Standards and industrial ontologies as Industry 4.0 enablers

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Abstract. One of the pillars of the Industry 4.0 paradigm is the vertical and horizontal integration of systems and devices that need to interplay in this digital ecosystem. Interoperability is crucial to attain this ambitious goal. It is the ability of systems to transact with other systems to exchange data, services and coordinate activities in a seamless fashion. In the last decades, industry has pursued technical interoperability by developing and adopting standards. More recently, in the context of Industry 4.0 reference architectures have been proposed, which aim at providing a roadmap for the use of standards in smart factories. Despite their success, standards still present weaknesses that are addressed in this contribution along with the drawbacks of some of the reference architectures. So far, our work has mainly focused on standards ISA-88 and ISA-95, but it is currently being extended to other ones. On the other hand, industrial ontologies play a key role in reaching semantic interoperability. Unfortunately, each community assumes that the proper strategy to solve this problem is to create its own ad hoc ontology, thereby recreating the initial problem of data siloes but now at the ontology level. The Industrial Ontology Foundry (IOF) is trying to solve this problem by developing a suite of open and principles-based reference ontologies, from which other domain dependent or application ontologies can be derived in a modular fashion, so that they can be reused in various industrial domains. However, this initiative has other weaknesses, which are described and critically addressed in this work.

Keywords: Industry 4.0, Interoperability, Industrial Standards, Industrial Ontologies.

1 Motivation

Industry 4.0 [1 - 2] refers to a profound transformation process, based on the collaborative use of a wide variety of digital technologies, which affect the entire value chain, as well as its associated products along their entire life cycles. Such transformation allows enterprises to become true digital organizations, which are capable of reacting to customer-centered markets, offering highly personalized physical products that increase their capabilities/ functionalities by incorporating digital interfaces and innovative digital services. One of the pillars of the Industry 4.0 paradigm is the vertical and horizontal integration of systems and devices that need to interplay in this digital ecosystem. In order to fully embrace this paradigm such interaction should be fully achieved. As we move towards Smart Cyber-Physical Systems and the Internet of Things (IoT) ecosystems, millions of devices interconnect among themselves, providing and consuming information available on the network, and become capable of exchanging capabilities and collaborating in order to reach common goals [3]. According to Colombo and co-workers [3], collaboration occurs along three axes: (i) Enterprise axis: from field to the highest business level; (ii) Value chain axis: from suppliers to customers; and (iii) Lifecycle axis: from product design to product support. It should be remarked that these three axes are not independent and collaboration also should involve their interrelation.

The interoperability concept, which is domain specific, is crucial to attain these ambitious collaboration goals [4]. It is the ability of systems to transact with other systems to exchange data, services and coordinate activities in a seamless fashion. It provides two or more business entities – from the same organization or different organizations and irrespective of their location – with the ability of exchanging or sharing information, wherever it is and at any time and of using functionality of one another in a distributed and heterogeneous environment. According to experts there are different levels of interoperability [2]. There is agreement on the following four types: operational, systematic, technical, and semantic. Technical issues (open interfaces, data presentation and exchange, accessibility, and security, etc.) are important and there have been more progress on this topic than on the other ones. In the last decades, industry has pursued technical interoperability, which is syntax-related, by developing and adopting standards. More recently, in the context of Industry 4.0, reference architectures, such as RAMI4.0 and IIRA, have been proposed [3] [5]. They aim at providing a roadmap for the use of standards in smart factories. Despite their accomplishments, standards present weaknesses that are addressed in Section 2 along with the drawbacks of some of the reference architectures.

On the other hand, semantic interoperability assures that the exchanged information is well understood among different groups. Industrial ontologies [6] play a key role to reach semantic interoperability, as they provide the foundation and capability for machines to interpret and infer knowledge from different data sets. Unfortunately, each community assumes that the proper strategy to solve the problem of semantic interoperability is to create its own ad hoc ontology, thereby recreating the initial problem of data siloes, but now at the level of ontology siloes. Several initiatives have emerged to try to solve this problem, which are described, compared, and critically addressed in Section 3. To conclude, the Final Remarks section presents activities that are being pursued to cope with the current limitations of industrial standards and industrial ontologies.

2 Adoption of standards

In relation with Industry 4.0, different standardization committees and organizations exist in various regions of the world, on top of well-established Standards Development Organizations (SDOs), such as IEC, ISO, ISA. The most important consequence of this disparity is the emergence of inconsistencies among standards [5] [7], which are mainly concerned with semantic issues, as pointed out by Vegetti and Henning [8] regarding the ISA-88 and ISA-95 standards. In an effort to address inconsistencies in a systematic way, Melluso et al. [5] have identified six groups of Semantic Interoperability Conflicts (SICs): Domain (SIC1), Schematic (SIC2), Granularity (SIC3), Representation (SIC4), Missing Item (SIC5) and Language (SIC6). The detection of these conflicts can be manually done by domain experts, which also need to be have a strong foundation on ontologies. Professionals having these two types of abilities are quite uncommon in practice. Currently, the author is expanding the work done so far [8], according to the guidelines given in [5]. Since the detection process is quite tedious and time consuming, automatic methods have been proposed to harmonize standards [5]. However, to effectively resolved the identified SICs, the proposed harmonization needs to be understood, agreed and adopted by the involved professional committees, which is something that is still far from reality.

3 Industrial ontologies

The development and usage of industrial ontologies is particularly challenging due to variety of reasons. One of the most significant ones is the lack of adherence to Ontology Engineering (OE) principles. The lack of application of OE principles has handicapped the community in making far more substantial contributions. Among others, the most important weaknesses are linked to the lack of an evaluation stage. Work done so far shows how aspects like content, structure, syntax, and semantics can be properly analyzed by adopting suitable methodologies/tools. Furthermore, there is an important trend taking place in the industrial ontology domain, which attempts to avoid the existence of ontology siloes and promotes reusability. It refers to efforts, like the IOF (Industrial Ontology Foundry), which are related to the development of a suite of open and principles-based reference ontologies, from which other domain dependent or application ontologies can be derived in a modular fashion, remaining 'generic' (i.e., non-proprietary, non-implementation specific) so they can be reused in various industrial domains [9]. Reusing existing ontologies offers benefits such as improving the reliability of ontology development and avoiding redundant modeling of overlapped concepts. To avoid this last weakness, the IOF ontologies are based on a well-known upper level ontology, the Basic Formal Ontology (BFO) [10].

The IOF organizes itself around various Working Groups (WGs). A first analysis shows that the ontologies developed so far are mainly focused on discrete manufacturing industries, leaving aside enterprises having batch and continuous processes. Certain discrete manufacturing oriented developments cannot be extended to batch and continuous process environments. Due to the extremely wide scope of the IOF project, it has been recommended that the IOF ontologies should be extended to specific subdomains. Another limitation that was found is the natural overlapping among the ontologies developed by several WGs. This weakness could be associated with limited interactions among the WGs. Finally, another drawback is the lack of incorporation of knowledge associated with well-accepted industrial standards.

4 Final Remarks

It can be concluded that most standards have been devised by well-established SDOs by gathering the knowledge and efforts of thousands of professional practitioners having a lot of experience in their particular fields, but lacking background on semantic aspects. Unfortunately, when certain standards were developed, the focus was narrowed to very specific subdomains and syntactic issues were privileged over semantic ones. For example, ISA, has developed standards having various SCIs, such as ISA-88 and ISA-95 [8]. Overcoming these problems is one of the goals being pursued in this work, but it still demands a lot of efforts. The Industry 4.0 paradigm is quite complex and has strong differences in continuous, batch, and discrete manufacturing domains.

From the industrial ontologies perspective, the IOF [9] seems to be the most promising initiative [11]. However, it requires WGs being organized around the joint participation of professionals having real-world experience along with ontologists. The author contributes to several IOF WGs and has noticed this limitation, in addition to the lack of interaction among the different WGs, as well as the limited consideration of industrial standards knowledge. The ongoing work is addressing these issues.

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