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Improving the interoperability of industrial information systems with description logic-based models—The state of the art

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ABSTRACT

Semantic technologies that have arisen with web development have brought out new tools, concepts, and methodologies which are increasingly employed in Product Lifecycle Management (PLM) applications. This paper proposes a literature review of papers related to ontologies in the area of product lifecycle management. However, it only focuses on inference ontologies, i.e. ontologies that enable reasoning, for instance, models expressed in the Web Ontology Language (OWL). The goals of this paper are to explore the field of such applications, to figure out the advantages of inference ontologies in a PLM context and to synthesize major existing inference models in terms of methodology and structuration. Finally, this paper proposes several research perspectives.

1. Introduction

In order to reduce time-to-market and product costs while improving product quality, industrial companies face many challenges. Some of these challenges include managing the increasing diversity and complexity of products, and enhancing collaborative and integrated engineering. Product Lifecycle Management (PLM) is a research area known to focus on these issues, as it aims to improve collaboration between all actors involved throughout the whole product lifecycle [1]. One of the major issues of an efficient PLM approach is the ability to achieve full interoperability between all the information systems covering the product lifecycle [2]. Examples include Computer Aided Design (CAD)/Product Data Management (PDM) data exchange [3], PLM/Enterprise Resource Planning (ERP) bill of material transfers [4] and ERP/Manufacturing Execution Systems (MES) cooperation [5]. These three papers underline the need for interoperability as well as the difficulty in dealing with lossless model transformations occurring at the system boundaries.

Interoperability can be defined as the ability of two systems or more to communicate, cooperate and exchange data and services, despite differences in languages, implementations and executive environments or abstract models [6]. Three levels of interoperability have to be considered [7,3]:

- the technical level,
- the organizational level,
- the semantic level.

Interoperability can therefore be claimed to be achieved *if and only if* all three of these levels are fully completed. This paper focuses on the semantic part of the interoperability issue, which is to say, it attempts to figure out a consistent way to deal with inconsistent product and process models, which is still considered to be a challenge [8]. PLM standards [9] are known to provide a cost effective and consistent solution to deal with large scale interoperability issues over the extended enterprise. *Ad hoc* and standard product models are thus part of this study.

The early 2000s saw the emergence, development and widespread adoption of tools, models and methodologies originally designed for the internet, known as "semantic web" technologies [10]. Among them, ontologies address the semantic representation of information for the purpose of storing and exchanging shared knowledge over a worldwide network. PLM researchers have naturally attempted to benefit from these

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semantic technologies, especially ontologies, since they enable simple and exhaustive descriptions of any domain [11] and appear to be relevant to robustly formalize and exchange product information [12].

According to Gruber [13], an ontology is ‘‘an explicit specification of a conceptualization’’. In 1997, Borst [14] further specified the definition of an ontology as ‘‘a formal specification of a shared conceptualization’’. ‘‘Formal’’ has to be understood as machine understandable whereas ‘‘conceptualization’’ means that the ontology is a representation of an abstract domain. Indeed, Lee et al. [15] define a conceptualization as ‘‘the extraction of vocabularies from a domain and an abstract, simplified view of the world that we wish to represent’’. Finally, ‘‘shared’’ means that the information contained in the ontology can come from different sources [11].

According to Fankam et al. [16], ontologies can be classified under two categories:

- storage oriented ontologies, to improve information storage from heterogeneous sources or to provide a clear description of a large domain (e.g. a common vocabulary). They deal with only canonic data (this means that one datum exists in only one class at a time), and the standard appropriate languages are Part Libraries (PLIB) [17] and RDF Schema (RDFS) [18],
- inference oriented ontologies: inference is defined as the ability to make deductions about instances regarding the classes, properties and axioms explicitly defined in the ontology [19]. They deal with non canonic data, which makes it possible to have individuals in different classes at the same time (and also to merge different points of view of the same object).

In industrial use cases, storage ontologies are commonly used for knowledge management [20] or for storing, reusing or sharing information. As they successfully support multiple knowledge types and sources [21], they enable layered solutions to represent a domain or a database [22]. Product and process models for PLM, however, have different requirements [23], such as dealing with different abstraction levels [24]. This has led to the increased use of inference ontologies for product, process or service models, which are the scope of this study.

This paper provides a literature review related to inference ontologies intended to PLM applications, based upon a review of scientific papers dealing with both industrial and computer science literature. It aims to answer the following questions: what kinds of PLM issues lead to the use of inference models, with which scope and in which fields? Why are inference ontologies relevant for PLM applications? And how are they used in current research papers?

The following methodology will be used:

- classifying related papers,
- figuring out limitations and open issues,
- identifying research prospects according to the conclusions by authors.

Therefore, the paper is organized as follows: Section 2 reports the literature review of inference ontology applications in PLM since the emergence of standard ontological languages in 2004, regarding interoperability issues in PLM. Section 3 figures out the benefits provided by inference ontologies for PLM applications, based on their specific functionalities. Section 4 analyses in detail inference-based models in PLM, considering whether they are *ad hoc* or standard models. Section 5 discusses the limits of these models and suggests research prospects. Finally, Section 6 will conclude the paper.

2. Inference ontology applications in PLM

2.1. Semantic interoperability issues in PLM

Semantic interoperability issues in a PLM context, such as information loss or semantic inconsistencies, have in the past ten years led to the emergence of *unification* approaches [25] that provide direct mappings between both users, and are mostly based on standards. The lack of flexibility, dynamism and automation of such approaches and the increase of data volume have led to the development of *federative* approaches, based on ontologies. The high number of scientific papers related to applications of ontologies in PLM models can be explained, according to Ishak [11], by the fact that they propose a simple, exhaustive, implementable and humanly understandable description of the domain. An ontology is indeed composed of a set of classes (or concepts) that define the domain. These classes are connected to each other via properties or roles. Axioms (or restrictions) are applied to roles and classes and finally, the ontology is diversified with instances. From a mathematical viewpoint, an ontology can be defined as a 5-tuple [26]: $O := \{C, R, H, ref, A^0\}$. C are all the concepts (classes), disjoint from R (set of the roles). H expresses the hierarchy (or ‘‘taxonomy’’) between concepts and ref is a function to associate the roles to the diverse concepts. Finally, A^0 refers to the axioms, expressed in a logic language.

2.2. Industrial scope

Questioning which kinds of applications inference models can provide leads to further questions from the literature, such as which product lifecycle stages are concerned, what the scope of the proposed models is, and which fields are involved. Therefore, the 28 inference-based papers extracted from the literature review in Fig. 1 are classified as follows:

- The vertical dimension represents the *scale* of the proposed models. *Scale* has to be understood in this context as both the granularity and the scope of the model. Indeed, a business scale would include a model that is dedicated to a specific task. It would provide a comprehensive and complete description of the domain involved, without including neighboring domains. At the stage scale, ontology-based models describe the whole process (design, manufacturing or maintenance process for instance, see for example the work of Mun et al. [27] about process plant), integrating the different business areas involved in a meta view. Similarly, inter-stage models encompass different stages, and finally papers focusing on the whole lifecycle aim to provide a global PLM model. Hence, the more the scale increases, the more the model is global.
- The horizontal dimension represents the product lifecycle stage that each paper focuses on. It can be considered as a temporal dimension and then split into three main stages: the beginning of life (BOL, e.g. design and manufacturing stages), the middle of life (MOL, e.g. usage and maintenance stages) and the end of life (EOL, e.g. disassembly and recycling stages). However, it must be noted that papers at the lifecycle stage cannot be discriminated against following the time dimension, since they involve a long lifecycle period, or sometimes the whole lifecycle.
- Finally the frame of the different papers represents different industrial focuses: the product, process or service model. When the scale of the model increases, some papers can cover both product and process fields (P-P in Fig. 1), or product, process and service fields (P-P-S).

The selected papers illustrated in Fig. 1 were published later than 2004, when standard languages for inference ontologies