Ontology in Engineering Applications

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Abstract: The goal of this position paper is to introduce the research topics in engineering and the motivations for the application of semantic technologies. A group called Ontology Based Engineering – OBE has been created by the engineering community to share experiences in this field and the various challenges faced in using ontologies and related tools. The OBE groups aims at creating a dialog with the ontology specialists by sharing the research challenges and problems in ontology application.

Key Words: Ontology; Semantic technologies; Engineering; Design; Manufacturing

1. Introduction

The use of ontologies and semantic technologies in engineering applications is gaining in importance and popularity, while at the same time it seems to generate a lot of controversy in discussions within scientific and engineering communities. Yet, do we really need ontology based technologies in engineering environments? What challenges have been addressed in the state of the art so far and what are the challenges in front of us?

To address these questions, the Ontology Based Engineering (OBE) Group has been created in 2014 by active researchers in engineering fields. The group has three main objectives:

- Bring together active individuals and teams working on various aspects of ontology based engineering and create a larger community.
- Identify points of common views or elements of difference to be discussed.
- Establish a roadmap towards a harmonization of the main points of interests and potential areas of research and development.

The members, listed in the table below, were selected based on their expertise and willingness to participate in the activities of the group (Table 1).

BIBA, DE	POLIMI, IT
Birmingham University, UK	TU Dresden, DE
DFKI, DE	TU Darmstadt, DE
ENSAM Paris, FR	University of Lorraine, FR
EPFL, CH	University of Loughborough, UK
ITIA-CNR, IT	

Table 1: List of OBE Group Members

The goal of this position paper is to create a dialog with computer scientists and ontology specialists by sharing our research challenges but also our motivations and problems in ontology application. The paper is structured as follows. Section 2 presents the background of research conducted by the OBE group. Section 3 provides some examples of case studies derived from European projects. Section 4 discusses the motivations of using ontologies and which support tools can be adopted to build them. Finally section 5 concludes the paper.

2. Background

The shifts in social, economic and ecological systems are marking the global economy and society as a whole. These trends are also having profound effects on industry and raising several challenges with respect to manufacturing and engineering capabilities. New product development processes are supported through the integration of multiple systems (Schuh et al. 2008) namely: Enterprise Resource Planning (ERP), Product Data Management (PDM), Customer Relationship Management (CRM) and other CAx systems (Computer-Aided Design, Computer-Aided Manufacturing or Computer-Aided Process Planning). The aim of this integration is to streamline the value creation chain for faster innovation cycles combined with lower costs.

Despite the efforts that are being made towards the improvement of manufacturing engineering capabilities as a source of competitive advantage, there are still remaining challenges to be addressed in order to enable innovative design and realization of product-service succeed. These challenges relate particularly to intelligent, knowledge intensive and user-centered design and manufacturing engineering, and include the following:

- There is a need for effective engineering knowledge openness and diffusion to support fast sharing of product related information and knowledge across the entire value-chain.
- There is a need for innovative mechanisms to enable new feedback and feed-forward mechanisms to the various actors involved in the entire lifecycle.
- There is a need for decision support tools to enable innovative design and realization of product-service supporting reactivity to users' requirements and new demands.

In addition to the aforementioned business-oriented challenges, manufacturing engineering involves a number of already known problems and issues in information science such as information modeling, data integration, data analysis, data exchange, system interoperability, etc. It comes as no surprise that ontology and semantic technologies have been adopted by the engineering community as a promising approach to solve several of these issues. In product design, for instance, ontology is used for modeling the product structure and taxonomy or for design automation using existing engineering knowledge, or also for requirement engineering (Kitamura¸ Koji and Mizoguchi 2006; Kitamura and Mizoguchi 2013). In manufacturing, ontology is used for the control of production processes for dynamic orchestration (Loskyll 2012) or for factory automation including assignment of functions to networked resources, automatic mapping of device profiles to device descriptions and firmware, or mapping of data sources to Manufacturing Execution Systems function (Fumagalli 2014).

As a step towards developing semantically enriched product models, some initiatives have been carried out by standardization organizations namely with the OntoSTEP under ISO activities converting STEP Application Reference Models from EXPRESS language to OWL (Web Ontology Language). This work has been extended in order to define a semantic model supporting both the representation of product geometry concepts (STEP) and beyond-geometry concepts (Core Product Model and Open Assembly Model) resulting in a new semantically enriched product model (Barbau et al. 2012). The conversion from EXPRESS to OWL is also relevant in the field of Architecture Engineering and Construction with reference to the Industry Foundation Classes (IFC) standard (Pauwels 2015). Additional examples include ISO 15926 and PLCS (Product Life Cycle Support). Other efforts have been conducted also by the academic community, namely PRONTO defines a product ontology modeling the domain of complex product, primarily related to the product structure (Vegetti, Henning, and Leone 2005). An extension of PRONTO has been proposed providing the foundations for a distributed product data management (DPDM) system, with the core idea of managing product information according to two hierarchies: the abstraction hierarchy and the structural hierarchy (Giménez et al. 2008). OntoPDM is another initiative defining a Product-driven ONTOlogy for Product Data Management, and aims at conceptualizing, merging and reusing knowledge embedded into existing standards for product technical data and ERP/MES data (Panetto, Dassisti, and Tursi 2012). Furthermore, ontology can be used for representing tacit engineering knowledge by means of rules, thus enabling the inference of implicit knowledge (VISTRA[1], e-SAVE[2] and Flexinet[3] FP7 projects). Such feature not only enables rapid and code-free modifications to software applications when business conditions change, but it also facilitates the inclusion of contributions from business people and domain experts (e.g. designers, quality engineers, workers, etc.) into the implementation and adaptation of the system on a higher level of abstraction.

3. Ontology Application: Examples from FP7 European Projects

3.1. LinkedDesign Project[4]

LinkedDesign aims to develop an integrated information platform for manufacturing design that federates all relevant product lifecycle information, independent of its format, location, originator, and time. A first step towards achieving interoperability is the definition of a common semantic model. The semantic model enables common interpretations of data and information exchanged between people and systems that have no common recognition of data type or relationships. An ontology network has been developed to cover the requirements of various product lifecycle. An extract of this ontology is given in Figure 1. One of the project use cases involves mostly two different phases of the product lifecycle: the proposal (or product definition) phase and the operational phase. The goal of the platform for this use case is to have an automated system to calculate the Life Cycle Costs (LCC) of production line and to optimize the line configuration according to the costs and environmental impact. This is done in the proposal phase in such a way that more information can be attached to the offer presented to the customers. However, data used to calculate the LCC comes from databases that can be refined by collecting information from the shop-floor where the equipment is working. This connection between the operational phase and the concept phase of the equipment is reached through an automated data collection system able to record all the relevant information coming from the machine’s control system (production data, failure data, maintenance activities, energy consumption, etc.). In the proposal phase, designers take decisions on the line configuration to be presented to the customer. Assembly lines are generally made of many stations where a certain set of operations are performed either by an operator or by automatic equipment. The platform provides a component that automatically finds the composition of the line with the lowest LCC value, but it is not able to take into consideration the more complex requests from the user. A list of potential requests is given as a list of properties of the concept ‘Customer’ in ontology.

[1] http://www.vistra-project.eu/
[2] http://www.e-save.eu/
[3] http://www.tanet.eu/projects/current-projects/flexinet/
[4] http://www.linkeddesign.eu/

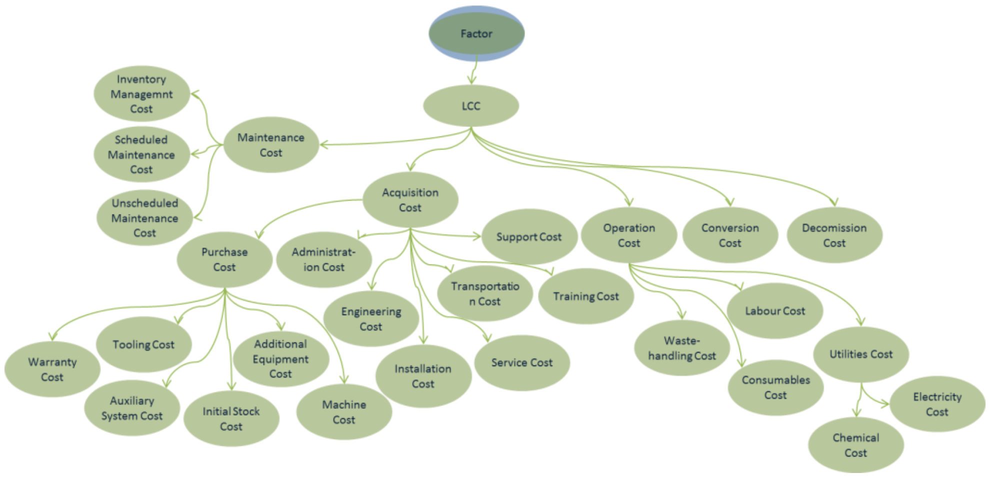

Figure 1: Graph representation of LCC Ontology

To enable advanced control of products design and maintenance, three groups of rules were created:

1) Rules for enforcing customer requests. These rules control if the current solutions according to LCC minimization are in correspondence with customer requirements for product properties.
2) Rules for inheritance of properties from part to product. This group of rules is used for automatic calculations of production line properties based on set of chosen stations. For example, the surface of a product is the sum of the surfaces of its parts, while the productivity of a product is equal to lowest part productivity.
3) Rules for alerts during stage maintenance. These rules are used to alert service teams when the production line is not functioning as it was designed to, using automated data collection from the field.

By implementing the domain knowledge and domain dynamics into one semantic model, a compact overview of the domain functionalities can be gained. The same methodology can be applied for diverse specific use cases and the result will be in a form of novel and practical tools. Finally, the LinkedDesign project developed an ontology inference behaving as online monitoring system that can further act as design decision support system.

3.2. VFF Project[5]

The Virtual Factory Framework (VFF) project (Kádár et al. 2013) aimed at developing an "integrated collaborative virtual environment aimed at facilitating the sharing of resources, manufacturing information and knowledge, while supporting the design and management of all the factory entities, from a single product to networks of companies, along all the phases of the their lifecycles". Semantic Web technologies were adopted to exploit the support for data distribution, data model integration and reasoning. In particular, an ontology-based data model, named Virtual Factory Data Model (VFDM), was developed to formalize the concepts of building, product, process and resource while taking into consideration geometric, physical and technological properties of the factory that are required to support its planning processes (Terkaj et al. 2012). The development of the VFDM aimed at re-using as much as

[5] http://www.vff-project.eu/

possible already existing technical standards for industry, thus trying to favor the interoperability between software tools. The Industry Foundation Classes (IFC) by buildingSMART[6] was the main reference standard adopted for the formalization of the information related to the architecture, engineering and construction. A fragment of the IFC standard available as an EXPRESS schema specification was automatically converted into an OWL ontology (named *ifcOWL*) by exploiting the work by Pauwels (Pauwels 2015). The most recent version of the VFDM consists of the following ontology modules linked by import relations:

- *ifcOWL* module is automatically converted from IFC4 EXPRESS schema (Liebich et al. 2013).
- *ifcOWL_rules* contains class expressions that are added to *ifcOWL* by converting WHERE rules in the IFC4 EXPRESS schema (Terkaj and Sojic 2015).
- *StatisticsOntology* defines basic concepts about probability distributions and descriptive statistics.
- *ifcOWL_extension* that integrates the previous modules and provides general purpose extensions of *ifcOWL*.
- *FactoryDomain* specializes *ifcOWL* with definitions related to products, processes, and production systems.
- *ISO14649-10* represents a fragment of the STEP-NC standard automatically converted into an OWL ontology. The STEP-NC standard is adopted to represent the concepts of workpiece, machining features and operations.
- *DiscreteManufacturingDomain* represents the integration of the *ISO14649-10* and *FactoryDomain* modules and their further specialization for the industrial domain of discrete manufacturing.

The VFDM facilitates the interoperability between various software tools that can exchange data with each other if they are endowed with a specific a software connector taking care of input/output data conversion from the ontology format to proprietary data structures and vice-versa. These software connectors have been developed for commercial and prototype software tools, while addressing various industrial cases, like for example:

- Design of production lines (Colledani et al. 2013). A 3D virtual reality tool for the layout design (Fig.2.a) was integrated with mathematical methods for the design and performance evaluation of production lines.
- Management of a De-manufacturing plant (Colledani, Copani, and Tolio 2014). A monitoring system was integrated with a 3D virtual reality tool (Fig.2.b) to support the synchronization between the real factory and its virtual representation.
- Design of Roll-shop systems (Terkaj, Tolio, and Urgo 2015). A Graphical User Interface (GUI) for the configuration of roll-shop systems was integrated with a commercial Discrete Event Simulation tool to evaluate the performance of the configurations. Furthermore, a 3D virtual reality tool (Fig.2.c) was used both to refine the configuration of the system and also to visualize the dynamic behavior of the system elements based on the simulation runs.

[6] http://www.buildingsmart-tech.org/

Figure 2: Ontology-based 3D virtual representation for a production line design (a), the demanufacturing plant (b), a roll-shop project (c).

3.3. FLEXINET Project[7] – Global Production Network design case study

The FLEXINET project focuses on developing approaches to provide decision support on how to best design and facilitate Global Production Networks (GPN) that can be both flexible and interoperable. One of the main aspects within this approach is the ability to re-configure these networks when considering and introducing new technologies. Production networks can sometimes be spread over vast geographical areas comprised of diverse and divergent organisations. Therefore numerous factors can influence and affect such networks. FLEXINET therefore seeks to apply cutting edge techniques to the assessment of these factors so as to enable rapid re-organisation of those networks by considering potential scenarios where benefits and disadvantages (i.e. costs and risks) can be assessed and the implications those have for configurations of production network systems and how they change over time.

The FLEXINET approach to intelligent production network configuration services consists of three main software services are being actively developed to provide the environment for the assessment of risks, costs against potential network configurations. These are being supported by a reference ontology to enable the consistent representation and usage of product-service production information and knowledge across the platform.

The development of the FLEXINET reference ontology seeks to answer a number of questions concerning ontology development and application:

1. To what extent can a reference ontology be developed to sufficiently represent three different manufacturing sectors?
2. If a reusable reference ontology can be developed, to what extent does it reduce the cost and time of developing information systems?
3. Can a method be developed to specialize concepts from generic to specific levels within a reference ontology?
4. What are the key concepts and relationships that need to be defined within the reference ontology?
5. To what extent can the rules and constraints be defined generally?

A number of use cases have been created to develop answers to a set of key issues raised by each of the three industrial end users. One such use case has been created to focus upon the configuration and assessment of Global Production Networks, it seeks to:

- Define and describe adapted GPN design options.

[7] http://www.flexinet-fof.eu/

- Describe the relationships between products and services.
- Detail potential choices for in-sourcing, out-sourcing, partnerships, logistics and associated restricting factors.
- Offer detailed analysis of the impact of GPN alternatives (by using scenarios).
- Lower process complexity within a GPN design.

The GPN configurator application is illustrated in Figure 3, showing a configuration of a GPN and the relationships between suppliers and producers of products and services.

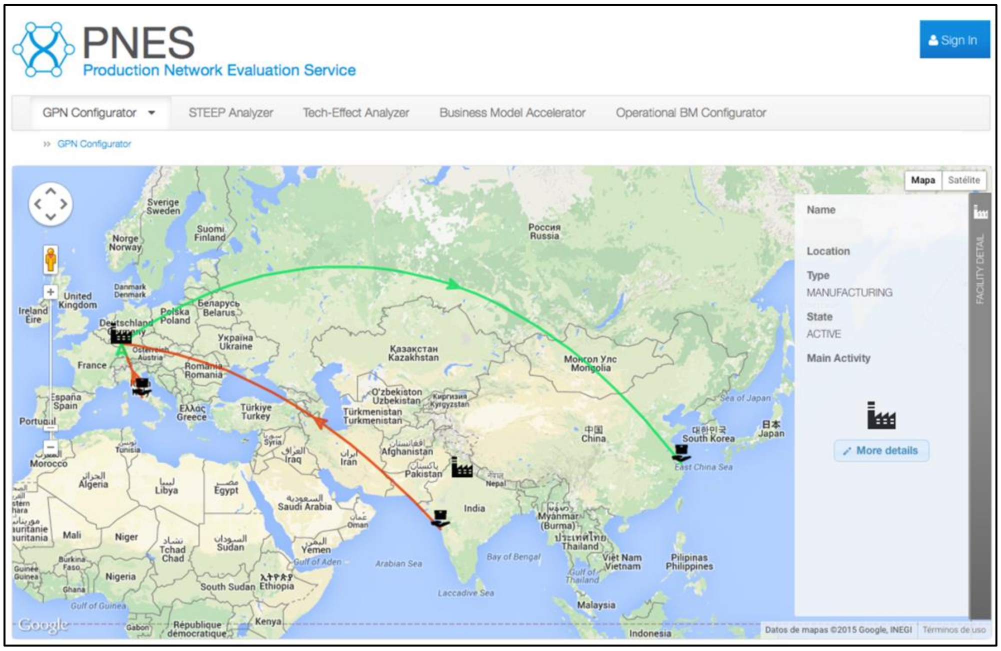

Figure 3: FLEXINET Global Production Network configuration tool.

The entire Global Production Network configuration application is underpinned by the FLEXINET reference ontology (Palmer et al. 2014). This ontology is being developed within the Highfleet[8] software environment using their Common Logic based Knowledge Framework Language (KFL). It has been chosen based upon the view that, due to the complexity of manufacturing environments, an ontological approach is needed to fully support commercial organisations which has the highest levels of expressivity available. Currently, a set of concepts, relationships, axioms and rules have been developed in KFL to form the reference ontology. These are being further developed and tested to support each of the use cases and end user needs within the research project.

[8] http://www.highfleet.com/

4. Motivations, Methods and Tools for applying Ontologies

Why is ontology required? This question is still subject to a lot of controversy in discussions within scientific and engineering communities. In a context where products are often highly complex and constantly evolving, the need for integrating business and technical systems calls for the design and deployment of novel integration framework and approaches for dealing with product information and engineering knowledge. Several motivations are commonly considered for using ontology in engineering problems listed hereafter, but not limited to:

- Solving semantic interoperability issues in close environments where systems, tools and data sources have no common recognition of data type and relationships. Ontologies are used as reference models for schema matching.
- Need for a common and trusted source of engineering knowledge shared by human or/and software agents using ontologies and mechanisms such as Onto Clean, Fuzzy Ontologies, Model verification and validation, Folksonomy, etc.
- Capitalization of engineering knowledge using ontology rules and axioms. Through reasoning mechanisms ontologies support the deduction of implicit engineering knowledge by processing rules using inference engine to generate more complex conclusions.
- Visualization of linked information and data stored in ontologies and represented as foldable trees whose nodes consist of classes and instances provides improved ways of knowledge visualization.
- Separation of domain knowledge from proprietary systems using ontology enables rapid and code-free modifications to applications when business conditions change. This supports the incorporation of domain experts into the implementation and adaptation of the system on a higher level of abstraction.

Three common and potential approaches to ontology features are used in engineering problems. First approach consists of semantic interoperability using upper and domain-specific ontologies. The main reason of having an upper ontology and domain specific ontologies as a top-down approach is to establish a well-defined meaning (semantics) that is consistent across contexts and which can be easily adjusted and adopted for different application domains. The upper ontology is a core meta-model representing a minimum and generic set of concepts and relationships, and which can be considered domain-independent. A domain specific ontology represents a domain-specific description that addresses its particular set of requirements, and should also have the minimum set of concepts and relationships required for describing its determined domain. The addition of domain specific ontologies should have a minimum impact on the upper ontology. Second approach consists in the elaboration of common product data models based on existing technical standards. These standards have some properties and features in common, but are also distinguishable by many remarkable differences. They were designed by different organizations, with different scopes and for different targets. As already mentioned in the background section, various models exist already such as OntoSTEP, PRONTO, OntoPDM, etc. Third approach consists of using reasoning and inference analysis for knowledge discovery. Using forward and backward chaining, reasoning engines are capable of generating new rules and inferring properties of concepts. Various tools and algorithms are being used by the OBE community to build ontologies. These tools are: Protégé and various plugins; TopBraid Composer; Anzo; OSF (Open source Semantic Framework); XKS (Extensible Knowledge Server) and FluidOps a cloud based solution.

5. Conclusion and General Discussion

Ontologies are more and more used in the engineering academic community, but there is still a relevant gap between scientific studies and industrial applications, thus hindering the full exploitation of the ontology potential and even its reputation. Indeed, there is a strong need of more efficient and effective software environments to support the various phases of an ontology-based software tool lifecycle. The development and use of an ontology-based software tool is particularly challenging because it asks for the collaboration between experts in knowledge engineering, ontology engineering, computer science, database management systems, and software engineering.

First of all, real industrial applications require the management of typically large amount of data. This problem was traditionally solved using high-performing relational databases, but it must be re-addressed taking into consideration the specific requirements of ontology storage. In case of OWL ontology, several RDF stores have been developed during the last few years (see Modoni et al. 2014 for a survey on this topic), but a *killer application* is still missing and the available solutions present limitations related to the one or more of the following characteristics: license, operating system, implementation language, repository mechanism and performance, programming language for client connectors, query language, security, versioning, and handling of binary data. Most of the RDF stores offer a SPARQL endpoint that can provide a standard and platform/language independent access to an RDF store, but then the problem is shifted to the development of effective SPARQL clients within an ontology-based software tool.

The development of professional ontology-based tools asks for programming environments that can ease the work of software developers without requiring inordinate expertise on the ontology theory. Several solutions have been proposed during the recent years but, like in the case of RDF stores, a *killer application* is missing. Indeed, very few programming environments provide multi-language support and high-level functionalities to avoid directly handling the basic elements of an RDF graph (e.g. triples, nodes, arcs). Moreover, the semantic web community is historically committed to Java programming language, therefore it is even more challenging to develop ontology-based application in other languages. Finally, it is particularly critical the lack of functionalities to develop a software program based on a specific ontology Tbox; the automatic generation of programming libraries from an OWL ontology is a promising solution to this problem, but again only few prototype implementations are available (e.g. Owl2Java[9] and Protege-OWL Code Generator[10]) and they are limited in their functionalities and usually restricted to Java language.

The possibility to generate new knowledge via reasoning is one the key features of ontology, but also this activity is currently jeopardized by the lack of high-performing reasoning tools and programing libraries. Moreover, OWL language do not support the definition of rules, thus limiting the set of inferences that can be obtained. Semantic Web Rule Language (SWRL) (Horrocks et al. 2004) can be combined with OWL, but SWRL is not yet recommended by W3C even several years after its submission. Furthermore, even if OWL is combined with SWRL, still the reasoning capabilities are affected by the underlying Open World Assumption (OWA) that may represent a strong limitation in practical engineering applications. Therefore, solutions based on Closed World Assumption (CWA) should be further investigated, for

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[9] http://www.incunabulum.de/projects/it/owl2java/
[10] http://protegewiki.stanford.edu/wiki/Protege-OWL_Code_Generator

example taking in consideration Common Logic-based solutions (e.g. Highfleet software environment mentioned in Sect.3.3) or Answer Set Programming technology (Lifschitz 2008).

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