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Requirements and languages for the semantic representation of manufacturing systems

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ABSTRACT

In the last years, attention has been devoted to the development of ontologies, which are ICT conceptual models allowing a formal and shared representation of a particular domain of discourse, and to the use of these representations in a variety of contexts, among which also the industrial engineering can be counted. Within the industrial engineering field, the manufacturing domain has not yet seen a wide application of ontologies. This paper firstly shows the use of ontologies for the semantic annotation of a Web Service-based architecture for the control of manufacturing systems; and then contributes to the research field of manufacturing domain ontologies by proposing a thorough literature review and analysis of the available languages supporting such objective. The paper collects the main requirements that semantic languages must meet to be used in the manufacturing domain with the outlined purpose. In fact, the available semantic languages are several and characterized by different features: the paper identifies the most proper ones for the manufacturing domain representation thanks to their analysis against the main requirements. Lastly, the paper shows how the discussed topics are deployed in a real industrial example.

1. Introduction

Current market conditions require companies to be highly flexible to remain competitive on a global scale. Flexibility is the key to face the more educated and demanding customers that ask for quicker delivery, higher variety and more customized products [1–4]. In particular, one of the levers to achieve higher flexibility is to have manufacturing systems that are reconfigurable with reasonable time and cost efforts, in order to produce new generations of products [5]. Higher levels of re-configurability require an effort for the development of better conceptual models of the manufacturing domain. A promising direction to this aim could be the development of a manufacturing domain ontology as explained in Section 1.2. In fact, ontologies, as a way to model conceptually and logically a system, have been widely proposed and exploited also in other industrial engineering fields [6] and in general engineering was among the earliest fields that applied ontologies [7].

1.1. Research statement

Conceptual models and ontologies can be developed basing on different languages, each with its own characteristics and limits, that are available nowadays [8]. In order to start modelling the manufacturing systems domain, one of the first steps is the selection of a precise and proper language.

After having motivated the industrial interest for ontologies of the manufacturing domain, the first aim of this paper is to investigate what are the requirements for the selection of the proper language for the representation of the manufacturing domain and to put them in a proper framework.

Then, the paper will briefly illustrate the features of the available semantic languages to evaluate them against the identified requirements in the framework.

Eventually, a real case is presented that reflects the industrial relevance of the abovementioned approach and framework and shows the importance of the role of ontologies to face the requirements.

This is also reflected in the structure of the paper: Sections 1.2 and 1.3 motivate the industrial interest for manufacturing domain ontologies and review the current state of the art in this research field; Section 2 illustrates the requirements that must be met by the semantic languages for the representation of the

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manufacturing domain; Section 3 reviews the available semantic languages and discusses the matching between them and the identified requirements; Section 4 shows how the role of ontological modelling and the identified requirements are deployed in a real industrial case and Section 5 is dedicated to the concluding remarks and suggestions for future work.

1.2. The role of ontological modelling in the manufacturing domain

Despite the fact that a high level of flexibility is reached at the mechanical level, the re-configurability level of the control systems is still poor [9]. It has been estimated by Colombo in 2005 that 70% of the engineering teams' effort is directed to modify the control system when a new machine is introduced in the production system [10].

Literature suggests that a possible answer to the issues related to control architecture flexibility and re-configurability at software level is the use of a distributed control architecture, based on Cyber Physical Systems, smart components that are put into communication thanks to well-established standards such as Profibus, or into a Service Oriented Architecture (SOA) [11–15]. In particular, the SOA architecture offers the potential for device interoperability, thanks to its features of message-based communication, loose coupling and open standards. Such a control architecture encapsulates the manufacturing processes in services (namely, Web Services) that are offered on a Web-based communication network, where the control system may find them and invoke them through the orchestration and choreography mechanisms [16]. These are needed for the composition and execution of the services related to the manufacturing processes in the proper sequence [10]. In this way, re-configurability at the software level is made possible. However, high costs and a long time are still required to implement new configurations. In fact, changes in the physical manufacturing system must correspond to modifications in the control software by human programmers. This is due to the lack of a machine-readable semantic description of the system and of the operations to be performed in the specific context of the manufacturing system at hand: therefore, semantics is still interpreted by the human programmer who will include the necessary changes into the control software. A possible solution to this issue could be the development of a proper semantic model of the production system and make it accessible to the control software through the use of semantically-enriched Web Services (i.e. Semantic Web Services) [72]. Within such an approach, human interventions are no more needed, or only limited to a very small extent, because the semantics makes the knowledge about the manufacturing system itself understandable to the control software: this opens the way to automatic reconfiguration of the control software in case of physical modifications in the production system [9,10].

A way to add semantics to Web Services is their annotation with ontological models, that provides a semantic description of the production system and can be exposed as services on a Web-Service based SOA control architecture [17]. According to the definition by Gruber, an ontology is an "explicit specification of a conceptualization", where a conceptualization is an abstract, simplified view of the world that we need to represent for some specific purposes [18].

Ontologies support class-based, or object-oriented, description of a knowledge domain, expressing taxonomies and semantically rich relationships among concepts, supporting information retrieval through reasoning. Moreover, by their nature, distinct ontologies can be integrated by creating "bridge" relationships among some concepts of the different ontologies [19]. This characteristic is particularly useful in the description of complex manufacturing systems.

Already in 1999, Schlenoff understood the potential of ontologies in the manufacturing domain (unambiguous communication, shared terminology and semantic alignment, and industrial information infrastructure in that they provide data in computational form) [20]. The possible uses of ontological representations of the manufacturing domain are not limited to the applications in control architectures, but, as pointed out by Garetti and Fumagalli, they can also support design, simulation, planning and scheduling, performance assessment and data integration in the field [21].

1.3. State of the art on conceptual modelling in manufacturing

Since many years, the topic of conceptual modelling for the manufacturing domain is an open research stream. Some of the first works on this topic date back to the 1990s, when early research on conceptual modelling and ontology development of the manufacturing systems was proposed by Politecnico di Milano [22]. The P-PSO, Politecnico di Milano—Production Systems Ontology was proposed as a complete modelling of the manufacturing domain that could be used for information exchange, design, control, simulation and other applications [21,23].

Since then, many other research groups and research projects have worked on this topic. The success of semantic and conceptual models in the manufacturing domain can be justified by the many characteristics and potentialities of such models. In particular, they are implemented as ontologies that allow sharing the same vocabulary, not relying on human programmers' interpretations of the natural language that can sometimes bring to misunderstandings, according to Guarino [24].

The developed ontologies for the manufacturing domain range from the most general, the so-called foundational ones, to the very specific for a certain context within the more general manufacturing domain. Each of them has its importance, regardless of the detail level they have [25]. Also the motivations that lead to their creation can be different: ontologies applications bring benefits covering automatic re-configurability, interoperability, creation of a common vocabulary, and knowledge sharing and reuse. The various applications in manufacturing differ also on the level of the potentials offered by ontologies: some are simply structured machine-understandable vocabularies of a certain domain, others are built with the purpose of inferring new knowledge starting from the structured information in the model.

The applications of ontologies in the manufacturing domain may depend on various reasons, the main of which are listed below:

- Some claim to use them for the support to *reconfiguration of manufacturing systems* without human intervention; in particular, a reconfiguration agent is based on the ontological knowledge of the manufacturing system [16,26,27].
- Colledani et al. [28] conceptually modelled the manufacturing domain perspective on products, processes and production systems in order to *model them in an integrated way*. Other example references for ontologies used as integrated models of manufacturing systems are: [29–31].
- In [17,32] ontologies are also created that represent the manufacturing domain but with another objective: the *inter-enterprise interoperability*; for this reason, along with classes representing resources and operations, they also inserted enterprise- and strategy-related classes. Also other authors deem ontologies in manufacturing the way to address inter-enterprise interoperability issues: [33,34].
- The problem of *interoperability among different systems in the enterprise* has been addressed by [35], which proposes a development approach for formal ontologies and use it to represent