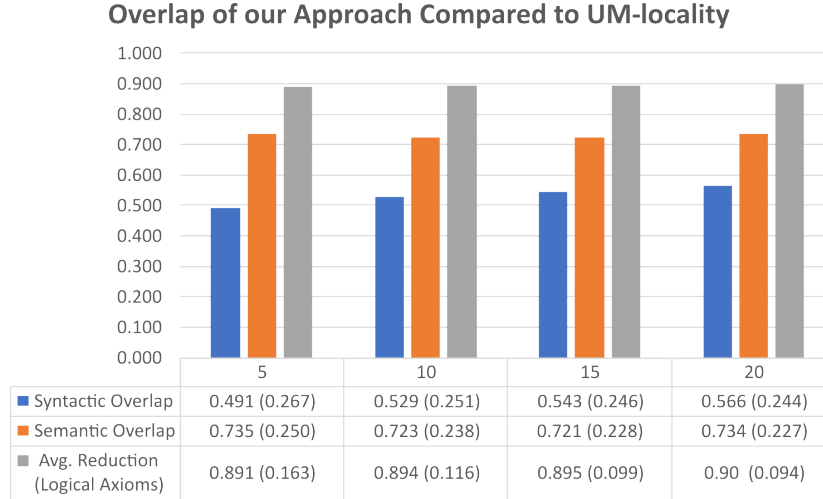


Figure 5: Syntactic and semantic overlap between UM modules and ours, along with the relative size of our modules (Reduction) compared to UM ones (our modules are about 10% smaller than UM ones). The X axis depicts the size of the signature, and the results in the table are read as *average (standard deviation)*.

718 We can see how the *syntactic overlap* increases as the signature does: bigger sig-
 719 natures lead to bigger UM modules, which in turn allows for bigger signatures and
 720 more choices for our extraction approach. However, note how the *semantic overlap*
 721 remains stable, implying that we keep important knowledge (in this case, the taxon-
 722 omy skeleton which we decided to include in our conservation language, is important
 723 for both extraction techniques). Moreover, we have to take into account as well that

our modules are about a 10% smaller than UM ones, so it can be argued that we still have some room for adding more axioms we deem important, to increase the overlap without exceeding the upper bound number of axioms to be extracted.

Comparison to the Original Ontologies

In this case, we focus on the 1,892 ontologies that were predicted to be above the 10 s timeout as they were the ones subject to reduction. We established a combined timeout of 1,200 seconds for materialising both ontologies (the original and the extracted one), and calculating both syntactic and semantic recall values (which, following the work by Euzenat et al. (Euzenat, 2007), required checking whether each axiom was inferred from the original ontology), which led to a final set of 1,360 analysed ontologies.

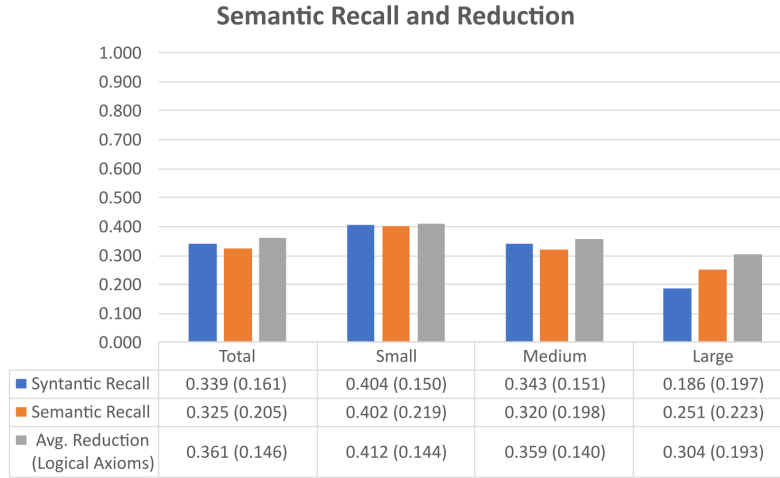


Figure 6: Syntactic and semantic recall between the original ontologies and our subontologies, along with the relative size (Reduction): global recall without taking into account any signature. The results in the table are read as *average (standard deviation)*.

Figures 6–8 show the *syntactic* and *semantic recall* for these ontologies calculated in three settings: a) globally (Definition 5) in Figure 6, b) restricted to the signature of the extracted subontologies (Definition 6) in Figure 7, and c) restricted to the original seed signature (Definition 7) in Figure 8. We show the total averaged values along with

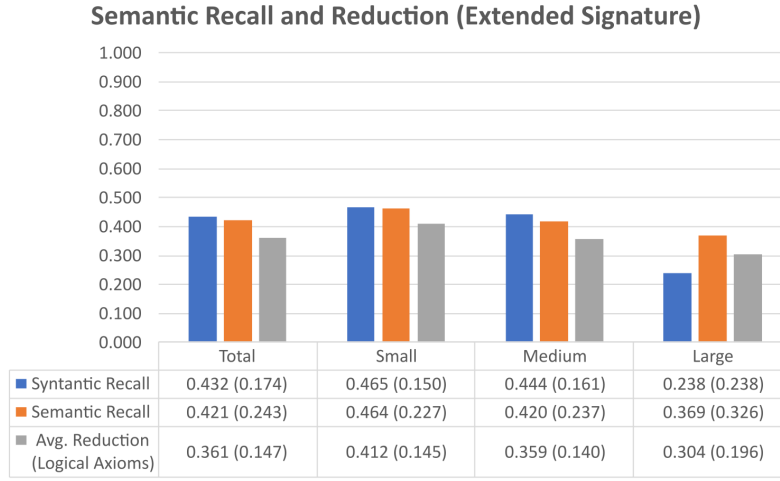


Figure 7: Syntactic and semantic recall between the original ontologies and our subontologies, along with the relative size (Reduction): recall conditioned to the extended signature. The results in the table are read as *average (standard deviation)*.

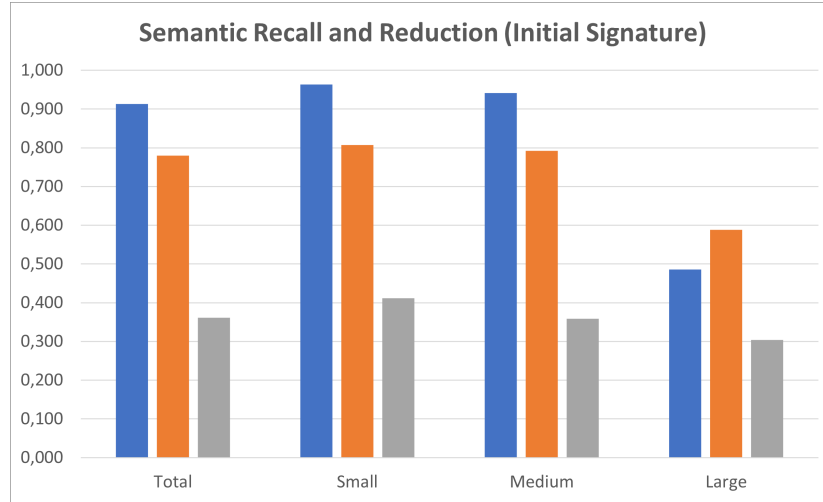


Figure 8: Syntactic and semantic recall between the original ontologies and our subontologies, along with the relative size (Reduction): recall conditioned to the initial signature. The results in the table are read as *average (standard deviation)*.

739 the standard deviations (between brackets, as well as the values aggregated regarding
740 the size of the original ontologies, namely, *small* ontologies ($\#axioms \leq 500$), *medium*

741 ones ($500 < \#axioms \leq 5,000$), and *large* ones ($\#axioms > 5,000$)¹².

742 We can see how the results are stable across all the ontology sizes, and strongly
743 correlated to the reduction achieved conditioned to the signature of the subontology¹³,
744 but for the initial signature, which show that the main information about the initial
745 signature is kept in our extracted subontology. When analysing the data clustered by
746 ontology size, we can see that, for small and medium ontologies, both syntactic and se-
747 mantic recall values are quite similar, but syntactic recall is notably lower than semantic
748 one for large ontologies, which remarks that the information we keep in subontologies
749 is semantically relevant. These results, along with the overlap achieved by our approach
750 with UM-modules, show that our proposal is capable of adapting the knowledge with-
751 out losing the most important parts, regarding the given signatures. Therefore, our
752 definitions of semantic loss, based on the proportion between the number of inferences
753 with respect to the ideal number of inferences, seem realistic.

754 6.4. Detailed examples

755 In this section we show two concrete cases of our prototype and architecture, using
756 real ontologies for ontology visualisation and retrieval, respectively.

757 **Example 1 (Ontology visualisation).** *A final user is navigating through an ontology
758 and want to visualise its relevant classes and their individuals. More precisely, 00104
759 (3,573 logical axioms, 641KB file), one of the ontologies in the ORE 2015 dataset
760 which includes information about geographic locations (#GEOREF), types of food com-
761 modities (#FOODS-COMMODITY), and different languages (#LANGUAGE), among many
762 others things. The user is located at class #FOODS-COMMODITY and wants to navigate
763 through more specific classes. To do so, the ontology navigation would call a semantic
764 reasoner to retrieve the subclasses of the original class. (Note that retrieving the sub-
765 classes of class could be interesting in other scenarios, such as to refine the results of
766 an instance retrieval query when there are too many results.) Unfortunately, semantic*

¹²We classified them as in the ORE 2013 Workshop, by counting the logical axioms in the original ontology (that is, before doing any reasoning) (Gonçalves et al., 2013)

¹³Note that this signature might be quite larger than the seed one.

767 reasoning does not finish in a 300 seconds timeout: the ontology is too complex for
768 his/her device (this actually happens using the environmental setup described in this
769 section). Therefore, using a traditional reasoner, the user would receive an empty an-
770 swer (reasoners do not retrieve subclasses as they compute them, but at the end of the
771 process, where all of them have been computed).

772 Instead, using our prototype (with #GEOREF, #LANGUAGE, and #FOODS-COMMODITY
773 as signature), reasoning finishes within 10 seconds, so the final user could happily
774 navigate to any of the subclasses of #FOODS-COMMODITY.

775 In fact, if we query the subontology retrieved by our prototype to obtain the descen-
776 dants and instances of the following concepts, we get the following results:

- 777 • #GEOREF: 100% (265/265) of the instances (the original concept did not have
778 subclasses).
- 779 • #LANGUAGE: 100% (77/77) of the descendants and a 100% (263/263) of the in-
780 stances.
- 781 • #FOODS-COMMODITY: 100% (45/45) of the descendants (the original concept did
782 not have instances).

783 While the available knowledge is not complete, at least, we managed to provide
784 the user with information about these concepts and an application could use it, maybe
785 notifying the user that is not complete. For example, if we take SWEET Ontology
786 Phenomena Atmosphere¹⁴, and we would like to retrieve all the phenomena that have
787 a planetary scale (Phenomena and hasSpatialScale value PlanetaryScale),
788 our approach it is able to retrieve a 3.81% (13/341) of the subclasses, being able to
789 answer some concepts such as Climate or AtmosphericPhenomena. This is due the
790 fact that the prediction is not so accurate in this case and reduces the amount of axioms
791 too conservatively (we have checked that our approach, adding more axioms, increases
792 the retrieval results). Note that while the percentages might seem low sometimes, the
793 alternative was to raise directly an error and not providing any answer at all.

¹⁴00412d8c-f97f-4e3d-b184-9a8133e74e61_phenWave.owl functional.owl in the dataset.

Example 2 (Knowledge Retrieval). *In this example, a final user wants to know as much as possible about any pathology that can occur in the Liver. In this case, the application would be using GALEN-Full-Union_ALCHOI(D) (37411 logical axioms, 11MB file), which cannot be processed by HermiT¹⁵. For this ontology, our prediction module was timing out and we found out that calculating the metrics for such an ontology was quite expensive sometimes (they are quadratic in the size of the underlying graph), but we opted to leave their optimisation as future work. This said, we directly reduced the size of the ontology to a 25% percent of the original logical axioms¹⁶. With this setup, our approach, using Liver and hasLocation as signature, is able to extract a subontology where asking for hasLocation some Liver retrieves 9 classified concepts, among which we can find Hepatitis, HepaticNecrosis and FattyLiver. Note that those are not directly related to Liver by hasLocation but by hasSpecificLocation, its subproperty. Extracting a subontology in this case is not only about performance, but a matter of enabling the application to work (approximating the reasoning).*

In both real-world examples, the original ontologies could not be processed by a regular desktop computer. However, our prototype was able to compute a subontology so that the original problem can be partially solved, even when some inferences are missing.

7. Conclusions and Future Work

In this paper, we have discussed and developed strategies to adapt ontology reasoning to the limitations of the device where such a reasoning will take place, particularly in the case of devices with heavily constrained resources, such as mobile devices or IoT infrastructure.

¹⁵In fact, we have used different versions of HermiT and Pellet to handle it, but the original one could not be processed.

¹⁶We tested it with 25% and 12.5% with exactly the same results of the reasoning, but higher materialisation times for 12.5%.

818 We have proposed an architecture to perform adaptive reasoning, taking into ac-
819 count several criteria (such as the maximum running time or memory/battery limits).
820 The key idea is to perform a knowledge extraction step that is suitable for the device,
821 possibly after several iterations of the process. Reasoning will thus be executed against
822 a subontology that can be processed on the device, although, in general, the reasoning
823 results would be incomplete. We have discussed several issues to be taken into account
824 during the process, such as the use of a signature (possibly including automatically
825 discovered key concepts) as a starting point, or a preservation language as a strategy to
826 decide which axioms to be kept. We have also discussed how to measure the impact
827 of our approximations. In particular, we proposed a novel definition of semantic loss,
828 adapted from the ontology alignment field.

829 To illustrate some important steps of our architecture, we have implemented a pro-
830 totype that is able to compute subontologies on desktop computers according to the
831 predicted values of a single criterion (the reasoning time), which obviously depends on
832 the device resources. The prototype illustrates the joint use of feature selection, strate-
833 gies to compute a signature (KCE), and modularisation to give a possibly incomplete
834 answer to the ontology materialisation problem with limited resources.

835 We think that this paper clearly shows the potential of this line of research but also
836 that there is a long road ahead, and there exist many directions for our future research.
837 More experiments on mobile devices (or other devices with constrained resources) will
838 also be necessary to properly evaluate the feasibility of the approach. In particular,
839 although considering as many possible criteria as possible is desirable, first it has to be
840 confirmed empirically that their costs can be successfully predicted.

841 To do so, our prototype could be extended in several ways. Firstly, using more com-
842 plex (but efficient) prediction strategies, possibly including features selected for mobile
843 devices, and different machine learning techniques. Secondly, to compute the signature
844 locally, we need a more efficient implementation of KCE or another algorithm. Thirdly,
845 our prototype could be generalised to decide whether to perform local reasoning or not.
846 Last but not least, we would like to test the pipeline on resource-constrained devices
847 such as mobile phones. However, to do so, it is firstly necessary to develop models to
848 predict the ontology reasoning time, which so far has only considered desktop comput-

849 ers.

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