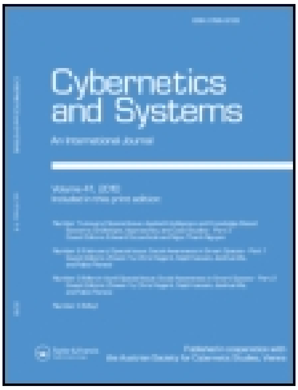


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# BUILDING DOMAIN ONTOLOGIES FROM ENGINEERING STANDARDS

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# Building Domain Ontologies from Engineering Standards

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*The use of engineering standards in virtual engineering and their potential as models for the specification of a given domain's ontology are arguably unexplored. The importance of domain modeling in virtual engineering deals directly with the potential benefits that the semantic technologies may bring, allowing to discover implicit knowledge that can be beneficial for engineers. This work presents a state-of-the-art review of the technologies used in our approach, a successful case study where our methodology was applied, and the description and results of an experiment designed to provide a quantitative validation of our methodology.*

*KEYWORDS* *domain modeling, knowledge-based systems, ontologies*

## INTRODUCTION

In computer science, a knowledge domain is visualized as a region of a virtual knowledge space identified by a name, describing the elements and characteristics that will be gathered in a knowledge base (KB). As defined in the classical knowledge engineering (KE) literature (Feigenbaum and McCorduck 1983), domain ontology models the knowledge in a specific knowledge domain, giving the particular meanings for the terms contained within it. The knowledge domain definition problem goes beyond elementary concept definition. Any concept in a domain also requires characterization of its properties.

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Interest in industrial applications of ontologies has surged in the last years. They have been proposed for issues as diverse as the efficient knowledge transfer from the research center to the production center (Frank and Gardoni 2005) or supply chain control (Chandra and Tumanyan 2007). There is a growing research effort on the use of ontologies to specify the knowledge involved in product manufacturing at the algorithmic (Novak and Dolšaka 2008), structural (Huang et al. 2008), and functional levels (Li et al. 2010). They are also being applied to multi-agent control of manufacturing processes (Leitao 2009), and the improvement of customer service for troubleshooting (Chua et al. 2008). The question of developing appropriate methodologies for ontology building is not an easy one. For instance, Blomqvist and Öhgren (2008) dealt with a case of developing an enterprise ontology following manual and automatic approaches. Their results were inconclusive, and they tried to merge them and use the results of both approaches simultaneously. In some cases, when well-defined information flows are defined it may be possible to semi-automatically generate ontologies that describe the system's knowledge (Paredes-Moreno et al. 2010). Thus, defining the appropriate methodologies for building ontologies or, equivalently, domain modeling, is a key problem in order to bring semantic technologies into the industrial domain. In our approach, we use domain-specific standards to guide the construction of the domain ontology. In this article we present a state-of-the-art on the different topics relevant to our work before providing a detailed description of our methodology for domain modeling based on engineering standards introduced in Toro et al. (2009) and an example where we successfully applied our methodology. We also present the conclusions extracted from a study we performed on a group of engineers experimenting with the use our methodology. Lastly, we provide some conclusions and future lines of work.

## BASIC CONCEPTS

*Knowledge* may be defined as (i) the expertise and skills acquired by a person through experience or education via a theoretical or practical understanding of a subject, (ii) what is known in a particular field related to facts and information, or (iii) experimental knowledge, the awareness or familiarity gained by experience of a fact or situation (Feigenbaum and McCorduck 1983; Posada 2005). Knowledge bases can be modeled and used by computer systems to enhance their capacities. Modeling a KB means building the ontology that captures the knowledge elements and their relations.

### Engineering Standards

Engineering standards (ES) help to increase the reliability and effectiveness of many goods and services we use. A standard is defined as an agreed-upon, repeatable way of doing something. It is a published document containing technical specification or other precise criteria designed to be used consistently as a rule, guideline, or definition (British Standards Institute).

Lead times for the development of standards vary from a matter of months to several years. As an example, British Standards are usually developed within 12–15 months, whereas international standards usually require around 3 years for their definition and approval.

## Benefits of Using Domain-Specific Standards

The ability to demonstrate compliance with widely recognized and respected standards is an effective means of differentiation in a competitive marketplace. In addition, manufacturing products or supplying services to appropriate standards maximizes their compatibility with those manufactured or offered by others, thereby increasing potential sales and widespread acceptance. As consumers become increasingly informed about their choices, conformity to recognized standards becomes pivotal for product acceptance.

The use of ES as models to build the ontology for the underlying KB provides the following benefits:

- *Consensus*: The process of defining the standard requires a lot of effort to establish a consensus about terminology, organization, and logic of the domain. Therefore, KB models based on standards will profit from the already built-in consensus; thus, they likely will be widely accepted and recognized as relevant.
- *Information format support*: Many virtual engineering applications (VEA) support standards as input/output information formats. This helps in the categorization of elements and the mapping of such elements into the KB.
- *Minimal semantic loss*: Semantic loss occurs when the meaning of a specification is partially lost in the process of building the specified product. The definition of an ES usually considers not only the element's concept in isolation but the relation of such an element to surrounding objects. This is indeed a very valuable feature of ES when supporting ontology building, because it helps in the conservation of the semantic properties of such elements.
- *Ease of knowledge transfer for a new domain modeling based on existing standards*: If there is no existing ES for a given domain, an ES complying with similar characteristics can be used.
- *ES are revised on a regular basis*: The nature of an ES is eminently evolutionary due to the development of new technologies for fabrication and the continuous innovation inherent in engineering paradigms. When using ES as a base for KB, there is an intrinsic guarantee that the most recent data models will be used (if the KB is updated accordingly).

The above benefits have been proven in diverse practical problems in our professional experience (Posada 2005; Toro 2009). It is on these experiences that we base our recommendation of the use of ES for an ontology engineer or knowledge engineer wishing to develop solutions for real-world applications.

## Knowledge Engineering

The acquisition of knowledge involves complex cognitive processes that are the result of personal development and closely related with intelligence. The word *knowledge* is also used to mean the confident understanding of a subject with the ability to use it for a specific purpose if appropriate. In this article we will address a very specific application of the term for the fields of engineering and computer science. According to Feigenbaum and McCorduck (1983), KE is an engineering discipline that involves integrating knowledge into computer systems in order to solve complex problems that normally require a high level of human expertise.

## The Semantic Web

Though the applicability of semantic modeling to industrial processes was acknowledged early on (Fox et al. 1996), it could be said that the explosion of the applications of knowledge modeling was due to the efforts to develop the so-called semantic Web. Leading search engines, such as Google, introduced these techniques in order to obtain better accuracy and performance in their search processes for the answers to submitted queries. The semantic Web is said to be an extension of the traditional Web that is derived from the idea of Tim Berners-Lee, according to which the known Web acts as a universal medium for data, information, and knowledge exchange. In essence, the semantic Web consists of a set of design principles, collaborative working groups, and technologies, of which some remain unimplemented. Standardization initiatives by the W3C (World Wide Web Consortium) are in fact recommendations, including some of the predominant technologies such as Resource Description Framework (RDF), a variety of data interchange formats (e.g., RDF/Extensible Markup Language [XML]), and notations such as the RDF Schema (RDFS) and the Web Ontology Language (OWL), all of which are intended to provide a formal description of concepts, terms, and relationships within a given knowledge domain. Humans are capable of using Web resources in order to find information on a given subject. However, it is difficult for a computer to accomplish this task without direct human interaction because traditional Web pages are designed to be read by people, not by machines.

## Knowledge Domain Modeling Using Ontologies

We base our approach on the widely accepted definition of *ontology* given by Gruber (1995) in the computer science domain: ontology is the explicit specification of a conceptualization; that is, it is a description of the concepts and relationships in a domain. Some of the reasons to use ontologies in knowledge domain modeling are (i) to separate a domain's knowledge from actual knowledge, (ii) to analyze a domain's knowledge, (iii) to share a common understanding of the structure of information between people or software agents, (iv) to enable the reuse of domain knowledge, and (v) to make domain assumptions explicit. To our knowledge, there are few reported cases where standards are used along with semantic technologies. The best example is the notorious case of CIDOC-CRM (CIDOC Conceptual Reference Model; Posada 2005), whose primary role as a formal ontology is to facilitate the integration, mediation, and interchange of heterogeneous cultural heritage information from heterogeneous sources. Some of the main reasons to build an ontology as a domain model are to (Posada 2005; Morbach et al. 2009; Toro 2009)

- share common understanding of the structure of information,
- enable the reuse of domain knowledge,
- make domain assumptions explicit,
- separate domain knowledge from operational knowledge, and
- analyze domain knowledge.

## Virtual Engineering

Virtual engineering (VE) is defined as the integration of geometric models and related engineering tools (such as analysis, simulation, etc.) within a computerized environment that facilitates multidisciplinary and collaborative product development (Toro 2009).

The goal of VE is to improve the engineer's focus on solving the problems at hand, saving precious time and efforts on gathering, managing, modeling, and analyzing information about the problem. VE is centered in the user, providing a collaborative framework to integrate design models, simulation results, test data, and other decision support tools in a computational environment that eases its access. According to McCorkle et al. (2003) "a key aim of virtual engineering is to engage the human capacity for complex evaluation." However, VE is highly dependent on implementation issues and on the software and metatools employed for its design. Virtual engineering applications (VEAs) are instantiations of the VE concept in a particular domain of practice. Any engineering-focused software helping the engineer to perform a design task with some degree of integration of computational resources is a VEA. Nevertheless, current VEAs still barely exploit the potential for the use of contextual information, user experience, and, in general, knowledge that can be modeled and inferred with the aid of semantic-based techniques.

## A METHODOLOGY FOR THE USE OF ES AS MODELS FOR DOMAINS

The use of ES as models for knowledge domains is beneficial for the semantic enhancement of VEAs because a consensual domain provide the capability of more accurate real-world–to–VEA mapping tools that ease the identification and pairing of real-world elements with the virtual objects that belong to the VEA. No matter where the elements were modeled, if they are in compliance with the standard, such elements will share a common name and properties across the whole product life cycle, making them more usable by knowledge-based tools.

Our methodology is divided in a series of logical stages that must be performed to assure a correct modeling of the knowledge domain. As can be seen in Figure 1, it is decomposed into four layers, namely, define, identify, model, and instantiate, encompassing eight stages described as follows:

- *Stage 1—Definition*: an identification of the purpose and requirements of the domain is made. We specify the purpose of the KB, the information that will be stored, and the needed level of detail of such information.
- *Stage 2—Selection of the standard*: there is a search of a standard that suits the defined needs. To fully grasp the usefulness of this selection, the chosen standard must be studied in detail: how it is constructed, what can be done in order to extend it, etc.
- *Stage 3—Class identification*: an identification of the possible data representation classes that model the domain is performed; classes are categorized in a tree-like structure of the more general terms.
- *Stage 4—Property identification*: the characteristics that can be measured or determined by data types (string, integer, etc.) are identified in each class (e.g., length). Then, characteristics that relate a class with other classes (relation types) are identified. In general, data type characteristics are easily recognizable and obtained by simple interrogations. Relation

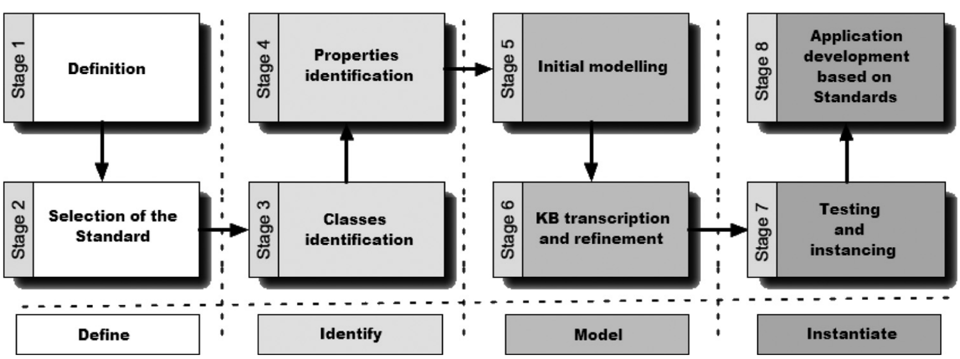



**FIGURE 1** Our methodology for domain modeling based on standards.

types are more difficult to find, because generally when talking about a geometric model, sets of elements are categorized as geometric primitives rather than functional objects. For the aforementioned case, solutions like the process of branding and matching presented by Posada (2005) can be used.

- *Stage 5—Initial modeling*: a subset of the domain is chosen in order to verify the complexity of the overall modeling and the real capabilities of the KB. Because the elaboration of a KB is an iterative incremental process by nature, this small test must answer initial modeling needs.
- *Stage 6—KB transcription and refinement*: sometimes the initial modeling is enough for the KB to fulfill the design requirements in stage 1. However, verification of the transcription using the capabilities of a reasoning tool to check the congruence of the KB is highly recommended. Once the transcription is done, a refinement process takes place. In this stage any needed extension of the standard takes place.
- *Stage 7—Testing and instancing*: testing of the instances and the creation of an automatic instancing mechanism are performed. As a final step, some individuals conforming to the specification of the classes can be manually modeled using an ad hoc editor. This process can be automated if any Application Programming Interface (API) tools are available. This step does not strictly fall into the model design process but is for any KB model to be of practical use.
- *Stage 8—Application development based on standards*: the VEA using the domain model is developed. This last stage comprises the actual usability of the domain. It is here where the VEA takes advantage from semantics, via the enhancement obtained by having a better described and consensual domain model.



Using ES in this scenario could be very beneficial, for reasons explained earlier. However, there are possible drawbacks to such an approach:

- *The design of the standard could be functional biased*: In some cases, the ES is oriented toward a functional description, leading to potential semantic loss, because the standard does not include all of the parameters required for a complete domain modeling. For those cases an extension of the class should be performed in order to obtain a complete KB, and it is advisable to double-check whether the parameter is a fundamental one or if there is a way to obtain its value by interrogating neighbor elements. If the need to specify the parameter is fundamental and the model extension is unavoidable, it should be clearly specified as an "outside the standard feature."
- *The standard can disappear or be absorbed by another standard*: Due to lack of use or administrative reasons, some standards disappear. In such cases, the use of a KB based on such an ES could be maintained, but it would be advisable to migrate the KB to a new paradigm when available.

In the case of absorption by another standard, the model should be reviewed in order to check its robustness.

- *The standard falls short of the domain needs*: This indicates a possible immature ES or an inappropriate election by the domain designer. For both cases, reading and understanding of the standard and an extensive review of the problem's characterization (domain requisites) is advised.
- *The standard could be used to model a different domain*: This feature is not a bad situation at all; it means that the same domain modeling could be shared by different VEA without the need for further specifications.

## CASE STUDY

The methodology for knowledge domain modeling based on ES as described in the previous section is rather abstract, because at this level of definition it is intended for a wide variety of situations. In this section we will follow a case study that can clarify most of the issues than can appear while trying to apply this methodology.

- Stage 1—Definition: Let us consider the general problem of modeling the knowledge involved in the design of an industrial plant and, more specifically, the issues involved in the modeling of a flange element.
- Stage 2—Selection of the standard: Searching standards-related public information, we find that there is an International Organization for Standardization (ISO) standard that could be used as a guide for the modeling of the flange: ISO 10303 AP 227, related to industrial plants (Toro 2009).
- Stage 3—Class identification: Upon examination of the standard we find that a description of a flange element exists; this description as obtained from the published standard is depicted in Figure 2.
- Stage 4—Identifying properties: Looking at the properties of the flange element, we create the classification shown in Table 1. The criteria for choosing the concept are provided by an expert in the field who works as a knowledge engineer.

**4.2.84 Flange**

A Flange is a type of Fitting (see 4.2.83) that is an annular collar that permits a bolted connection to a similar collar. Each Flange contains two end connectors, one of which shall be a Piping_connector of type Flanged_end. Each Flange may be one of the following: a Blind_flange (see 4.2.3), an Expander_-flange (see 4.2.75), an Orifice_flange (see 4.2.146), or a Reducing_flange (see 4.2.202). Each Flange may be one of the following: a Lap_joint_flange (see 4.2.118), a Slip_on_flange (see 4.2.222), a Socket_-weld_flange (see 4.2.224), a Threaded_flange (see 4.2.252), or a Weld_neck_flange (see 4.2.266).

NOTE Figure 12 depicts a typical weld-neck Flange.

The data associated with a Flange are the following:

— end_1_connector;
— end_2_connector;
— hub_through_length;
— hub_weld_point_diameter.

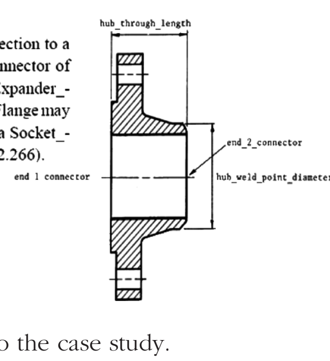



**FIGURE 2** STEP standard excerpt relevant to the case study.

**TABLE 1** Flange Identified Properties

| Name | Property_type | Value |
|---|---|---|
| hub_through_length | Data | Doubts |
| hub_weld_point_diameter | Data | Double |
| end_1_connector | Relational | Element |
| end_2_connector | Relational | Element |

- Stage 5—Initial modeling: We use the Protégé ontology editor to build the model of the flange element, as shown in Figure 3.
- Stage 6—Knowledge base transcription and refinement: For the case under study, we decide than the standard contains enough information for our modeling needs; hence, no extension is needed. The process is finalized by running a reasoning process to check the ontology for any problems at a logical level (not shown).
- Stage 7—Testing and instancing: We use the Protégé OWL API for the generation of Java source code suitable for the semi-automatic instancing of individuals.
- Stage 8—Application development based on standards: As pointed out before, this last stage comprises the actual usability of the knowledge domain model. In our case we used the modeled domain in order to match graphic elements coming from a 3D model with parameters for a semantic synonym graphical adaptation as explained in Toro (2009). Figure 4 depicts such a matching for the example.

## FIELD VALIDATION OF OUR METHODOLOGY

In order to test our methodology and obtain some empirical evidence of the benefits gained when dealing with real problems, we conducted a field study that consisted of asking groups of people to solve a modeling problem following the application of our methodology. The study was performed on a group of engineers comprising two differentiated subgroups. Computer science fieldworkers who had a basic knowledge of task, user, and even

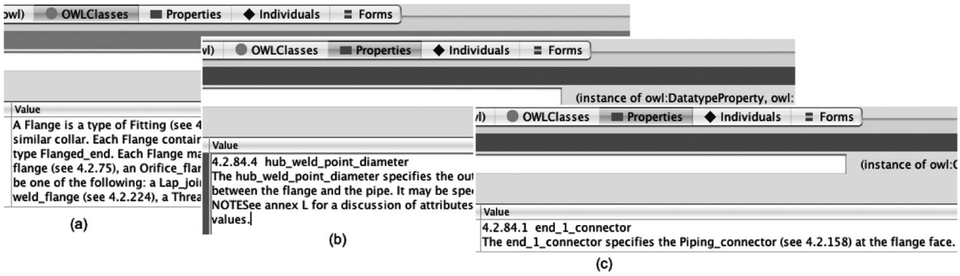



**FIGURE 3** Modeling of the (a) flange class, (b) data type, and (c) relational properties.

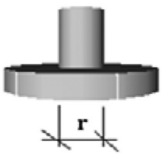
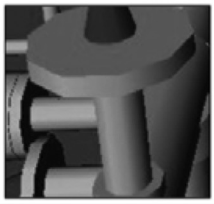
| 3D CAD (Geometric LOD) | Semantic Synonym representation (parametric) | ISO-STEP Matched parameters |
|---|---|---|
| ISO-STEP 10303-AP227 | | |
| <br> | <br>r = radius<br>s = side<br>XYZ = Coord. System<br>P = position (px,py,pz) | **STEP 4.2.84.3**<br>Hub through length = s<br>**STEP 4.2.84.4**<br>hub weld point diameter = 2*r<br>**STEP piping**<br>connectors : give XYZ, P. |

**FIGURE 4** Application development.

knowledge domain modeling techniques composed the first subgroup. The second subgroup was a more technically oriented group of individuals who had a certain degree of expertise in ES because they have worked on implementing products that follow some ES (e.g., digital TV broadcasting standards, education-related standards). Both groups were presented with the task of a fluid transport element composition modeling problem comprising a pipe, a valve, and a 90° elbow; these are sketched in Figure 5.

Subject tests in both groups were told to proceed in two steps: first they had to define the elements using only their expertise. In a second stage, after provide each subject test in both groups with reduced versions of two ES (ISO-STEP and CIS/2) (including the parts describing the set of elements needed to model the element composition) and a complete explanation of our methodology, they were instructed to follow our methodology step by step. Therfore, they produced two models of the system, one of which was produced prior to being introduced to our methodology. That was intended to measure the improvement in the model's quality.

After the modeling stage, the models were exchanged among the participants; that is, each subject took a model built by another subject. Then, the subjects were asked a series of questions about the composition. Such questions had to be solved on the basis of the received model. If the model was not able to answer some of the questions, the subject test had to indicate this fact. Table 2 depicts the composition of the test groups in our study and their standard choice.

As can be seen, of 57 participants, 25 (43.8%) were familiar with some standard. The majority of the participants chose to work with one of the

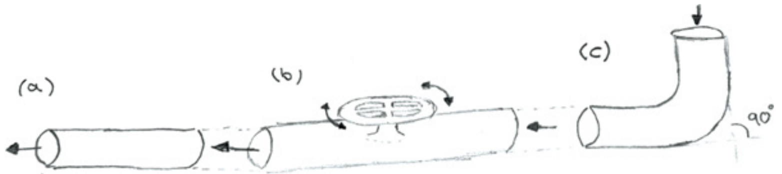



**FIGURE 5** Modeling problem (color figure available online).

**TABLE 2** Test Groups and Their Selected Approach (Standards for ES Experts, Knowledge for Knowledge Engineers)

| Group affinity | Participants | Chose STEP | Chose CIS | Chose OWN |
|---|---|---|---|---|
| Standards | 25 | 16 | 8 | 1 |
| Knowledge | 32 | 12 | 9 | 11 |
| **Totals** | 57 | 28 | 17 | 12 |

**TABLE 3** Questions Posed to Test Groups

| Questions | Input for *(a)* | Radius of *(b)* | Input for *(b)* | Input for *(c)* |
|---|---|---|---|---|
| Radius of *(a)* | Output for *(a)* | Type of *(b)* | Output for *(b)* | Output for *(c)* |
| Length of *(a)* | Rugosity of *(a)* | Rugosity of *(b)* | Radius of *(c)* | Rugosity of *(c)* |

standards we provided. Of those who declared a certain familiarity ES, the STEP standard was chosen by 16 participants (64%) and CIS/2 by 8 participants (32%), only one did not use either standard (roughly 0.4%): those who implemented standards perceived the usefulness of standardization processes. Of the participants with some knowledge engineering expertise (32), the selected source for modeling was more equilibrated between options the provided (38% chose STEP, 28% chose CIS/2, and 34% used neither standard). Following our experiment, we randomly chose 25 of the 32 KE expert subjects to test the degree of understanding of the task imposed and asked them the questions shown in Table 3.

The questions aimed to explore the quality of the models provided to the subjects, in the sense that they must notice if it is possible to answer the question using the information given by the model. Poor modeling methodologies lead to information loss in generated models, resulting in the impossibility to answer some of the questions. We found that the test subjects did not answer around 30% of the questions when the models handed to them were those produced before being exposed to our methodology. Information involving relations with other elements were frequently overlooked in the domain models designed without taking into account our methodology. Moreover, we observed that knowledge engineers' domain models had an almost complete lack of information related to physical measurements (e.g., rugosity).

## CONCLUSIONS AND FUTURE WORK

The use of ES as a model for knowledge domains is clearly beneficial for the semantic enhancement of VEA. In this article we presented a new methodology for domain modeling based on ES. We discussed some of the benefits of standards as guidelines for knowledge-based domain modeling and some potential challenges along with possible approaches to overcome them. We detailed a case study to illustrate the processes involved in our methodological approach. Finally, we performed a field study with a group of volunteer engineers to evaluate the improvement in knowledge model quality introduced by our approach. We conclude from the field study that for both knowledge engineering and novice subjects the use of our methodology was clearly beneficial because it led to the construction of models that allowed more questions about the modeled systems to be answered. To our knowledge it is the first time that a proposed knowledge modeling methodology was tested empirically. Validation of such methodologies is usually subjective. We intend in the future to perform a new series of field tests on mixed working groups composed of one knowledge engineer and one standards expert involving a similar test. We hypothesize that this kind of tandem would benefit even more from our methodology We conclude that a domain expert is always needed in a domain modeling problems, no matter which methodology the knowledge engineers follows; however, a simple and clear modeling paradigm such as the one we present provides good guidelines for the modeling tasks and at the same time simplifies diversification and responsibilities of the domain modeling team. As future work, we also intend to test and compare our methodology and other established methods that could be used for domain modeling such as commonKADS (Schreiber et al. 2000), etc.



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