Implementing Semantic Interoperability in Cloud Collaborative Manufacturing: A Demonstration Case for an Ontology-Based Asset Efficiency Testbed

Jaime Pereira, Daniel Pimenta, Daniel Dias, Paula Monteiro, Francisco Morais, Nuno Santos, João Pedro Mendonça, Fernando Pereira, and João P. Carvalhal

Abstract Industry 4.0 provides intelligent factories, intelligent processes, and cyber-physical systems. Systems of the future will have to be able to handle adversities autonomously. Nowadays, engineering practices are increasingly distributed and decentralized, thus causing challenges to the level of interoperability between the various systems developed. Regardless of the structure of the databases, it is necessary to have a mechanism that guarantees the interoperability between these systems. In this paper, we present two types of integrations through ontologies: vertical integration that is a way to achieve semantic interoperability between industrial plant, MES, and ERP and horizontal integration to achieve interoperability throughout the product lifecycle. Finally, this interoperability contribution was crucial to develop an asset efficiency system.

Keywords Semantic interoperability · Cloud manufacturing · Ontologies · Asset efficiency

1 Introduction

One of the greatest challenges faced nowadays is how to deal with great volumes of data coming from an increasing number of different sources. The capture of information is easier, but knowing how to do it is far harder. Newly developed architectures have focused in higher availability and affordability of sensors, in ways of acquiring data and computer networks [1]. Consequently, it has the number of uses

J. Pereira · D. Pimenta · D. Dias · P. Monteiro · F. Morais · N. Santos (✉) · J. P. Mendonça
CCG/ZGDV Institute, Guimarães, Portugal
e-mail: nuno.a.santos@algoritmi.uminho.pt

F. Pereira
Inocam, Soluções de Manufactura Assistida por Computador, Lda., S. J. da Madeira, Portugal

J. P. Carvalhal
Vanguarda—Soluções de Gestão e Organização Empresarial, Lda., M. da Maia, Portugal

B. Archimède et al. (eds.), *Enterprise Interoperability IX*, Proceedings of the I-ESA Conferences 10, https://doi.org/10.1007/978-3-030-90387-9_8

sensors, networked machines are fast-growing, and in parallel, higher volumes data are generated, i.e., big data [2].

Industry 4.0 (I4.0) or Industrial Internet of Things (IIoT) aims to promote an increase in industrial productivity and efficiency through an integration of different systems, which leads to a need for integrating different software systems either at business or at manufacturing levels, inside a single plant or within a networked enterprise. Cloud computing has provided infrastructure for centralizing this information.

Different enterprise systems need to share information between each other. However, it is many times the case that data is stored, processed, and communicated in different ways by several and heterogeneity systems. Problems of misunderstanding and loss of semantic information may arise when exchanging information between them. This phenomenon is the so-called babel tower effect [3]. This effect induced by the heterogeneity of distributed systems and different domains may lead to loss of information. This is an interoperability problem.

IEEE defines interoperability as "*the ability of two or more systems or components to exchange information and to use the information that has been exchanged*" [4]. To avoid loss of information, it is required to address semantic interoperability between legacy components with different data models.

Ontologies are a way to solve interoperability problems. An ontology is a representation vocabulary, often specialized to some domain or subject matter. More precisely, it is not the vocabulary as such that qualifies as an ontology, but rather the terms in the vocabulary intended to be captured. The term ontology is sometimes referred as the body of knowledge describing a domain [5]. Ontology modeling, namely in IIoT/I4.0 settings, may refer to different integrations for supporting digital twin and digital thread lifecycles [6], namely product (vertical) and application (horizontal integration).

Thus, this paper proposes an approach for defining an ontology for both vertical and horizontal integrations able for supporting digital thread concept. ISO10303 (or Standard for Exchange of Product Data—STEP) [7] allows supporting horizontal integration. ISA-95 [8] allows supporting vertical integration. It is also needed to ensure tolling support for making use of the ontology, where typically ontology-based database access (ODBA) [9] is used. Orchestration of the data flows for a collaborative manufacturing is afterward enabled by a cloud computing architecture. This research was conducted under the project "*PRODUTECH-SIF—Soluções para a Indústria do Futuro*" (Solutions for the Industry of the Future), which is used as a demonstration case.

This paper is structured as follows: Sect. 2 describes the method that supported the ontology development for both vertical and horizontal integrations; Sect. 3 presents the approach for the ontology-based data access; Sect. 4 describes the designed interoperability platform; Sect. 5 presents the PRODUTECH-SIF scenario and its asset efficiency tested; and finally, Sect. 6 presents the conclusions.

2 Ontology Development

We address semantic interoperability between systems supported by an ontology. Our ontology is based on Uschold and King Methodology that established a method that helps those interested in developing ontologies. The method encompasses four distinct phases [10]: identify the ontology purpose; build the ontology, that means capture the ontology, code the ontology, and integrate with existent ontologies if possible; evaluate if the ontology corresponds to the expected result; and finally, documentation that explains the main concepts of the ontology.

The ontology development aimed two separate models, one toward vertical integration and one toward horizontal integration. The vertical integration ontology uses the ISA 95 standard, and the horizontal integration ontology uses STEP standards. Both ontologies were modeled in the Protégé software tool.

For addressing the vertical integration (ISA 95-based) ontology, we divided our model into three sub-ontologies: hierarchy, operation type, and resource.

The hierarchy model refers to the breakdown structure of the involved actors in a process. Figure 1 depicts some of the classes of the model, and Table 1 depicts some of the ontology properties.

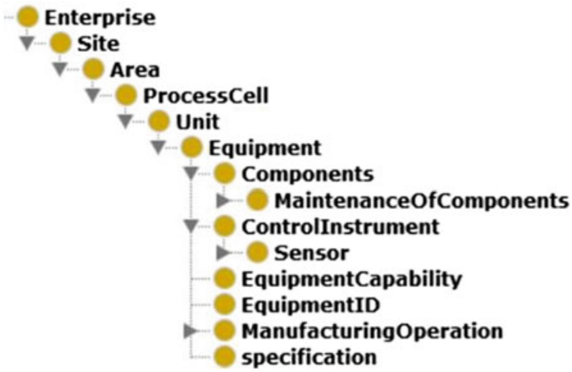

Fig. 1 Excerpt of the hierarchy sub-ontology classes

Table 1 Some hierarchy sub-ontology properties

Property type	Property name	Domain	Range
Object property	hasSite	Enterprise	Site
Object property	hasArea	Site	Area
Object property	hasProcessCell	Area	ProcessCell
Object property	hasUnit	ProcessCell	Unit
Object property	hasEquipment	Unit	Equipment
Data property	hasDescription	Owl:thing	Xsd:string
Data property	hasEquipmentID	Equipment	Xsd:string
Data property	hasEquipmentCapabilityType	EquipmentCapability	Xsd:string

The operation-type model refers to the breakdown of all tasks and jobs. This model aims to include semantics used in MES, since the model's domain is in line with typical MES' data models. Figure 2 depicts some of the classes of the model, as well as their properties in Table 2.

The resource model includes every element that is part of the production and manufacturing process. This model aims to include semantics used in ERP, since the model's domain is in line with typical ERP data models (workers, materials, machinery, etc.). Figure 3 depicts some of the classes of the model, and Table 3 depicts some of the ontology properties.

The horizontal integration was promoted by adopting STEP. STEP is the de facto standard for the information exchange between CAD/CAM/CAE systems. The objective was to transform the information into an ontology in order for the information to be more easily processed. To do that, we used a NIST plug-in for Protégé, called ontoSTEP [11], that allowed the transformation of a STEP file to an OWL file.

Fig. 2 Excerpt of the operation type sub-ontology classes

Table 2 Some operation type sub-ontology properties

Property type	Property name	Domain	Range
Object property	hasQuality	OperationType	Quality
Object property	hasproduction	OperationType	Production
Data property	hasJobListID	JobList	Xsd:string
Data property	hasPriority	JobOrder	Xsd:string
Data property	hasPublishedDate	WorkSchedule	Xsd:string
Data property	hasWorkMasterCapacityType	WorkMaster	Xsd:string
Data property	hasWorkPerformanceID	WorkPerformance	Xsd:string
Data property	hasWorkScheduleID	WorkSchedule	Xsd:string

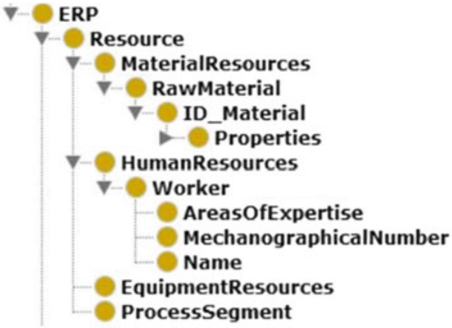

Fig. 3 Excerpt of the resource sub-ontology model classes

Table 3 Some resource sub-ontology properties

Property type	Property name	Domain	Range
Object property	RequiresMaterialDefinition	ProcessSegment	MaterialResources
Object property	RequiresPersonnel	ProcessSegment	humanResources
Object property	RequiresPhysicalAsset	ProcessSegment	EquipmentResources
Data property	hasPhysicalAssetCapabilityType	Equipment	Xsd:string
Data property	hasPhysicalAssetID	Equipment	Xsd:string
Data property	hasPhysicalLocation	Equipment	Xsd:string
Data property	hasVendorID	Equipment	Xsd:string

3 Ontology-Based Data Access Approach

This section describes a design approach for enabling software access to heterogeneous databases using an ontology model described in the previous section. Access mechanism to databases is based on an ontology-based data access (OBDA) application. As depicted in Fig. 4, an application OBDA receives as input a SPARQL query,

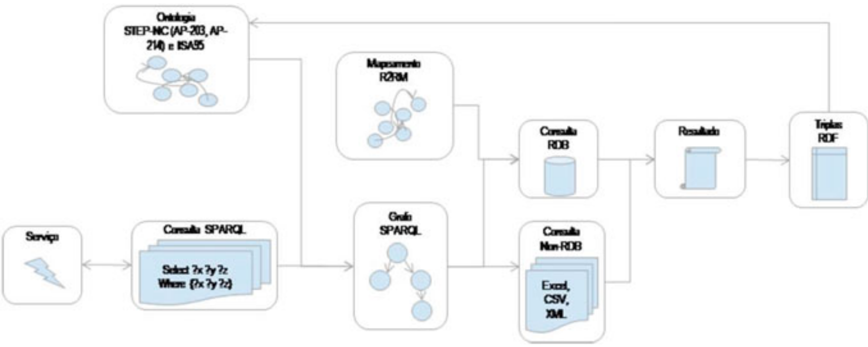

Fig. 4 Interoperability of all system

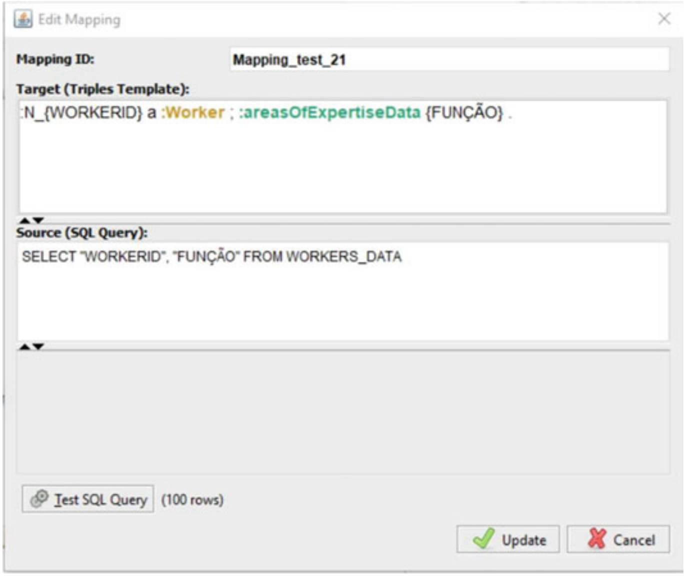

Fig. 5 Example of the ontology and the database mapping

then that SPARQL query is converted to a SQL query capable capturing the data and answering the question satisfactory.

In order to develop our OBDA, we used ONTOP. As all OBDA systems, ONTOP needs two things, a conceptual layer and a database. Our conceptual layer is both ontologies: the ontology that guarantees the vertical integration and the ontologies that guarantee the horizontal integration. The databases are from our ERP, MES, and Thingsboard. After having the conceptual layer and the database, we map one to another. The language used on ONTOP to the mapping is R2RML (RDB—relational database to RDF mapping language). The mapping between the ontology and the database was composed by mapping ID, source, and target (Fig. 5.). After the mapping phase, we can start using SPARQL queries on our databases.

4 The Cloud Collaborative Manufacturing Architecture

Industrial and manufacturing organizations are part of enterprise networks that work together, structuring themselves in product development flow activities. Efficiency of the flow is thus promoted by a harmonized collaboration between the enterprises, rather than each one working in a silo.

It is thus crucial that modern enterprise networks take advantage from existing technological infrastructures for orchestrating such collaboration. Cloud computing solutions have enabled exchange of process information through services that execute on the web. Namely, such services rely in protocols such as Application Programming Interfaces (APIs) for real-time communication.

Architecture design must include taking decisions on the orchestration of the collaboration within the enterprise network, the product development process, and the communication requirements (this one more related with the systems involved in each of the enterprises).

The orchestration of the collaboration is promoted by developing a set of services responsible for connecting different enterprises, where typically a set of APIs assure the information flow. The OBDA solution, proposed in the previous section, is included in such services, requiring an API for it as well. The API allows any service to query the existing SPARQL services included and hence use it as a service for the semantic interoperability between the enterprises.

The product development process must be addressed in the cloud architecture by developing a set of domain-oriented services, capable of managing information regarding different manufacturing scenarios. Other services like gateways, brokers, security, and data integrity may be included as well, as best practices for orchestration of the services.

Finally, defining needs for communication relies in the different existing layers within the enterprise. For this matter, industrial reference models like *Industrial Internet Reference Architecture* (IIRA) or *Industrie 4.0 Reference Architecture Model* (RAMI 4.0) propose division of layers, like enterprise (ERP, MES, and other business users), platform (cloud management), and edge (devices and assets). Between these layers, communication typically relies in protocols such as OPC-UA, MQTT, AMQP, or HTTP.

5 Collaborative Manufacturing in the PRODUTECH-SIF

In the project scope, our mission was to guarantee the interoperability between different hierarchies of an enterprise. Enterprises are dealing with a panoply of software's from different software houses, which produces different information types.

For example, an enterprise resource planning (ERP) usually does not show any distinction between workers and equipment's. What we really are trying to say is that for an ERP, both are nothing more than resource. On the other hand, for a manufacturing execution system (MES), normally, an equipment is a "machine", and the term "personnel" refers to a "human resource". The loss of semantic information is addressed using ontologies, as described in Sect. 3.

In this research, an ERP is considered a centralized system that facilitates the exchange of information between different enterprise systems, while a MES is a system that monitors and manages all productions. MES will be seen as in-between from the ERP responsible for taking the decisions and the shop floor the place where things are actually manufactured.

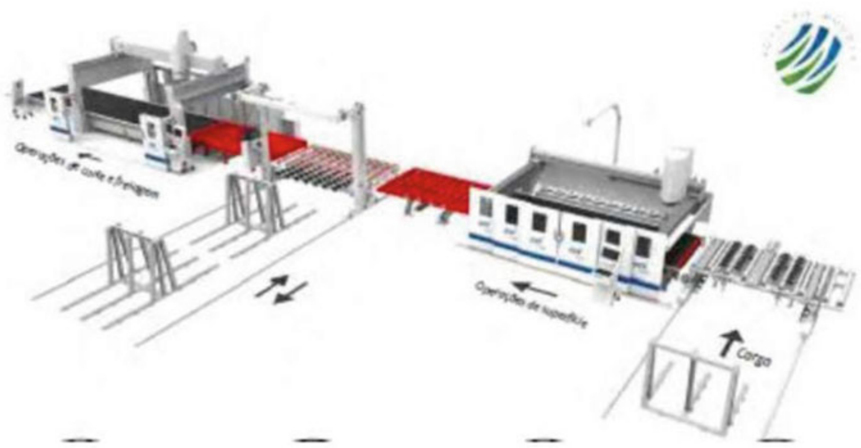

Fig. 6 Industrial scenario

Our objective is to integrate all the manufacturing system, vertically and horizontally, from the shop floor to the ERP; in other words, what we are trying to create is a cyber-physical system.

As a scenario, we are going to use a factory responsible for the manufacturing of tabletops, tombstones, and other types of stone products. As depicted in Fig. 6, generally, we can say that type of factory possesses two kind of machines, on one hand, you have three-axis CNC machine responsible for the polishing of the stone, and a second one, five-axis CNC machine responsible for the cutting of the stone. Associated with them, the factory also has all sort of other equipment.

We want to guarantee the factory interoperability from the shop floor to the ERP. In our scenario, the ERP system was developed by *Vanguarda Soluções De Gestão E Contabilidade Empresarial, Lda.*, and the MES system was developed by *INOCAM Soluções de Manufactura Assistida por Computador, Lda.* Additionally, computerized numerical control (CNC) machines were manufactured by *Companhia De Equipamentos Industriais, Lda.* (CEI), part from the *Zipor group.* The data is going to be captured thanks to the new Internet of Things (IoT) technologies and then sent to an IoT platform, namely Thingsboard.

The asset efficiency (AE) testbed in the PRODUTECH-SIF project was designed, so operational information from equipment's in a shop floor—in this case, only from a CNC—could be analyzed from users inside and outside of the enterprise. The analyzed data included working hours, temperature, energy consumption, and vibration. Additionally, process data was included as well. Bills of materials, warehouse stocking materials, and production orders were gathered from the Vanguarda's ERP. Production operations and control data were gathered from INOCAM's MES.

Following trends such as product lifecycle digital thread and digital twins, equipment's, materials, and processes were modeled in an ontological representation (OWL), aggregating ISA-95 and STEP (AP-203, AP-214). The ontology was able to be queried by means of an API, which enabled other services gaining access to the SPARQL queries.

Finally, data visualization in the Thingsboard platform was performed through acquisition of the data from the CNC, by means of the configuration of telemetry analysis services using MQTT, HTTP protocols. Thingsboard platform includes data analysis services like dashboards, which were used to monitor the AE.

Now that the operational data is available in the cloud (i.e., the Thingsboard platform), that data is able for usage in the business perspective. The services deployed in Thingsboard that promoted cloud collaboration rely mainly in business configurations—customers, users, devices, business rules.

6 Conclusions and Future Work

This paper presented the results of an ontology development for achieving the semantic interoperability. One of the results is an OWL based on ISO10303 and ISA-95. The adoption of these standards promotes a common data model that a widespread number of heterogeneity systems could relate to and communicate with. These data models now possess meaning, whereas materials relate to the capabilities included in their industrial digital twin model. STEP covers a wide range of products (electronic, electromechanical, mechanical) and stages of product development (design, analysis, manufacturing). On the other side, the data model also possesses meaning, whereas process monitoring and control are traced within the industrial digital thread model. ISA-95 was used for the concepts relating to interoperability between ERP, MES, and the shop floor systems. Both standards are widely recognized for application and product lifecycles, respectively.

Then, an OBDA-based approach was implemented for allowing different systems to interoperate using an implemented API that allows access for external services to the SPARQL queries. It was used as one of the services within the cloud collaborative manufacturing architecture. Other services aimed at connecting enterprises and acquiring shop floor data from a CNC to the cloud, to be visualized in a Thingsboard platform. Based on an interoperable scenario, we have the objective to develop an asset efficiency, but it still needs to be deployed and tested in a real shop floor. As the future research, it is still needed to address concerns regarding acquisition of material data, access to CNC machines, acquisition of sensors, among others.

Acknowledgements This work was carried out within the scope of the project "PRODUTECH SIF-Soluções para a Indústria do Futuro" reference POCI-01-0247-FEDER-024541, co-funded by Fundo Europeu de Desenvolvimento Regional (FEDER), through Programa Operacional Competitividade e Internacionalização (POCI), and by FCT—Fundação para a Ciência e Tecnologia within the R&D Units Project Scope: UIDB/00319/2020.

References

1. Jay Lee, B. B. H.-A. K. (2014). A cyber-physical systems architecture for industry 4.0-based manufacturing systems. *Manufacturing Letters.*
2. Jianhua Shi, J. W. H. Y. H. S. (2011). A survey of cyber-physical systems. In *Proceedings of the Inernational Conference on Wireless Communications and Signal Processing.*
3. Tursi, A. (2009). Ontology-based approach for product-driven interoperability of enterprise production systems.
4. Hřebíček, J. Semantic Interoperability. [Online]. Available: http://www.iba.muni.cz/obr/File/organize/semanticka_interoperabilita.pps.
5. Chandrasekaran, B. J. J. B. V. R. (1999). What are ontologies, and why do we need them?, *Intelligent Systems and their Applications, IEEE*.
6. Lin, D. S.-W. (2017). Industrial IoT/industrie 4.0 viewpoints. [Online]. Available: https://industrial-iot.com/2017/09/iiot-smart-manufacturing-part-2-digital-thread-digitaltwin/. Accessed May 2018
7. ISO. (2003). ISO/DIS 10303–238. Industrial automation systems and integration—product data representation and exchange—part 238: application protocols: application interpreted model for computerized numerical controllers. ISO.
8. ISA-95. (2000). ANSI/ISA-95.00.01–2000, enterprise-control system integration part 1: models and terminology. ANSI/ISA.
9. Calvanese, D. G. G. L. D. E. A. (2009). Ontologies and databases: The DL-lite approach. In *Reasoning Web. Semantic Technologies for Information Systems* (pp. 255–356). Springer.
10. Uschold, M., & King, M. (1995) Towards a methodology for building ontologies. In *Workshop on basic ontological issues in knowledge sharing.*
11. Raphael Barbau, S., Krima, S., Rachuri, A., Narayanan, X., Fiorentini, S. F., & Sriram, R. D. (2012). OntoSTEP: enriching product model data using ontologies.