Journal of Communication and Computer 13 (2016) 171-180
doi:10.17265/1548-7709/2016.04.004

An Ontology-Based Framework for Virtual Enterprise Integration and Interoperability

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Abstract: Virtual enterprise integration and interoperability between its different information systems are the first systemic paradigms to achieve a successful collaborative product development. In such a context, the information flow has a centric place. Therefore, our aim in this paper is to propose a new ontology-based framework, exploiting the expressiveness of ontologies to ensure collaboration and semantic interoperability between partners and using, at the same time, ontologies inference capacities to support the decision making processes. An industrial application will be developed in the context of the simultaneous design of products and their optimized supply chains.

Key words: Ontologies, integration, semantic interoperability, collaborative product development, simultaneous design.

1. Introduction

Today, industrial companies are evolving in a very dynamic environment which forces them to operate in high competitive conditions. Indeed, customers' needs are becoming very changing over time and consequently products' lifecycles are becoming increasingly shorter. Therefore, reactivity and constant innovation are absolutely necessary for companies to compete better in the current market.

In order to achieve this level of reactivity and flexibility, companies have become aware that local efforts to improve their own production processes and schedules are not enough. A complete integration of the different members of the virtual enterprise is essential to the achievement of cost, quality and deadlines goals. As well, the development of new products has become a collaborative process conducted by a set of multidisciplinary teams who coordinate between them.

Therefore, the virtual enterprise integration and its complex management have increased needs for information exchange, sharing and archiving [1, 2]. In fact, each collaborator contributing to the development of the product needs to accede to a set of data and knowledge distributed in several information systems (internal or external to his own organization) so that he can make effectively his choices and take into account all the constraints required. He also needs to share his decisions and data with other partners who will need them.

The problem is that each inter-actor has his own expertise domain and speaks his own language. Yet, data must be transmitted to every member, correctly interpreted by every receiver, managed, reused and stored in a consistent and standardized manner in order to achieve the expected goals.

We conclude then that in addition to technical and organizational interoperability problems, we notice semantic interoperability requirements, which makes the virtual enterprise integration much more complicated.

Therefore, many researchers were interested in the resolution of interoperability problems [3-6]. The 14258-1998 ISO standard [7] regroups all

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interoperability resolution approaches into: Integration, Unification and Federation. In our context of the collaborative product development, we will demonstrate that the federative approach seems to be more relevant and able to meet agility, robustness and flexibility requirements. Recently, with the emergence of ontologies as a new modeling paradigm in industry, the achievement of federation has become possible [8].

The aim of this work is twofold. First, we want to use the expressiveness of ontologies to ensure systems integration and to support semantic interoperability among the virtual enterprise members and second we want to use ontologies inference capacities to support the decision making processes.

Therefore, the rest of the paper is organized as follows: The next section demonstrates the need of integration and interoperability to achieve a successful collaborative development of products; while Section 3 explains why ontologies are suitable to respond to these needs; In Section 4, we propose a new ontology-based framework, exploiting the potentialities of ontologies through four distinct semantic and reasoning layers; then Section 5 provides an industrial application in the context of the simultaneous design of a product and its optimized supply chain through the proposition of a new hybrid approach based on the dynamic interaction between ontologies and mathematical models of optimization; Finally, Section 6 draws conclusions and states future works.

2. The Need of Integration and Interoperability

2.1 Information Systems as a Complex System

Nowadays, product development is becoming more and more based on collaboration between various partners of the virtual enterprise. In this context, the information flow has a central place. At the level of the virtual enterprise, this information flow is composed by the technical exchanged information relating to products and logistical functions, in addition to the decisions flow.

Today, this information flow is no longer following a linear direction from the supplier to the customer but it is rather based on the simultaneous sharing of data between all partners and this thanks to electronic exchanges and to the use of IS (information systems). In fact, if we take only the design phase for example, we will find a multitude of IS dedicated to automating and managing this strategic phase of the product lifecycle [9]: The authoring IS , constituting CAD (computer-aided design) tools, simulation applications, etc.; the technical data management tools, such as PDM (product data management) systems and currently the PLM (product lifecycle management); and application dedicated to the control of the design activities, for example, MS Project or PTC Wind chill Project-Link.

So, we conclude that the number and the diversity of industrial information systems is more and more increasing. Consequently, the whole of the IS can be considered as a complex system [9]. This leads us to talk about interoperability problems between all these industrial information systems contributing to the management of the virtual enterprise complexity especially that IS interoperability is a corner stone for virtual enterprise integration.

2.2 Interoperability Paradigm

Interoperability can be defined as the ability of two systems (or more) to communicate, cooperate and exchange data and services despite the differences in their languages, implementations and execution environments or abstraction models [10].

According to Ref. [11], a system is interoperable only when it meets at the same time the three levels of interoperability, which are:

- The technical level: which is related to the standardization of hardware and software interfaces;
- The semantic level: concerning the understanding on the business level between the different actors;

- The organizational level: which concerns the identification of the inter-actors and organizational procedures.

In the following section, we will conduct a comparison between the different interoperability resolution approaches in order to identify the most appropriate approach for our context of the collaborative product development.

2.3 Comparison of the Different Interoperability Resolution Approaches

The ISO standard-14258-1998 [7] defines three different approaches to deal with interoperability problems: Integration, Unification and Federation. Table 1 describes the principle of each approach as well as the main limitations that they present [12].

The analysis of these three approaches shows that integration and unification present several limitations. In fact, integration is based on the idea of finding a consensus between the different actors of the networked enterprise, yet it is not possible to propose a unique common model that fits perfectly all actors' needs at the same time [9]. And for the unification approach, it reposes on the establishment of direct connections between the different models manually in general. Thus, regular updates must be made at the level of the intermediate model [12].

Therefore, we can say that these first two approaches are not suitable in our context because they cannot afford the dynamic information exchange needed in the current virtual enterprises. So, we have a big interest to explore the benefits of Federation.

2.4 Federation: The Most Appropriate Interoperability Resolution Approach in Our Context

In our context of collaborative product development, a large amount of data must be exchanged without any loses of semantics. Moreover, a great flexibility must be allowed in order to ensure a dynamic exchange and a better decision-making at the right time. Then, it is obvious that a federative approach is the most appropriate to meet these requirements and to overcome integration and unification rigidity [13].

In fact, federation is based on the idea that each member must preserve its own information model in order to ensure comprehensiveness and flexibility [9]. As well, to realize information exchange between systems, automatic connections between models are established using logic.

Today, with the recent advances in the field of ICTS (information and communication technologies), including the web, the federation has become attainable. In fact, new modeling paradigms based on the use of ontologies have been developed.

3. Emergence of Ontologies Based Models

3.1 Why Ontologies?

The term ontology derives from the ancient Greek "Ontos", which means "being" and "Logos", which means, "discourse". Then, ontology has assumed other meanings. According to Ref. [14], ontology enables formally representing knowledge as a set of concepts within a domain, using a shared vocabulary to denote the types, properties and interrelationships of those concepts.

Fortineau et al. [8] have explained why ontologies are relevant to solving interoperability problems. In fact, they have explained that the expected benefits from using inference models can be classified into three categories that refer to different capabilities offered by inference ontologies:

Table 1 Comparison of the different interoperability resolution approaches.

Approach	Principle	Limits
Integration	Proposal of a data model common standard (a consensus)	The compatibility level reached is limited
Unification	Establishment of semantic matches direct links between actors (of mapping)	It requires a priori knowledge of the ontologies of each peer of the network, in addition to a regular update
Federation	Dynamic association of distinct models	The current results are still disappointing

- Integration and completeness, provided by language expressivity,
- Embedded intelligence, due to the reasoning capabilities of description logic languages,
- Dynamism and flexibility, through queries and web services.

These capabilities explain the considerable number of papers dealing with the industrial applications of ontologies for the resolution of interoperability problems [15].

3.2 Comparison of the Main Ontology Based Approaches

According to Refs. [16, 17] there exist three main ontology architectures that have been employed in the previous literature:

- Single Ontology approaches which use one global ontology providing a shared vocabulary for the specification of the semantics. In these approaches, all information sources are related to the unique global ontology. Then, they can be applied to integration problems where all information sources to be integrated provide nearly the same view on a domain but otherwise, these approaches becomes unsuitable.
- Multiple Ontologies where each information source is described by its own ontology. This approach presents the advantage that each source ontology can be developed without respect to other sources or their ontologies which facilitates integration and supports the change. Yet, the lack of a common vocabulary makes it difficult to compare different source ontologies.
- Hybrid Approaches which were developed to overcome the drawbacks of the single and multiple ontology approaches. In these approaches, the semantics of each source is described by its own ontology. But in order to make the local ontologies comparable to each other they are built from a global shared vocabulary. This avoids the disadvantages of multiple ontology approaches and gives the advantage of flexibility.

In our context of virtual enterprise integration, a large amount of data provided by many sources must be exchanged without any loses of semantics. Moreover, a great flexibility must be allowed in order to ensure a dynamic exchange and easy updates and modifications.

Therefore, we will propose an ontology-based architecture based on the principle of the hybrid approach in order to overcome any rigidity. The proposed framework will be described in the next section.

4. Proposition of an Ontology-Based Framework for Virtual Enterprise Integration and Interoperability

The proposed ontology-based framework is represented in Fig. 1. It aims to support integration and interoperability within the virtual enterprise through a semantic modeling of the whole of the information related to the product, its manufactoring process and the whole of its associated supply chain.

Throughout the proposed architecture, we aim to: support integration and collaboration between members, build models rich in semantics in order to ensure semantic interoperability, allow the integration of new knowledge (archiving and capitalization), and generate a more dynamic and effective information exchange between applications. In addition to these goals centered on the information flow, we aim to use the inference capacities of ontologies to support the decision making process throughout the whole collaborative product development cycle and this is the main innovative side in this contribution.

We propose for this a four level modeling solution represented in Fig. 1.

A division based on only three layers already exists in the literature. It has been formalized by Ishak [17] who proposed to use in a simple hierarchical way: A meta-ontology allowing to define multiple domain ontologies, which will then be instantiated through various application ontologies.

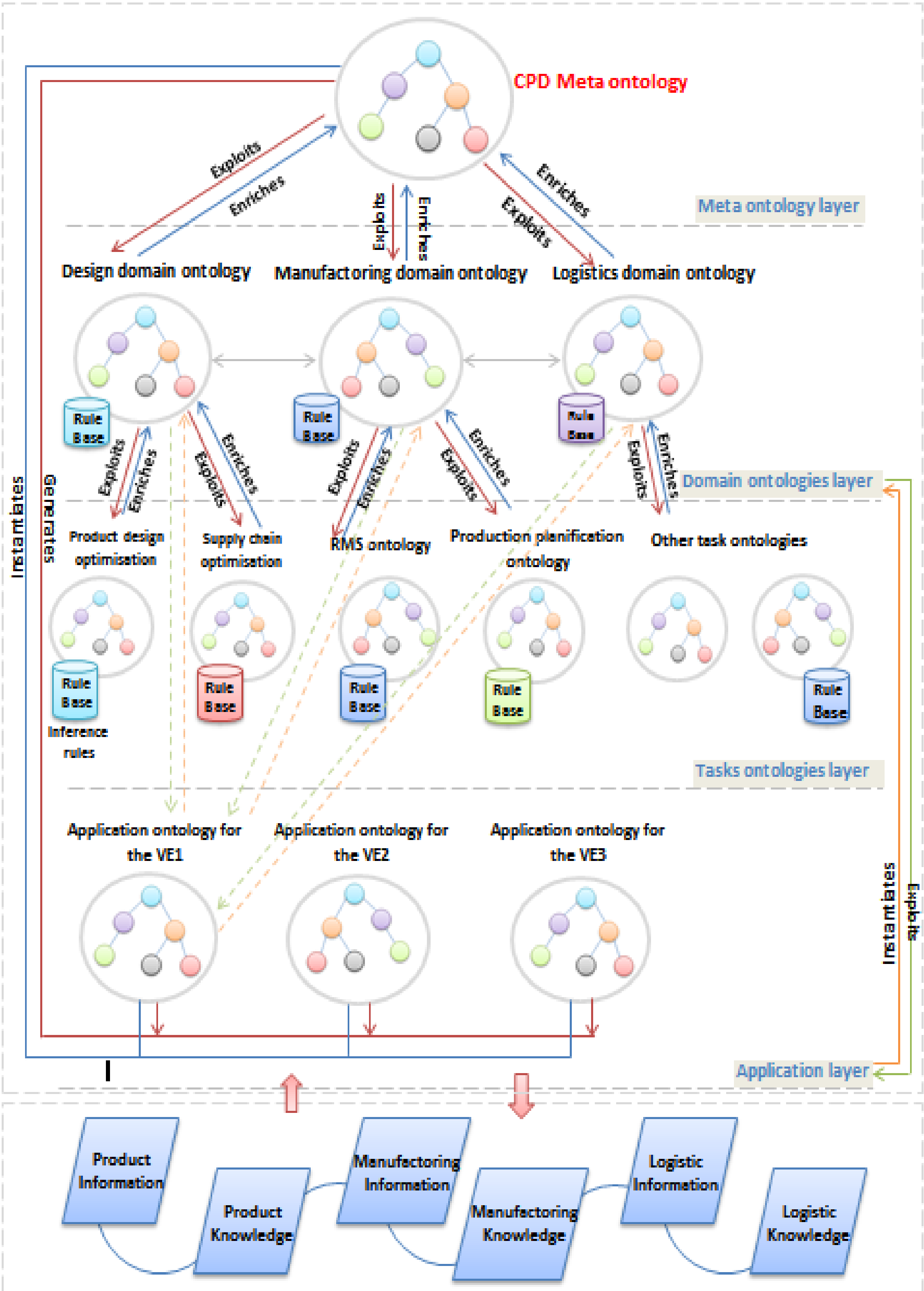

Fig. 1 The proposed ontology-based framework for virtual enterprise integration and interoperability.

The proposal of this paper is fundamentally different because it associates different semantic and reasoning roles to each layer. The envisaged semantic and reasoning roles then are the following:

- The Meta Ontology Layer, which corresponds to the highest level of abstraction, allows to represent and to unify all information needed during the whole CPD (collaborative product development) cycle, and to share them between the set of inter actors in a consistent and correct manner. The common information is thus represented according to a common meta-model, allowing to unify their representation and exploitation.
- The Domain Ontologies Layer is dedicated to the representation of the information related to a specific domain in the CPD cycle. In fact, this layer is dedicated to experts and it contains three domain ontologies. One specific to the design domain, another to manufactoring domain and finally a last ontology dedicated to other logistics information. Each of these domain ontologies has its own SWRL inference rules which enable to automate the information and knowledge acquisition. This second layer enables information sharing in a small area with a specific and smart way preserving to the Meta layer its simple and generic representation and providing to domain experts the specific data they need. This layer is the intermediate between Meta and tasks layer.
- The Tasks Ontologies Layer allows to realize some specific tasks in the CPD cycle. This layer constitutes the particularity of the proposed architecture because it is through it that we will exploit in a smart way the inference capacities of ontologies to support decision making processes in different phases of the lifecycle. A demonstration will be provided in the next section. It concerns the design phase and reposes on the dynamic interaction between ontologies and mathematical models of optimization.
- Finally, The Application Layer which is instantiated by the specific virtual enterprises applications. It depends on the application specifies but conserves the information of the meta-model, and thus allows to guarantee consistency and interoperability.

As well, which is particularly innovative in this modeling architecture, is that there is no confusion between domain and tasks layers. Each layer has its own specific semantic role and reasoning role. In fact, it is the specification of the tasks layer which provides to us the ability to exploit in a smart way the inference capacities of ontologies to support the decision making processes.

In addition, all the modeling layers are linked through the Meta layer which unifies the representation of their respective information, guarantees their mutual semantic understanding and gives to experts a new concise dedicated area to realize specific consistent tasks and to share much more specialized information.

The CPD Meta-ontology constitutes the center of the proposed architecture. Therefore, we describe the different root concepts of our ontological meta-model in the Table 2:

Table 2 The different root concepts of the proposed ontological meta-model.

Root concept	Modeling role	Sub concepts
Product	Models product data	Idea, digital product and physical product
Logistic_ actor	Models supply chain data	Supplier, production company, transport, warehouse and customer
Mathematical _ model	Models the data relating to the optimization programs	
Constraint	Models the logistical and functional constraints	Logistical, functional
Rule	Consolidates the different types of the inference rules	
Resource	Models the different resources required for the collaborative development of the final product	Personal, material and software resources
Phase	Models the specificities of each phase of the product lifecycle in order to extend the utilization of our model	Design, production, distribution, use and dismantling

The root concepts that we have defined respond to the ambitions of our approach. In fact, they define a clear and generic model which structures at the same time the products data, those relating to the supply chain and also those relating to the optimization process.

In addition to that, the ontological model proposed is generic and independent of any type of product or industry which enables the exploitation of our approach by a large spectrum of applications.

5. Application in the Simultaneous Design of a Product and Its Optimized Supply Chain Context

We suppose in this example that we are dealing with the general case of the design of a new product by a manufacturing company. Nowadays, many firms are moving away from the traditional sequential design approach to the simultaneous design of the product and its associated supply chain. Therefore, we have chosen to illustrate the proposed architecture in this context and particularly in the strategic design phase.

The idea is to exploit the inference capacities of ontologies to support the integration of the logistical constraints in the early phases of the product lifecycle and also to improve the decision-making during the process of the supply chain optimization. Therefore, we propose a hybrid approach combining ontologies and mathematical models of the supply chain optimization (Fig. 2).

The proposed approach is based on the dynamic interaction between ontology and mathematical models of optimization via the use of queries and two types of inference rules expressed in SWRL to increase OWL expressiveness. These rules are divided into:

(1) Functional inference rules: expressed by the members of the supply chain and allowing, on the one hand, to automate the formalization of knowledge necessary for the design of the product and the members of the supply chain and on the other hand, to facilitate and to automate the determination of the different constraints that must be taken into consideration in the design phase. The use of business rules will limit the repetitive actions of knowledge

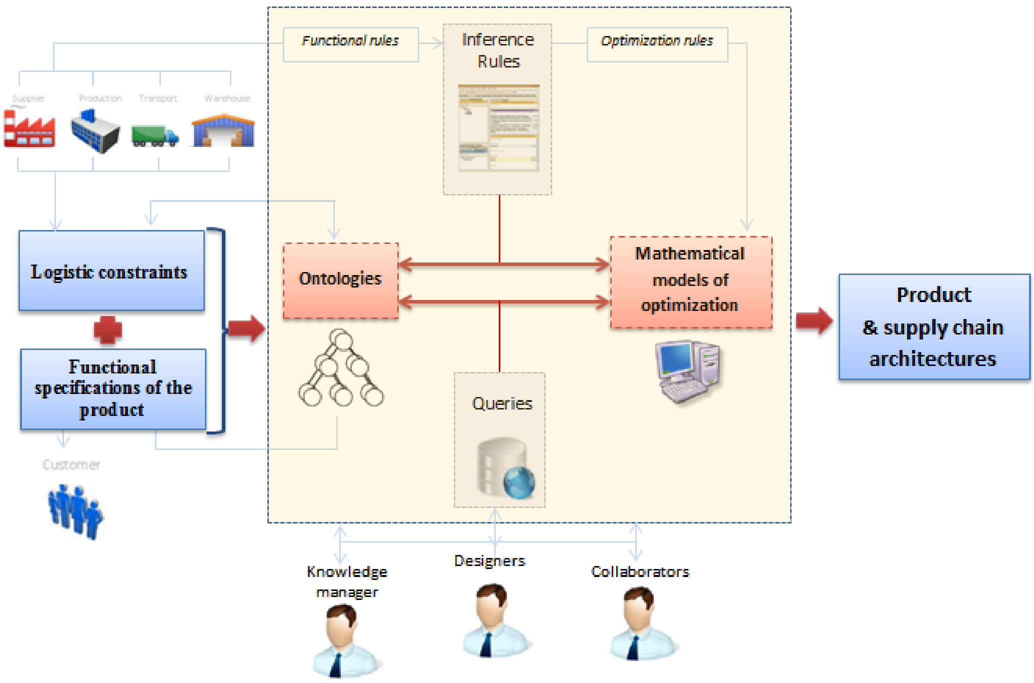

Fig. 2 Proposition of a hybrid approach combining ontologies and mathematical models of optimization.

acquisition and formalization and it will, at the same time, help the product and supply chain designers to identify and represent in a more exhaustive and homogeneous way the information, including the constraints to take into consideration (e. g: Power_motor<|Power_brakes| in the case of automotive brakes design).

(2) Optimization inference rules: This second category of rules plays essentially the role of the trigger for the different sub-parts of the optimization program. In fact, we will define for each subprogram a Boolean variable which will take "1" as a value if this part must be executed and "0" if not. The inference rules will determinate the value of the Boolean Variable associated to each subprogram according to the specificities of the extended enterprise and to the case of study. Therefore, the optimization inference rules will automate the determination of the program subparts to run and then they will realize a gain of time.

Fig. 3 represents the flowchart of the proposed approach. First, the designers receive constraints from

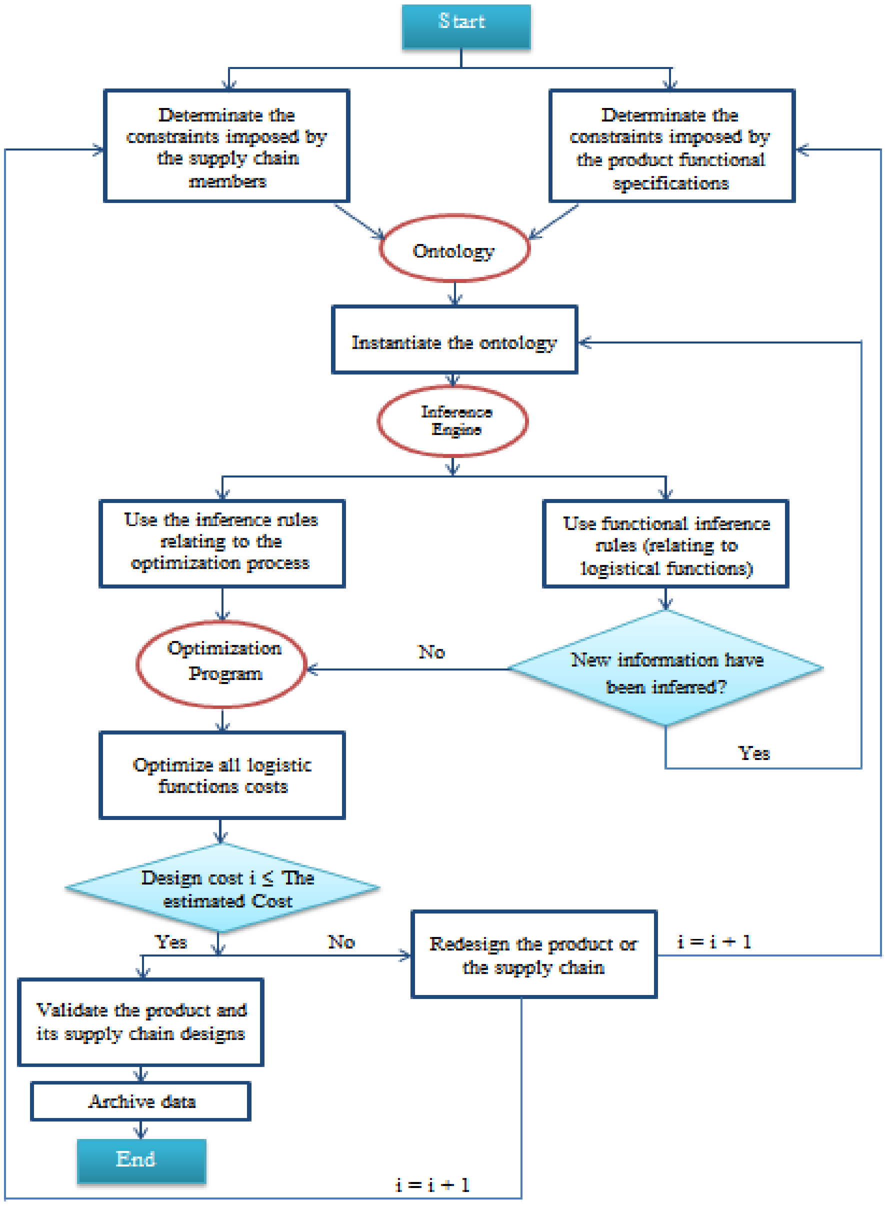

Fig. 3 The flowchart of the proposed approach.

the existing elements of the supply chain and from the customer specifications [13, 18]. The constraints of the non-existing elements must be anticipated also (the addition of a new supplier for example). The aim of this step is to integrate logistical constraints in the early phases of the product design. These constraints can be grouped into cost, quality and deadline constraints.

Once identified, the constraints will be introduced as instances of the concept “constraint” of the ontology. Through our new approach, we try to improve and automate the constraints identification. These two objectives will be provided using the inference capabilities of the ontology. In fact, we will define, as we have already explained, a set of rules relating to the logistic actors which will be introduced to the inference engine. Then, a new list of constraints and data that the designers have not taken into consideration during the first constraints census will be given.

Once the data is inferred and the list of constraints is completed, the execution of the optimization program will be made. The constraints list will constitute the inputs of the optimization program and the second category of inference rules will play the role of the trigger and the support for the optimization process as previously described.

At the end of each iteration, we will check if the cost of the designed product satisfies the cost estimated by the company for the product to be cost-effective. If yes, the designers will validate the product and its optimized supply chain architectures. Otherwise, it will be necessary to make changes either on the product architecture, or on its supply chain. In this case, a new iteration will be done. Finally, all the project knowledge will be archived by the ontology.

6. Conclusion

In this article, we presented a work related to the field of integrated engineering, particularly in collaborative product development context. In fact, we have exploited the recent information modeling paradigm in industry which is ontologies, to support systems integration and semantic interoperability within the virtual enterprise.

Therefore, we have proposed a new ontology-based architecture composed of four distinct layers: Meta layer, domain layer, tasks layer and application layer. The particular originality in this work consists essentially in the fact that each layer has a twofold role, a semantic one and a reasoning one. In addition, we envisaged a specific tasks layer enabling us to exploit the inference capacities of ontologies to support decision making through the use of SWRL rules, and so to give to experts a new concise dedicated area to realize specific consistent tasks and to share much more specialized information without complicating the Meta common layer.

An application to the design phase has been developed. It reposes on the dynamic interaction between ontologies and mathematical models of optimization. The ontology constitutes the center of the proposed methodology and it played two major roles: An integrator, allowing to solve semantic interoperability problems and an efficient support for the decision-making process in the simultaneous design of the product and its optimized supply chain through the expression of two types of inference rules allowing reasoning and then a generic automatic deduction of the constraints to take into consideration during the design and optimization processes.

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