A Preliminary Method to Support the Semantic Interoperability in Models of Manufacturing (MfM) Based on an Ontological Approach

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Abstract. The product design and manufacturing complexity have been increased in the last few years. This has challenged the manufacturing industry to rationalise different ways of bringing to the market novel products in a short lead-time with competitive prices while ensuring higher quality levels and customisation. Design and Simulation systems bring to the product developer experts an abstraction required for the design of complex products. However, for a complex product manufacturing process has required simultaneously collaborations with multiple groups, producing and exchanging information from multi-perspectives within and across institutional boundaries. Thousands of different information must be exchanged across heterogeneous systems. Semantic interoperability obstacles have been identified in view of the information heterogeneity from multiple perspectives and their relationships across different phases of product manufacturing. In this context, this paper presents a preliminary method for Models for Manufacturing (MfM) to support the semantic interoperability across the manufacturing system based on reference ontologies, application ontologies and semantic rules. The MfM has been modelled in reference ontologies and specialised to perform multiple specific applications according to the product to be manufactured. Semantic rules are used to share, convert or translate information from multiple perspectives in order to infer the relation between multiple manufacturing levels. The main research contributions are: (i) the intelligence structuring information in elementary concepts responsible for representing the MfM, modelled in the core ontologies (Reference Ontologies) and (ii) the improvement of information exchanging (translation, conversion and sharing) from heterogeneous domain across different phases of manufacturing process based on the semantic rules.

Keywords: Models for Manufacturing (MfM) · Semantic interoperability · Reference ontologies · Semantic rules

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1 Introduction

Currently, in the aerospace industry, the 3D definition of the product using PLM, CAx tools and MBSE models are in a huge improvement in the Functional Design processes [1]. Additionally, globalization has impulse a new trend in the Product Development Process (PDP) through the creation of business collaborative and/or cooperative alliances between enterprises [2]. However, across the manufacturing system, despite the use of ERP, PLM, MES CAx tools and bespoke tools that has been improved along the last years, information and knowledge sharing across the product design and manufacturing systems are still undergoing [1].

This trend requires new methods to share information in an efficient way, without misinterpretation and mistakes. The traditional ERP, PLM, MES, CAx approaches is often hindered by the lack of clarity, multiples taxonomy and structures used by different designers, engineers and other stakeholders. Thus, thousands of heterogeneous information and knowledge must simultaneously share across different phases of the manufacturing system [3–5]. The information and knowledge sharing, therefore, presents two main problems that are known as semantic heterogeneity, (i) the same term is being applied to different concepts (semantic problem) and (ii) different terms are being applied to the same concept (syntax problem) [6].

The solution to this problem lies in addressing interoperability issues [7, 8]. Interoperability is the capacity of two or more systems to share information and to use the information that has been shared [9]. The European Commission [10] classifies interoperability, according to the typology, in three major categories: (i) technical interoperability, (ii) semantic interoperability and (iii) organizational interoperability. Technical interoperability concerns technological issues as data format and protocols, computational connections, etc. Organizational interoperability concerns the sharing of business models and processes as organization structure, business cooperation, etc. Semantic Interoperability concerns the information meaning that is proper and understandable by different systems (human, computer, machine, etc.). According to this definition, the misinterpretation and mistake issues across the product development cycle is a typical problem of semantic interoperability.

Related works [11, 12] present different approaches to support semantic interoperability through the ontology. Ontology is defined as a formal, explicit specification of a shared conceptualization [13]. In this definition, the formal model indicates that ontology isthis research, showing the essential methods and tools machine-readable, that is, the format of the ontology can be understood and processed by computers. Furthermore, ontology-based models have had an increase in their role of achieving semantic interoperability among the different stakeholders across the manufacturing systems. Nonetheless, the process of integrating and interoperating across several ontologies is still a difficult one as physical and logical differences among information sources complicate information retrieval and formalization. Even though ontology mapping and matching techniques were developed to tackle the issues of cross-ontology interoperability, they remain weak in their ability to enable relationship formalization and verification in the cross-model approach for the product design and manufacture.

In this context, this paper presents a preliminary method for Models for Manufacturing (MfM) to support the semantic interoperability across the manufacturing system based on reference ontologies, application ontologies and semantic rules. The MfM has been modelled in reference ontologies and specialized to perform multiple specific applications according to the product to be manufactured. Semantic rules are used to share, convert or translate information from multiple perspectives in order to infer the relation between multiple manufacturing levels. Moreover, the main research contributions are: (i) the intelligence structuring information in elementary concepts responsible for representing the MfM, modelled in the core ontologies (Reference Ontologies) and (ii) the improvement of information exchanging (translation, conversion and sharing) from heterogeneous domain across different phases of manufacturing process based on the semantic rules.

2 Problem Statement

Product Development Process (PDP) is used to speed up the new product launching and markets expansion while fulfilling the costumer's demand and desires. PDP has a holistic view and provides the necessary information to the different stages of product development and manufacturing. However, semantic problems can be identified across the PDP as the developers do not use the same product taxonomy, which may cause requirements misinterpretation and mistakes during the product realisation due to the information heterogeneity [2]. In this context, the research focused on the information and knowledge formalisation to support the development of a conceptual framework to provide seamless information interoperability across multiple domains in the PDP [3, 8, 12].

Semantic Interoperability issues become a significant problem as the activities of the design and manufacture cost 85% of the products final cost [12]. Therefore, the information sharing across the different stages of product development and manufacture must be done efficiently to ensure that the product developed has the desired quality with cost and time optimization.

For a complex product manufacturing process has required simultaneously collaborations with multiple groups, producing and exchanging information from multi-perspectives within and across institutional boundaries. Figure 1 illustrates the semantic interoperability obstacles which have been identified in view of the information heterogeneity from multiple perspectives and their relationships across different phases of product manufacturing. During the product design, manufacturing and production of aerospace, the information must be shared with multiples experts by different systems in across multiples phases (design, manufacturing and production).

The standardized and formalised knowledge that is captured by an ontology-driven system allows it to be retrieved, shared and reused in different stages of the product development and manufacture and, also, through the process of relating concepts made in the ontology design the information can be captured in its entirety as well as extended as the need arises. This system capability improves the collaboration in a multiple domain environment and across network based designs as it conveys several characteristics, that are often ambiguous, in a non-ambiguous manner, while the high degree of expressiveness of an ontology-driven structure enables the establishment of resolvable and meaningful

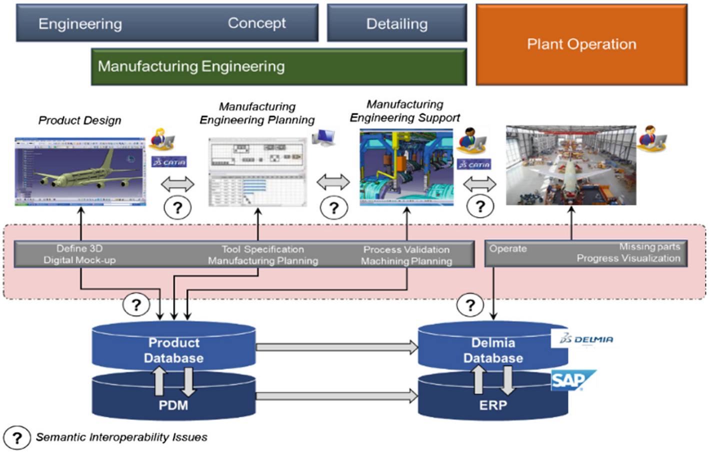

Fig. 1. Product design, manufacturing and production interdependency.

mappings across knowledge models which help support the consistency of the ontology matching while also avoiding the drawbacks of subjectivity in the mapping transaction that are a consequence of extensive human intervention.

3 Technological Background

This chapter shows the literature review responsible for the presentation of the necessary concepts to the development of this research, showing the essential methods and tools for the completion of the research. The topics approached in this review are: Semantic Interoperability and Concurrent Engineering.

3.1 Models for Manufacturing (MfM)

MfM is an approach proposed by the authors to apply Model-Based Systems Engineering (MBSE) concepts to Manufacturing [1]. Functional and data models have been published and deployed using data structures available from commercial PLM systems [14].

Some related works [15–17] are exploring the development and deployment of MBSE methodologies and tools in manufacturing systems. Some recent research topics address aspects like process planning, human resources, robotics, IoT (Internet of Things).

The MfM proposed in [18] is based on 3-Layers Model, Data Layer, Ontology Layer and Service Layer. The Ontology layer defines (i) Scope model, (ii) Data model, (iii) Behaviour model, and (iv) Semantic model, to further instance information from existing databases [18]. Scope model is required because manufacturing systems have a large and wide part of the artefact lifecycle. Data model covers different several uses across the manufacturing systems. As discussed in (Mas), software architecture to support the methodology is being developed using Free and Open Source Software (FOSS) tools. A PLM tool, ARAS Innovator [19], is the core of the system. Other tools like IDEF0 [20] and CMap [21] are used by [1] as modelling tools.

3.2 Ontology-Driven Semantic Interoperability

Even though the product development process presents a holistic approach to provide the necessary information to the different phases of the product design and manufacturing, it has been identified misinterpretations and mistakes during the latter stages of the product development [12]. The information sharing across the different stages of product development and manufacture must be done efficiently to ensure that the product developed has the desired quality with cost and time optimization.

This is a semantic interoperability issue for which the meaning associated with the captured information must be shared across different domains inside a system without any loss of meaning and intent during the exchange process [8]. The most common method to ensure that there is no loss of meaning in the information exchange process has been the definition of common information models [22]. In this context, the construction of ontologies is a viable solution on the formalization of these common information models and on the sharing of the formal information throughout the stages of the product development process, which, consequently, provides increased knowledge in the domains of application [23].

An Ontology is defined as "a lexicon of specialized terminology along with some specification of the meaning of terms on the lexicon" [24], where the lexicon is the vocabulary of a knowledge domain. The use of ontologies is restricted to the purpose of its application, that is, the knowledge structure formalized in an ontology has little reusability outside the scope of its application [8]. Despite the semantic formalism created using ontologies, a limitation appears when the need to work in multiple knowledge domains is presented, as the semantic formalism of the ontology cannot ensure the sharing of the information and its meaning through different domains. However, this problem is moderated with the development of ontology mapping methodologies, which can create relationships between terms in different ontologies of different domains [25].

The Web Ontology Language (OWL) relies only on description logic, however, both description logic and rules are required for a semantic web application because they can overcome expressiveness limitations through extensions of different knowledge domains. Nevertheless, each paradigm supports specific reasoning services and for them to work efficiently there is a need to close integration between the description logic and semantic rules [2].

3.3 Concurrent Engineering in Manufacturing Systems

The intensification of the economic competitive environment due to globalization has put more pressure on the industries to release new products to the market. This happens because an industry long time survival in this environment is made through new products, that is, in order to maintain its competitiveness, it is necessary to the industry to develop and release new products. Therefore, in the last decades, tools and methodologies to increase the efficiency and reduce the cost and time of the product development process have been developed [26]. The author uses as an example of these methods the Lean Product Development, which uses the concepts proposed by the Toyota Production System and applies them in the stages of the product development, and Concurrent

Engineering, which aims to parallelize the tasks of the product development in order to reduce costs and time.

In this context, the objective of [26] is to create a lean product development environment through the application of concurrent engineering. According to [26] and [27], concurrent engineering happens when the development team think, communicate and search solutions in a parallel way, that is, the development team communicates through the stages of the PDP searching for solutions as soon as they can identify a problem. [28] assesses the application of concurrent engineering in the Toyota enterprise and made a comparison between the parallel and sequential product development.

4 Interoperable Manufacturing System Method Concept

The Interoperable Manufacturing System method proposed in this research uses two main approaches: (i) Models for Manufacturing (MfM) approach proposed by [1]; and (ii) the Interoperable Product Design and Manufacturing System (IPDM) proposed by [29]. The MfM approach considers 3-Layers Model: (i) Data Layer, (ii) Ontology Layer, and (iii) Service Layer. The IPDMS approach is structured with 3 main perspective/view: (i) Reference View, (ii) Application Domain View and (iii) Semantic Reconciliation View. IPDMS uses semantical well-defined Core and Constraints concepts formalized in Ontology References with knowledge and information from multiple domains to simultaneously instantiate with data from the real process in the Application Domain View, according to the specific product information and technological limitations. In addition, semantic relationships can be established between instantiated information, allowing their semantic mappings of translation, sharing and conversion between different phases of product design and manufacturing. Based on two approaches, Fig. 2 presents the preliminary architecture of the Interoperable Manufacturing System Method (IMSM). ISMS is composed of 4-layers: (i) Ontology Layer; (ii) Application-Domain Layer; (iii) Semantic Reconciliation Layer; and (iv) Data Layer.

- **Ontology Layer** (Detail "A" of Fig. 2) – It defines the reference of knowledge, modelling in an elementary form, to represent different perspectives of the product and its manufacturing in a formal way. The knowledge is modelled in a common logic-based formalism using Web Ontology Language (OWL). Reference ontologies may be composed by Product Engineering, Manufacturing Engineering Reference Ontology, Machining Reference Ontology, etc. The reference ontologies formalization was explored in [30].
- **Application Domain Layer** (Detail "B" of Fig. 2) – The concepts from the Ontology Layer are specialized into a manufacturing system ontology (application ontology), according to the specific data about the product or the manufacturing process. This specialization process must respect the semantic rules to ensure the correct relationship of this information. The data constitutes the Knowledge Model with information about the Product and/or Manufacturing and comes from different phases of the lifecycle. As this information is formally defined in a common language, it is possible to compare and verify the information without losing their meaning in an interoperable manner with semantic rules. Additionally, an inference reasoner (Pellet) is in a continuous analysis to identify information inconsistencies and information traceability.

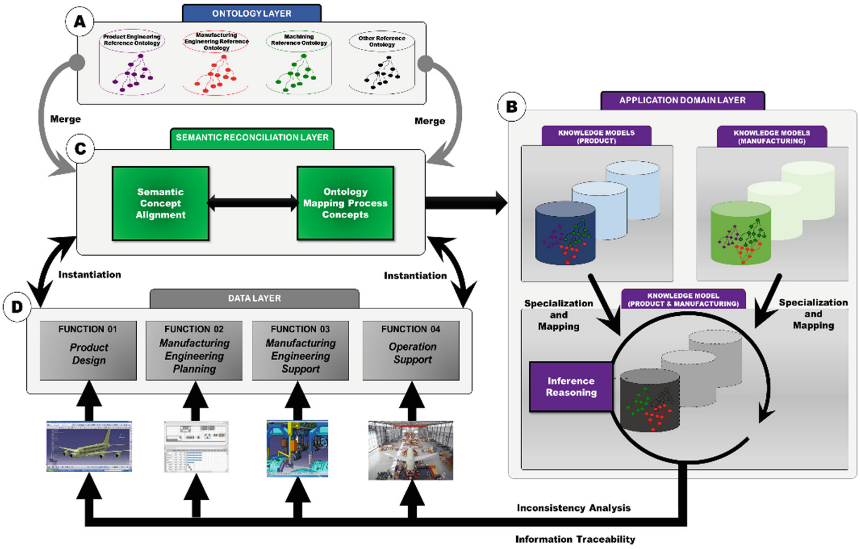

Fig. 2. Preliminary interoperable manufacturing system method architecture.

- **Semantic Reconciliation Layer** (Detail "C" of Fig. 2) – It defines the semantic rules for information relationship from Ontology Layer, Application Domain Layer and Data Layer. The Semantic Reconciliation Layer is composed of three main modules: (i) Context Alignment; (ii) Ontology Intersection; (iii) Semantic Mapping. Context Alignment is the first phase of semantic reconciliation and executes the alignment of data from data layer with the concepts in the ontology layer, i.e. the context is aligned according to the product that will be developed. Ontology Intersection is responsible for connected multiple ontologies from the ontology layer and specialized them according to specific information from the Data Layer. Finally, the semantic mapping is responsible to relate all information in the Application Domain Layer. It allows the establishment of the relationships with the information from multiple perspectives. The alignment process is enabled by the specialized semantic rules that allow inferring the semantic mapping during the Product Design, Manufacturing Engineering Planning, Manufacturing Engineering Support and Operation Support. The semantic rules are a binary relation that describes the semantic relationships from "A" to "B" ($A \Rightarrow B$), where "A" is the antecedent and "B" is consequent. "A" has multiple conditions that are from product constraints, technological restrictions, etc. All conditions in "A" must be "true" to infer the semantic mapping with "B". Table 1 presents the syntax to build the semantic rules.

Data Layer (Detail "D" of Fig. 2) – It collects all the information, databases and interfaces: legacy databases from the legacy software, databases from the commercial software applications, clouds and data lakes databases and many others. Included in the Data layer are those databases to hold the information instanced using Ontology layer.

Table 1. Syntaxes to build the conditions of semantic rules [30].

Rules	Syntax	Description
Equivalence	Equal(C_1,C_2)	Satisfied iff the first argument and the second argument are the same
Contradiction	NotEqual(C_1,C_2)	The negation of equivalence
Lesser than	LessThan(C_1,C_2)	Satisfied iff the first argument is less than the second argument
Greater than	GreaterThan(C_1,C_2)	Satisfied iff the first argument is greater than the second argument
Lesser or equal than	LessThanOrEqual(C_1,C_2)	Satisfied iff the first argument is less than or equal to the second argument
Greater or equal than	GreaterThanOrEqual(C_1,C_2)	Satisfied iff the first argument is greater than or equal to the second argument
Sum	Add(R,C_1,C_2)	Satisfied iff the first argument is equal to the arithmetic sum of the second argument through the last argument
Subtraction	Subtract(R,C_1,C_2)	Satisfied iff the first argument is equal to the arithmetic difference of the second argument minus the third argument
Multiplication	Multiply(R,C_1,C_2)	Satisfied iff the first argument is equal to the arithmetic product of the second argument through the last argument
Division	Division(R,C_1,C_2)	Satisfied iff the first argument is equal to the arithmetic quotient of the second argument divided by the third argument

5 Conclusion and Further Work

A preliminary method to support the semantic interoperability in Models of Manufacturing (MfM) based on an ontological approach is a novel way to integrate and establish the semantic relationship of multiple information from different platforms across the manufacturing system. Additionally, this method contributes to the decision support systems area and providing the right information for design and manufacturing activities. The preliminary ISMS method is based on the 4-Layer Model, that allows the development of aerospace projects in an integrated manner via formal information originated in well-defined structure data and relationships mechanisms (translation, conversion and sharing). In this way, heterogeneous data from multiple views of the Product Design and Manufacturing are instantiated in the core concepts, in a well-defined manner, through semantic rules, which enables the creation of an interoperable environment for the manufacturing system. Knowledge of the relationships between multiple views has been captured in semantic mapping mechanisms for translating, converting and sharing information across multiple views, which certifies the correct semantic information interoperability in the product design and manufacturing.

The further ISMS method tasks planned are: (i) improve the definition of semantic reconciliation layer and application domain layer; (ii) define the methods to the semantic mapping (iii) detailed the instantiation approach from the data layer. Finally, there is a requirement to evaluate the framework with an aerospace experimental case.

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