On the Use of Description Logic for Semantic Interoperability of Enterprise Systems

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Abstract. With the growing advances in computing and communications technologies, the concept of system-of-systems (SoS) becomes widely recognized as it offers potential benefits and new challenges. Relevant perspectives related to SoS constitutes nowadays an active domain of research, among them those issues concerning the need of full interoperation. When it is related to enterprise information systems, the SoS paradigm may then be derived to a form of System-of-Information Systems (SoIS). This paper presents an overview of the features of the interoperation in SoIS and proposes guidelines to evaluate and formalize it in order to identify semantic gaps between information systems concepts and models. It provides, through an example, an approach to use Description Logic for evaluating semantic interoperability concerns.

Keywords: System-of-Systems, Information Systems, Semantic Interoperability, Description Logic, Ontology.

1 Introduction

Today's needs for more capable enterprise systems in a short timeframe are leading more organizations toward the integration of existing component-systems into broader intra-organizational or inter-organizational enterprise-systems. The remaining challenge of enterprise integration (EI) is to provide *the right information at the right place at the right time for decision-making* by integrating these heterogeneous information-intensive product-systems to achieve vertical business-to-manufacturing as well as horizontal business-to-business integration [1]. Advances in information technologies (IT) facilitate the implementation of applications interoperability but are not efficient to support the single enterprise as well as the networked enterprise to move from tightly coupled systems based on enterprise application integration (EAI) to loosely coupled systems based on service-oriented architectures (SOA) [2].

The *integration in manufacturing paradigm* (CIM concept) which underlies the global optimality of a monolithic enterprise-system fails to face this evolution, mainly because the related modelling frameworks are not appropriate to solve problems that continually change as they are being addressed. The *intelligence in manufacturing*

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paradigm (IMS concept) which is addressing the complexity to architect heterarchical enterprise-systems has difficulty to demonstrate its efficiency in real industrial environment [3], mainly because of the lack of a modelling framework to define, to develop, to deploy and to test self-organizing systems [4]. These integration issues are not handled well in traditional systems engineering templates (SE) because of the increasing complexity to architect enterprise-systems as a whole for each opportunistic collaboration; this from the bottom set of heterogeneous component systems to the system-of-systems (SoS) that emerges from their relationships, while they continue to exist on their own missions [5].

We agree that *the essence of enterprise integration is the recursively interoperation of constituent systems to compose a system to achieve a specific purpose in a given context* [6].

The related interoperability relationship can be implemented in several ways to compose a fully, tightly or loosely integrated system or a SoS depending on the adaptability of the constituent systems and the assigned mission [2]. Bridging the gap from an integrated system to a system of interoperable systems underlies knowledge-intensive organizational and cultural issues beyond technological ones, requiring multi scale modelling frameworks to cope with the limitations of human abilities to face complexity [7]. Many definitions are being amended with a number a required properties [8][9] to make SoS a candidate rationale artefact to distinguish a very large and complex socio-technical system of interoperable enterprise-systems from a monolithic non-SoS [10]. However, when it is related to enterprise information systems, the SoS paradigm may then be derived to a form of System-of-Information Systems (SoIS) where each heterogeneous information system has to semantically interoperate to ensure the whole enterprise performance.

Semantic interoperability aims at ensuring that the meaning of the information that is exchanged is correctly interpreted by the receiver of a message. In centralized systems, this property improves the relevance of query answers. In distributed heterogeneous systems, such as systems-of-systems, it is compulsory to enable autonomous heterogeneous sources understanding each other to obtain relevant results. To provide semantic interoperability within a system, much research has been conducted on semantic representations. The main idea is to use meta-information which eases the meaning understanding. This approach needs the definition of ontologies which describe the concepts and relations between them, for a given domain. During the last fifteen years, much effort has focused on formal methods to describe ontologies, resource description languages, reasoning engines... All these methods represent the foundations of the semantic web. However, many works rely on the assumption that a single ontology is shared by all the participants of the system. Indeed, in systems-of-systems comprising autonomous sub-systems, this assumption is not realistic anymore. On the contrary, one has to consider that the sub-systems create their ontologies independently of each other. Thus, most often ontologies differ, more or less, even if they are related to some common concepts. The main issue is then, at least to detect and, even more, to formally identify the semantic gap arising when two heterogeneous systems, sharing common concepts, interoperate. Formalizing the semantic match between two information system models is still a first open issue. Then, in this context, scientifically founding the interoperation process towards a science of interoperability implies, at a first step, defining some metrics and a scale, in order to evaluate, quantitatively and better qualitatively, the maturity of this interoperation process.

This paper aims to sketch some issues in studying semantic gaps between information systems concepts and models coming from heterogeneous interoperable systems, in a SoIS context, with a tentative formalization of those concepts using Description Logic. After highlighting the need of interoperability formalization in SoIS and showing the relevance of Description Logic (DL) as a candidate for a formalization tool in section 2, a methodology to formalize interoperability in SoIS is proposed in section 3. Finally, in section 4, this methodology is illustrated through a particular SoIS: the enterprise systems in the domain of manufacturing applications.

2 Ontology and Semantic Interoperability

2.1 Semantic Interoperability

With the increasing complexity of Information Systems (IS) and mainly the evolvement of these IS from integrated systems to a system of interoperable ones, the need to achieve the interoperation becomes a critical issue in the research domain of information systems integration [11]. Interoperability is typically defined as *the ability of two or more systems or components to exchange and use information* [12]. Integration is generally considered to go beyond mere interoperability to involve some degree of functional dependence [13]. Many researches are trying to demonstrate that semantic interoperability can be enabled through setting up concepts via Ontology. The use of ontology is required as it acts as *a conceptual model representing enterprise consensus semantics* [14]. It aims at reducing the semantics loss among heterogeneous information systems that are sharing mostly common concepts from the same area of knowledge. Furthermore, ontology provides a common understanding and a formal model of the basic entities, properties and relationships for a given domain that are essential to overcome semantic heterogeneity. Generally, ontology is expressed with logic based languages; we can quote the first-order logics, the rules Languages, the non-classical logics and the Description Logics. All these languages are characterized by a formal specification of the semantics that allows expressing structured knowledge in one hand and promotes the implementation of reasoning support in the other hand.

In this paper we will attempt to use Description Logics that is one of the knowledge representation (KR) formalisms which allows modelling *the application domain by defining the relevant concepts of the domain and then using these concepts to specify properties of objects and individuals occurring in the domain* [15].

Description logics can be considered as a variant of first-order logic (FOL) as it borrows the basic syntax, semantics and the proof theory necessary to describe the real word. The choice of Description Logics can be justified by the fact that we do not need all the full power of FOL in term of knowledge Representation to achieve a correct level of expressiveness [16]. Description Logics are mainly characterized by a set of constructors that allow building complex concepts and roles from atomic ones. Besides, concepts correspond to classes and they are interpreted as sets of objects otherwise, roles correspond to relations and are interpreted as binary relationships on objects. We present in Table 1 the basic constructors and their interpretation Δ^I.

Table 1. The basic DL constructors

Constructor	*Syntax*	*Semantics*
atomic concept	A	$A^I \subseteq \triangle^I$
atomic role	R	$R^I \subseteq \triangle^I \times \triangle^I$
conjunction	$C \sqcap D$	$C^I \cap D^I$
disjunction	$C \sqcup D$	$C^I \cup D^I$
negation	$\neg A$	$\triangle^I$ - A
existence restriction.	$\exists$ R.C	$\{x \mid \exists y.<x, y> \in R^I \wedge y \in C^I\}$
value restriction.	$\forall$ R.C	$\{x \mid \forall y.<x, y> \in R^I \Rightarrow y \in C^I\}$
universal concept	T	$T^I = \triangle^I$ (the set of all individuals)
bottom concept	$\perp$	$\perp^I = \varnothing$ (the empty set)

Description Logics allow mainly to represent knowledge and logic reasoning through different inference engines such as Racer[1], Pellet[2], FaCT++[3]...

2.2 Ontology for Semantic Interoperability

To overcome the problem of semantic interoperability, there already exist some techniques; one solution is to use ontology mapping that consists in finding semantics correspondences between concepts from two given ontologies. Mapping is defined by [17] in this way: *Given two ontologies O1 and O2, mapping one ontology with another means that for each concept (node) in ontology O1, we try to find a corresponding concept (node), which has the same or similar semantics, in ontology O2 and vice versa.* Other but similar definitions are given by [18]. Formally an ontology mapping function can be defined in the following way [19]:

- *map:* $O_{i_1} \rightarrow O_{i_2}$
- *map*$(e_{i_1 j_1}) = e_{i_2 j_2}$, if $sim(e_{i_1 j_1}, e_{i_2 j_2}) > t$ with *t* being the threshold

  entity $e_{i_1 j_1}$ is mapped onto $e_{i_2 j_2}$; they are semantically identical, each entity $e_{i_1 j_1}$ is mapped to at most one entity $e_{i_2 j_2}$

  Where:
- O_i: ontology, with ontology index $i \in \mathbb{N}$
- $sim(x, y)$: similarity function
- e_{ij}: entities of O_i, with $e_{ij} \in \{C_i, R_i, I_i\}$, entity index $j \in \mathbb{N}$
- $sim(e_{i_1 j_1}, e_{i_2 j_2})$: similarity function between two entities $e_{i_1 j_1}$ and $e_{i_2 j_2}$ $(i_1 \neq i_2)$

[1] http://www.racer-systems.com/
[2] http://clarkparsia.com/pellet/features/
[3] http://owl.man.ac.uk/factplusplus/

Automatic or semi-automatic mapping may use some mapping tools such as FCA-Merge [20], IF-map [21], GLUE [22], COMA++ [23]. These automatic or semi-automatic mapping tools achieve accurate mapping results under the conditions of two ontologies defined in natural-language descriptions which are at the conceptual level. Most researchers [24] agree that automatic mapping between ontologies is important and critical for ontology integration for exploiting semantic relationships between ontologies, such as, the semantics of the subclass-of or part-of relationships, attachment of a property to a class, domain and range definitions for properties and so on. Thus, for higher abstraction level concepts, it is quite hard to automatically detect the semantic relationships.

When it is the case, another approach consists in using a top ontology and providing mapping between these high abstraction level concepts and the concepts of the top ontology [25]. Several suggestions for such Top Ontologies have been studied, for example: DOLCE[4], BFO[5], Cyc[6] and so on. This kind of upper ontology formalizes general or high level concepts such as processes, time, region, physical objects, and the semantic relationships of these notions. Our goal is then to provide a domain-specific ontology extending a selected Top Ontology. In the next section, we adapt this approach when ontologies are formalized with Description Logics.

3 Proposed Methodology for Semantic Interoperability

In the case of SoIS, when two (or more) heterogeneous information systems IS1, IS2… have to communicate by exchanging data based on ad-hoc models, we propose an approach for formalizing the semantic gap that occurs between those heterogeneous models. We are basing this formalization on ontology representation. The first step is analyzing the two ontologies O1 and O2 that are already created by conceptualising the different information systems IS1, IS2... Despite the fact that they share some concepts, those ontologies differ by their terminologies. Establishing mappings between these two ontologies represents a first issue and we propose to put it in practice in order to evaluate the semantic relationships between two ontologies in the frame of SoIS as shown in Fig. 1.

We assume that, in the same domain, two communities desire to share knowledge but each one has encoded knowledge according to its own local ontology O1 and O2 defined by concepts, axioms, and instances. The approach as shown in Fig.1 is defined as following: Let O1 and O2 be the local ontologies formalising the local domain of expertise. In order to compute some concepts mapping between O1 and O2, we must include an upper ontology U3. We are then mapping the relations over (O1, U3), (O2, U3). Then, a DL reasoner would be able to infer logical relationships over (O1, O2) from a set of asserted facts or axioms of (O1, U3) and (O2, U3): (O1, U3), (O2, U3) → (O1, O2).

However in order to get sound reasoning results between O1, O2, there must be some restrictions about the “upper ontology”. It must previously agree upon a

[4] http://www.loa-cnr.it/DOLCE.html
[5] http://www.ifomis.org/bfo
[6] http://www.cyc.com/

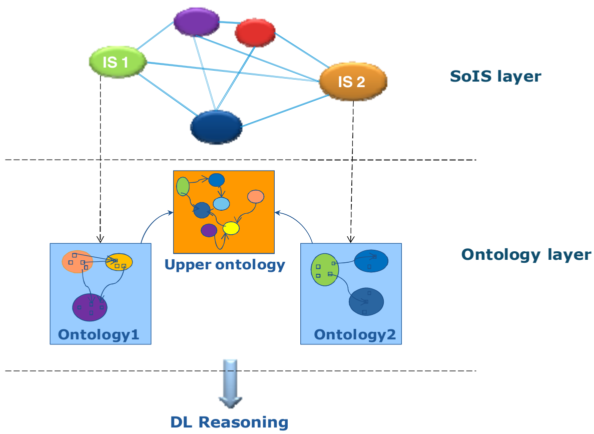

Fig. 1. Proposed approach

common understanding, in order to favour the sharing of knowledge. The "upper ontology" must be well-defined, expressive enough. A standard upper/top ontology can serve as the upper ontology here. We will talk about it in 4.2 in detail. We must notice that it is necessary that the reasoning result should be validated by domain experts.

4 Use Case

4.1 An Overview of the Context

Let us now illustrate the methodology proposed in section 3 on a particular system-of-information systems: the product manufacturing systems. Actually the increasing complexity on information flows on the one hand, and the distribution of the information in the whole supply chain on the other hand, had lead enterprises to use a lot of heterogeneous software applications like APS (Advanced Planning and Scheduling system), ERP (Enterprise Resource Planning), MES (Manufacturing Execution System), SCM (Supply Chain Management), PDM (Product Data Management)… to name only a few. Thus, all the enterprise systems have to interoperate to achieve global performances for the full manufacturing processes. In [26], it is suggested and we agree that it is the customized product which must drive the interoperability relationship in the manufacturing process. In this paradigm, the product is seen as an information system that embeds the information about itself and that is able to communicate with the software applications in order to be manufactured. [11] shows that when an "active product" interoperates with other enterprise systems, then the emerging system, with its own new mission, can be assimilated to a System-of-Information Systems. In the context of information exchange related to product data models, some efforts have already been made to facilitate enterprise applications interoperability. We can notice two standardisation initiatives: the IEC 62264 set of standards [27] and the ISO 10303 STEP PDM technical specifications [28]. These standards try to solve the problem of managing heterogeneous information coming from different systems by formalising the knowledge related to products technical data [29]. The first one *provides standard models and terminology for defining the interfaces between an enterprise's business systems and its manufacturing control systems* [27]. This standard defines concepts and models related to the product at the business and the manufacturing levels of enterprises (B2M). Applications interested by this standard are for example ERP systems at the business level and MES systems at the manufacturing level. The second one *aims to provide a neutral mechanism capable of describing products throughout their lifecycle* [29]. Applications interested by this standard are for example Product Data Management (PDM) systems or Computer Aided Design (CAD) systems. Together, the two standards are covering most information characterizing products and their related enterprise processes. They have been developed on the basis of a consensual expertise and, thus, may be considered as domain ontologies embedding domain knowledge with a high level of abstraction. Thus, in this context, the proposed methodology (see section 3) is relevant to study the interoperability relationship between enterprise information systems in the domain of manufacturing applications, through the existing standards.

4.2 Application of Proposed Methodology

In the SoIS layer, we consider information systems IS1 and IS2. The IS1 is based on IEC 62264 set of standards while IS2 is based on the standard ISO 10303 STEP-PDM. Our approach is developed within two phases.

- **Phase 1: Ontology Formalization of the Standards**

Using DL to formalize the concepts and axioms of IEC 62264 and ISO 10303 STEP-PDM can be done manually or semi-automatically. In order to build a knowledge representation manually, some steps must be followed during its design. It is significant that we must firstly make a list of elements of the domain and then distinguish which will become concepts, roles or individuals. Then we need firstly to define the classification of all the concepts and roles for identifying classes, sub-classes and roles, sub-roles and, then to develop concept axioms. We use Protégé[7] to develop the ontologies of both IEC 62264 and ISO 10303 STEP-PDM. Concerning semi-automatic transformation from the standard language to ontology, there exist several tools helping at generating, at least, the taxonomy of the concepts. One must then develop, manually, the related axioms defining the ontology constraints. Starting from the UML representation of the conceptualised Material model, derived from the IEC 62264 [29], the semantics of the modelling concepts, informally defined in the standard, have been formalized by DL axioms as shown on Table 2.

[7] http://protege.stanford.edu/

Table 2. Some of the important axioms of concepts in IEC 62264 material model ontology

MaterialClass	$\sqsubseteq \forall$ define_a_grouping. MaterialDefinition
MaterialClass	$\sqsubseteq \forall$ hasTestedMaterialClassProperty.
TestedMaterialClassProperty	
MaterialClass	$\sqsubseteq \leq 1$ part_of. MaterialInformation
MaterialClassProperty	$\sqsubseteq \forall$ hasValue.Value
MaterialClassProperty	$\sqsubseteq =1$ TestedMaterialClassProperty.TestedMaterialClassPropety
MaterialDefiniton	$\sqsubseteq \forall$ define_a_grouping^{-1}.MaterialClass
MaterialDefintion	$\sqsubseteq \forall$ defined_by. MaterialLot
.....	

The semantics of the some modelling concepts, informally defined in the ISO STEP-PDM standard models, have been formalized by DL axioms as shown on Table 3.

Table 3. Some important axioms of concepts in ISO 10303 ontology

Product_relationship	$\sqsubseteq \exists$ relating_product $^{-1}$.Product
Product_relationship	$\sqsubseteq \leq 1$ (relating_product $^{-1}$. Product) $\sqcup$ (related_product $^{-1}$. Product)
Product_relationship	$\sqsubseteq \exists$ related_product^{-1}.product
Product	$\sqsubseteq \forall$ Product_relationship.Product
Product	$\sqsubseteq \forall$ hasDescription.Description
Product	$\sqsubseteq \forall$ HasProduct_Category. Product_Category
Product	$\sqsubseteq \leq 1$ HasProduct_Version. Product_Version

For both the standards ISO and IEC, concepts, roles, axioms, properties were then formalized using DL. We have got two disjoined ontologies in term of concepts. But, they are sharing the common knowledge related to any manufactured product. Among those Top Ontologies that contain highly abstract concepts, we propose to use DOLCE.

- **Phase 2: Using the Top Ontology: DOLCE**

DOLCE is a Descriptive Ontology for Linguistic and Cognitive Engineering. It has clear cognitive/linguistic bias, in the sense that “it aims at capturing the ontological categories underlying natural language and human commonsense”. This is promoted with a rich axiomatisation, with at least 37 basic categories and 7 basic relations and 80 axioms and 100 definitions and 20 theorems. The idea of our work is to perform the mapping of the two standard ontologies in a consistent way with respect to the definitions of concepts formalized in DOLCE. This should allow finding correspondences between the concepts of ISO and IEC. Practically, it is impossible to achieve reasoning based directly on the DOLCE axiomatisation. We experiment semi-automatic reasoning (using an inference engine) by deriving DOLCE axioms to formalize our standard ontologies. We were not able to achieve any practical results as the concepts of the Top Ontology are too abstract for a practical use in engineering applications. The relevant solution would consist on designing a Top-Domain

Ontology that *holds the generic core classes of a given domain to interface both domain and top ontology* [30]. So mapping the Top-Domain ontology to DOLCE would facilitate a better understanding and clarification of the given domain.

Some efforts in our case domain (manufacturing) are already carried out to create a Top-Domain Ontology formalizing the technical data related to any manufactured products. In the literature, this is also called Product Ontology. We can quote two significant ones: (i) PRONTO (Product ONTOlogy) [30], ad-hoc ontology that focuses mainly on product structural information and (ii) a Product Ontology proposed by [29] based on existing standards and supporting the definition of product technical data. Independently of the terminologies involved in those two Product Ontology, it is primordial to point out that both share almost the main concepts related to the product. For instance, PRONTO suggests some concepts like Product family, Product, Property, Variant family…, that have correspondences on the other Product Ontology as the following: MaterialDefinition, MaterialClass, MaterialDefinitionProperty and so on.

We claim that the coherent way for applying our approach consists on (i) mapping a Product Ontology to the DOLCE Top ontology, and (ii) mapping each of the two domain ontologies to the Product Ontology. We present in the following

Table 4. Some Product Ontology concepts mapped on DOLCE Top classes

Concepts	*Axioms*	*DOLCE*
Material	$\sqsubseteq \forall$is _member_of. VariantSet	Physical Endurant
SimpleProduct	$\sqsubseteq$Material $\sqcap$ (RawMaterial $\sqcup \neg$ composed_of.T)	Physical Object $\sqcap\neg$atomic_part.T
ComplexProduct	$\sqsubseteq \geq$1 composed_of. SimpleProduct	Physical Object $\sqcap$ Atomic_part_of.T
MaterialClass	$\sqsubseteq \exists$ is _member_of^{-1}.VariantSet	Non Physical Endurant

5 Conclusion

The focus of this paper is mainly to formalize interoperability relationships between heterogeneous Information Systems, from which emerges a so-called Systems-of-Information System. The evolution of the interoperation complexity between existing enterprise and component systems asks the question about the science foundation of the interoperability domain. Current approaches to semantics interoperability for Enterprise Integration issues are examined as a first step to define such foundations. Nevertheless, these solutions are not sufficient when the number of relationships expands because of ad-hoc interfaces and specialised models that do not take into account existing standards. In this paper, we propose a new approach for studying the semantics gaps between existing information models, based on the formalization of domain ontologies with the expertise coming from standards of the domain. We proposed an approach to formalise, using Description Logic, such ontologies with regards to the DOLCE Top Ontology, through a Top Domain ontology (our Product Ontology) that *holds the generic core classes of our given domain to interface both domain and top ontology* [30]. Current work aims to scientifically found the interoperation process by defining some metrics and a scale, in order to evaluate, quantitatively and better qualitatively, the maturity of this interoperation process. To some extent, the work presented in this paper is a first step in contributing to the definition of a Science for Interoperability.

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