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Ontology-based solutions for Interoperability among Product Lifecycle Management Systems: A Systematic Literature Review

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Abstract: During recent years, globalization has had an impact on the competitive capacity of industries, forcing them to integrate their productive processes with other, geographically distributed, facilities. This requires the information systems that support such processes to interoperate. Significant attention has been paid to the development of ontology-based solutions, which are meant to tackle issues from inconsistency to semantic interoperability and knowledge reusability. This paper looks into how the available technology, models and ontology-based solutions might interact within the manufacturing industry environment to achieve semantic interoperability among industrial information systems. Through a systematic literature review, this paper has aimed to identify the most relevant elements to consider in the development of an ontology-based solution and how these solutions are being deployed in industry. The research analyzed 54 studies in alignment with the specific requirements of our research questions. The most relevant results show that ontology-based solutions can be set up using OWL as the ontology language, Protégé as the ontology modelling tool, Jena as the application programming interface to interact with the built ontology, and different standards from the International Organization for Standardization Technical Committee 184, Subcommittee 4 or 5, to get the foundational concepts, axioms, and relationships to develop the knowledge base. We believe that the findings of this study make an important contribution to practitioners and researchers as they provide useful information about different projects and choices involved in undertaking projects in the field of industrial ontology application.
Keywords: product lifecycle management; interoperability; ontology; roles of ontology; review

1. Introduction

The constant and irreversible influence of globalization has generated many development scenarios for industries due to greater competitive pressure. This situation has encouraged manufacturing companies to embrace new strategies to reduce product development lifecycle times without affecting quality [1]–[4]. One of these strategies is the collaborative interaction between geographically distributed suppliers, customers and partners to integrate their productive processes, as a competitive advantage. This type of collaboration aligns with the goals of Smart Factories, which are trying to reach interoperability among every single asset and information system in manufacturing industries [5].

The Smart Factory concept refers to the implementation of an Industry 4.0 approach in manufacturing, which requires information and knowledge sharing between industrial information systems across the enterprise frontier [6]. To provide this information exchange it is necessary to deploy functional data integration [7], [8], which involves employing a common vocabulary and data models shared between information systems. The lack of a common language may lead to interoperability issues.

To address interoperability, the International Organization for Standardization (ISO), one of the biggest standards publishing organizations, publishes standards to share consensus-based knowledge to support activities in a wide range of areas. Moreover, the ISO Technical Committee 184 [9] has focused on solving the interoperability problem in the product development related domain. The standards developed by this committee cover a variety of areas related to industrial automation and manufacturing system integration, including business modelling, product data exchange, plants, processes, mechanical interfaces, parts catalogues, and physical device control. Although many standards are available and applicable to production management systems at different levels, the joint use of a set of these standards shows some semantic interoperability problems. Among other problems, these include the lack of compatibility between the information models and the vocabulary used by each one; the lack of formalization in the definition of concepts, preventing the automatic processing of information [10]; multiple definitions of a term and several different terms used to refer to a single concept. Moreover, some terms may be misinterpreted depending on the knowledge background and domain expertise of each expert analyzing the standard [11]–[14].

According to Chen [15], reaching semantic interoperability requires in the first instance an understanding of the formal conceptualization behind the terms handled in each involved domain. From their initial appearance, ontological approaches have offered techniques and strategies that favor the consolidation of shared meaning in computational form. So, ontologies have begun to be considered as powerful tools to achieve semantic interoperability.

Several researchers, including Kim et al. [16], Costa et al. [17] and Lin et al. [18], have pursued ontology-based understandings to solve several semantic and knowledge modelling problems in product design and manufacturing. An important observation is that most of the related works tend to exploit the Web Ontology Language (OWL) [19] as an ontological formalism, although other proposals have used alternative formalisms such as the Knowledge Exchange Format [11], [20].

Motivated by this perception, the goal of this paper is to outline an overall picture of the use of standards and ontologies in the manufacturing area, through a comprehensive review of the literature on the topic, in order to identify the main overarching themes that have been discussed previously. To achieve this goal, the intention is to create a clear and objective way of visualizing the results, as a start point for those who intend to follow this line of research. From the start of the research it was clear that this field is very broad, and that the authors needed to find a way to promote adequate visibility of the results, focusing in all the areas in which manufacturing industries interact with the product development lifecycle.

As described by Kitchenham et al. [21] a systematic literature review (SLR) allows the identification, assessment, and interpretation of relevant material to answer specific research questions. So, an SLR creates an objective summary of evidence about technology, practice, etc. Moreover, a qualitative review, a sub-classification of SLR, is meant to address questions about the specific use of technology, and is more likely to be used when researchers want to study the barriers to adopt a certain technology, hence this kind of review covers research studies about methodologies and not only practices.

In this paper, the authors aim to give a detailed description of current technological problems and solutions related to standards formalization through ontologies to set up collaborative product development strategies between geographically distributed industries; the current adoption level; and the issues and limitations that arise from this technology. That is to say, this paper is a qualitative systematic review which emphasizes the specific use of technology in a domain. Furthermore, this paper aims to be a guideline for future researchers in this area.

For these reasons, the research questions that this review aims to answer are the following:

1. Which technologies are employed by the ontology-based solutions already implemented in industrial environments?
2. What types of problems do ontology-based systems solve or tackle in industries?
3. How are ontology-based proposals presented? Are they mature enough to be implemented in industry?
4. Which standards or family of standards are considered to solve the semantic interoperability problem in industry?
    4a. Have these standards been formalized or adapted as ontologies?
    4b. Have these ontologies been used in the development of an ontology-based system?
5. Which additional models, other than standard formalizations or ad-hoc ontologies, has academia used to develop a knowledge base for product lifecycle management systems?

This paper is organized as follows: section 2 introduces theoretical background information related to enterprise, integration, interoperability, ontology, and other related definitions. A summary of similar systematic and mapping reviews related to the aforementioned topics is also provided in section 2. Section 3 describes the research method adopted and the review protocol. Section 4 presents the article selection process and a brief description of the selected studies. Section 5 provides a synthesis of the data collected from those studies in light of the research questions. In Section 6, we discuss some points identified during data analysis, which may be useful for the research agenda in Ontology-based solutions to reach semantic interoperability. Finally, in Section 7, we state the conclusions and ideas for future research.

2. Theoretical Background

Defining every core term in the domain of this research study is crucial to understanding the context. Therefore, terms like product lifecycle management, enterprise, integration, and interoperability, as well as ontology, are introduced in the following paragraphs.

According to Giachetti [22], an enterprise is “a complex, socio-technical system that comprises interdependent resources of people, information, and technology that must interact with each other and their environment in support of a common mission". The International Organization for Standardization defines enterprise as "one or more organizations sharing a definite mission, goals, and objectives to offer an output such as a product or a service" [23]. Hence, enterprise integration can be defined as the process of ensuring the interaction between enterprise entities necessary to achieve domain objectives [24]. Enterprise integration can be approached in various ways and at various levels [25]. The following approaches can be considered: (i) physical integration (interconnection of devices, numerical control machines via computer networks), (ii) application integration (integration of software applications and database systems) and (iii) business integration (coordination of functions that manage, control and monitor business processes). Some other approaches also consider (i) integration through enterprise modelling (for example through the use of a consistent modelling framework) [26] and (ii) integration as a methodological approach to achieve consistent enterprise-wide decision-making. Particularly in manufacturing industries, the decision-making process is mainly related to product lifecycle management. [27] defines this cycle as a strategic business approach that supports all the phases through which a product goes from its first conceptualization to its final disposal, providing a unique and timed product data source. Product lifecycle management (PLM) enables organizations to collaborate within and across the extended enterprise by integrating people, processes, and technologies as well as by assuring information consistency, traceability, and long-term archiving. More precisely, an effective PLM enables any employee within an industrial organization to have a full understanding of the product and its environments throughout its lifecycle [28]. A PLM system is ideally an information processing system, which integrates the core processes of a manufacturing company and connects, integrates and controls the business processes of the company through the products to be made and information closely related to the products.

Moreover, we can state that PLM systems provide interoperability among the product lifecycle phases and involved systems that manipulate the product information. Interoperability can be defined as the ability of two (or more) systems to communicate, cooperate and exchange data and services despite differences in their languages, implementation and execution environments or abstraction models [29].

According to [30], a system is interoperable only when it simultaneously meets the three levels of interoperability, which are:

- The technical level, related to the standardization of hardware and software interfaces.
- The semantic level, related to the business-level understanding between different actors.
- The organizational level, involving the identification of the inter-actors and organizational procedures.

The semantic level of interoperability, which is what concerns us, involves reaching a common understanding of business entities. Ontologies are appropriate candidates to provide a shared conceptualization of the vocabulary and used data models in enterprises.

An ontology is an explicit specification of a conceptualization [31]. An ontology includes definitions of concepts and an indication of how these concepts are inter-related, which collectively impose a structure on the domain and constrain the possible interpretations of terms [32]. A more formal definition is the one proposed by de Reuver et al. [33], "An ontology is the conceptual and terminological description of shared knowledge about a specific domain. Leaving aside the formalization and interoperability of applications, this is no more than the main competence of the term: to make improvements in communication using the same system in terms of terminology and concept".

The definition of these terms sets the scene for the present study, which aims to provide a roadmap and guidelines for the development of ontology-based solutions in the manufacturing domain. The next section provides an overview of related studies which complement this review, and also introduces the research questions about manufacturing and ontology domains, proposed by these related studies.

3. Related Studies

This section gives an overview of some relevant reviews that focus on industrial interoperability, ontologies, and product lifecycle management. These studies are summarized in Table 1 with a brief overview of each. This table presents for each article: its title, publication year, the Journal or conference proceedings in which the study was published and, finally, the research questions it reports.

Table 1. Related reviews studies on industrial interoperability, ontologies, and product lifecycle management

Title	Year	Journal/Conference	Research Questions
A systematic review to merge discourses: Interoperability, integration and cyber-physical systems [34]	2018	Journal of Industrial Information Integration	RQ1: What is the main focus of research on interoperability assessment? RQ2: How can existing approaches for interoperability assessment be adapted to support tool integration during CPS development?
Semantic interoperability for an integrated product development process: A systematic literature review [35]	2017	International Journal of Production Research	RQ1: What are the recent papers regarding the formalization of heterogeneous information and product requirements (constraints) to provide a seamless semantic interoperability across PDP? RQ2: What are the recent papers regarding the formalization of information relationships from multiple domains to support a seamless semantic interoperability across PDP?
Approaches for integration in system of systems: A systematic review [36]	2016	4th International Workshop on Software Engineering for Systems-of-Systems	RQ1: How has the integration between constituent systems of an SoS been investigated? RQ2: In this type of study, which kind of tool has been used to aid in the integration of the constituent systems?
What does PLMS (product lifecycle management systems) manage: Data or documents? Complementarity and contingency for SMEs [28]	2016	Computers in Industry	RQ1: What information needs do these partial PLMS satisfy? RQ2: what advantages and disadvantages might these two partial PLMS types offer for information integration? RQ3: What effects on usage and practices might partial PLMS have during the detailed design phase?
Ontologies in the context of product lifecycle management: State of the art literature review [37]	2015	International Journal of Production Research	RQ1: What is ontology? RQ2: What challenges have been addressed so far? RQ3: What role does ontology play? RQ4: Do we really need ontology?
Enterprise ontologies: Open issues and the state of research: A systematic literature review [38]	2014	International Conference on Knowledge Engineering and Ontology Development	RQ1: How much research activity on the field of EO has there been since 2007? RQ2: What research topics are being investigated? RQ3: What research approaches are being used? RQ4: What applications are seen for EOs? RQ5: Which topics regarding EO need further research according to the authors?
Improving the interoperability of industrial information systems with description logic-based models-The state of the art [1]	2013	Computers in Industry	RQ1: What kinds of PLM issues lead to the use of inference models, with which scope and in which fields? RQ2: Why are inference ontologies relevant for PLM applications? RQ3: How are they used in current research papers?

Foundational Ontologies for Semantic Integration in EAI: A Systematic Literature Review [39]	2013	IFIP Advances in Information and Communication Technology	RQ1: How have foundational ontologies been used as part of EAI approaches? RQ2: Do the studies use the ontologies at development time, at run time or both? RQ3: Do the studies follow a systematic approach for performing the integration project? (Do they adopt or propose a method or a process model defining activities, inputs, outputs, guidelines, etc.?)

Gürdür and Asplund [34] review studies related to interoperability assessment models. These authors provide many definitions of the term "interoperability" and also a classification of different interoperability types. They suggest that the most interesting areas in which these models can be applied are companies or industries, particularly in the context of cyber physical systems (CPS). In their work, Gürdür and Asplund classify interoperability assessment models following the approach presented by Ford [40], which classifies interoperability assessment models into maturity and non-maturity categories. Maturity models are those organized by levels while non-maturity ones are not organized at all. These authors analyze in depth four assessment models that they consider the most important: Levels of Information Systems Interoperability (LISI), Organizational Interoperability Agility Model (OIM), Level of Conceptual Interoperability Model (LCIM) and System of Systems Interoperability (SoSI). All these models are limited by focusing on partial aspects of interoperability, i.e. Technological, Organizational, Conceptual and Operational respectively. Likewise, these four models have complex metrics and limited support for decision making. Regarding the analysis of the models, the only one that takes semantic interoperability into account at a maturity level is the LCIM. The purpose of the cited work is to review the mentioned models to extract concepts that are valuable in the context of CPS integration tools.

In turn, Szejka et al. [35] propose a systematic literature review to identify the main proposals and milestones of the articles that address semantic interoperability as a research focus. These authors have taken as a premise that semantic interoperability is achievable when the information and knowledge captured can be effectively exchanged in a collaborative environment without losing the meaning of information, knowledge, and intention during this process [11]. This review aims to analyze the different approaches to reach semantic interoperability among the phases of the product development process. It looks for a general method or approach to tackle the semantic obstacles, for example hard-to-formalize vocabulary, implicated in the product domain process (PDP), considering aspects such as the malleability, geometric dimension and tolerance, function and material, and the resource of the machining. Szejka et al. [35] conducted their review studying 14 articles and 8 authors from a batch of 3607 scientific studies. In their work these authors conclude that there is not a general or integrated semantic interoperability approach to solve the relationship between domain, PDP and Product Restrictions. The research works analyzed in [35] reveal several solutions based on semantic mapping; ontology; semantic annotations; data structures and relationships; as well as features models, applicable to the particular needs of each research workgroup. The limitations detected by this study help to identify problems and guide further studies.

Vargas et al. [36] investigated the state-of-the-art System of System integration (SoSI) and the software engineering methods that aid the integration of the SoS constituent systems (CS). Most studies selected in this review describe individuals and teams who have worked in isolation to develop solutions to certain problems in this area without the widespread adoption of an integration approach. The mentioned authors also identify the following issues as the main difficulties during the integration process of the SoS constituent systems: i) management to successfully integrate individual systems in the SoS; ii) single modelling representing the SoS as a whole; iii) the complexity of interactions between the SoS entities, given the diversity and heterogeneity of the CS's, and the complexity of the

CS's due to their inability to fully understand the features of those systems; iv) the heterogeneity of the CS's, leading to a low level of collaboration and alignment with the goals of the systems; v) the protocols and interfaces that define the systems are not effective enough to provide efficient communication; vi) the scalability of the SoS as a whole; vii) the documentation of legacy systems is not always available, or complete; and viii) the lack of script or tutorials that help software engineers to perform system integration in the context of SoS. The authors of this research also conclude that 25% of the selected papers mention the use of tools that facilitate integration, like FireScrum, Mind mapping tool, RDL (Requirements Description Language), SENSE, UPPAAL, DEVS, and M-Model.

Although their study detects an increased number of related contributions from 2003 onwards, and a significant increase from 2006, Vargas et al. [36] observe that SoSI is a topic of relevance, but it is still an area of research that requires deeper studies. They also mention that there are some approaches that use Service Oriented Architecture (SOA) to integrate CSs of an SoS. This is interesting because when taking into account the technologies and tools used to integrate heterogeneous systems Vargas et al. previously studied the topic but in the context of SoS and their CS.

David and Rowe's [28] review seeks to identify the advantages and disadvantages of the different types of PLM that exist and addresses the possible uses of these systems in the detailed design phase. The main aim of this proposal is to provide Small and Medium Enterprises (SME) with support in the selection and implementation of a PLM application that best suits their needs. These authors distinguish two types of PLM solutions. One type is oriented to document management and the other focuses on relational data management. Both solution types have very different properties. Therefore, this research focuses on the analysis of which of the types - document-oriented or data-oriented - an SME, having limited resources, should implement as its PLMS.

As far as the method is concerned, David and Rowe's proposal does not detail the selection process of the articles addressed but rather acts as a complement to their previous work [41].

El Kadiri and Kiritsis [37] present a state-of-the-art study of PLM system integration issues, highlighting the objectives of ontologies in this context. The most relevant approaches that [37] identifies from the articles selected in their work are: i) to provide a structure of entities, their properties, relationships and axioms of a specific domain in different levels of granularity, and ii) to serve as a reference point for designs to extract systems specifications. El Kadiri and Kiritsis state that the limitations of the analyzed ontology-based solutions include a lack of harmonization and normalization; deficiency in expressiveness; and absence of completeness. In addition, they observe that the roles played by these solutions are not exclusively related to the problem of system integration, but have also been employed for knowledge modelling and decision making.

Leinweber et al. [38] carry out a non-exhaustive revision of articles published between 2007 and 2013 about business ontologies. According to this article, a business ontology is a formal and explicit specification of a shared conceptualization among a community of people within an enterprise (or a part of it). This review includes static, kinematic, and dynamic aspects. The review shows that most of the papers' content is related to ontology development or particular uses of ontology. Other applications found in this review are supportive tools for information systems, as well as mapping and modelling tools and frameworks. It is also important to mention that Leinweber et al. observe that ontologies can contribute to the management of a company's knowledge and to translation or information mapping. Another important fact that these authors highlight is that business ontologies can be employed to provide a collaboration artifact among companies and to support business processes. The authors of this paper stress that there is a lack of deepening of validation approaches, business values, and collaboration through semantic synchronization.

Fortineau et al. [1] propose a state-of-the-art review based on articles related to ontologies applied to product life cycle management. This research is limited to inference ontologies, i.e. ontologies that allow reasoning. This work focuses on the semantic interoperability problem and includes an analysis of an ad hoc product model. The authors do not present their method in detail. They only state that 28 articles published between 2004 and 2012 were analyzed. These authors cluster the models that were proposed in the analyzed studies considering three dimensions: i) the product lifecycle stage, ii) the granularity and the scope of the model, and iii) the focus of the model: product, process or service. The authors of this review highlight that the benefits of using ontologies in PLM applications are:

- Integration and completeness
- Embedded intelligence
- Dynamism and flexibility

Fortineau et al. [1] find that ontologies can improve interoperability, especially as an interface tool, through specific modules or layered solutions and that inference ontologies enable the visibility of different points of view (or vocabularies) and describe them in a global perspective. Hence, industries can structure information from many sources to make it reusable.

Nardi et al. [39] review several proposals based on foundational ontologies for integration between companies, particularly mentioning semantic interoperability among information systems. The foundational ontologies are a kind of (meta)ontology, independent of a problem or domain, that describe a set of real-world categories. These authors classify the application of foundational ontologies as (i) direct (reusing existent ontology); (ii) indirect (creating new ontologies inspired by other base ontologies) or (iii) mixed. At the same time, this review emphasizes that the use of ontologies can be considered during development, as an artifact that provides a mapping between concepts, and later during execution, as a support for the application of rules and restrictions. The authors investigate the use of any kind of systematic method in solution development in the studied papers, and conclude that there were only ad-hoc methodologies.

Although many researchers have previously studied ontologies in product lifecycle management as systematic literature reviews [35], none of them presents a deep analysis of the deployed solutions showing available technologies and standards.

It should be noted that none of them focuses on the use of technology and how this new technology impacts on the industry. There is no proposal that mentions the maturity of the ontologies-based solutions and how they overcome the semantic interoperability problems in the manufacturing industries. Moreover, these articles show neither the conceptual validation of these ontology models nor the impact they have, once they are implemented in industries. Hence, in this article, we will focus on providing approaches to develop ontology-based solutions, identifying models and standards to be considered in the building of an ontology in the manufacturing industry domain. Our intention is to identify how far formalized standards or standard-based ontologies succeed in establishing implemented solutions in industries.

The next section describes the methodological issues related to this review. The research method, along with the research questions, and inclusion and exclusion criteria to filter studies, are introduced. Also, the quality assessment filter used to retain only the most relevant works, is described.

4. Research Method

This section describes the process involved in conducting the Systematic Literature Review (SLR) proposed in this article following the guidelines developed by Kitchenham et al. [21]. An SLR is a process for extracting, aggregating and synthesizing data from primary studies in order to answer a set of specific research questions and generate a secondary study as a result. An SLR employs inclusion and exclusion criteria to filter the research works that will be included in the review. Furthermore, we incorporate a complementary guideline described by Wester and Watson [42] as well as the use of the snowballing technique described by Wohlin and Prikladnicki [43]. Additionally, we consider the

recommendations on the importance of including a manual target search on popular venues, authors and journals as described in [44].
Regarding the proposal of Kitchenham et al. [21], an SLR involves three phases: i) planning, ii) conducting and iii) documenting or reporting the review (Fig. 1). Planning involves the set-up activities, including defining the research question, the search protocol, and a validation protocol. Conducting the review includes searching and filtering the studies, data extraction, and schematization. Documenting is the final phase and involves writing up the results, answering the research questions, making classifications and highlighting future work or potential trends.

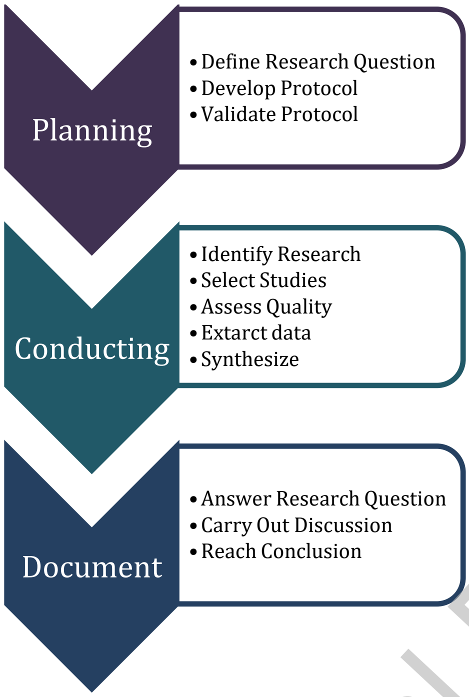

Fig. 1 Systematic review process and tasks

4.1. Objectives and Research Questions

This section states the objective of the literature review presented in this article and the research questions that guide it.
This systematic literature review started with the development of the PICOC matrix [45]. This matrix, which is presented in Table 2, helped to define the research questions around five elements: Population, Intervention, Comparison, Outcomes, and Context. The first two elements identify the entities to be included in the search, and the way such elements interact, respectively. Comparison addresses the alternatives that can be considered with regards to interaction between the studied entities. The possible results of the search and its domain are specified by the Outcomes and Context. As the Population of our search, we have included standards, ontologies, ontology-based systems, PLM systems, and product data models. The Intervention elements of the matrix are the moderator and mediator agents of the ontology-based industrial information systems. The Comparison is with ontology-based systems that are not inspired in standards. As Outcomes, we expect to extract the usability and technology of ontology-based systems in product lifecycle management. Finally, the Context of our research question is provided by the reviews of ontology-based systems approaches inspired by standards or simple models and their successes in implementation.

Table 2. Summary of PICOC

Population	Standards / Ontologies / Ontology-based systems / PLM systems /

	Product data models
Intervention	Moderators or Mediators of industrial information system using ontologies
Comparison	Ontology-based systems, which are not inspired by standards.
Outcomes	The usability and technology of the ontology-based systems in product lifecycle management (empirical validation)
Context	Reviews of ontology-based systems approaches inspired by standards or simple models and their successes in implementation.

The study has been conducted within the scope of a Collaborative Manufacturing and Ontologies project and its goal derives from the needs of that project. Collaborative product development across the geographically distributed enterprise must be set up to enable the company's production processes to remain competitive in the new industrial revolution. This collaboration means sharing knowledge between heterogeneous information systems. Enterprise collaboration requires interoperability at a conceptual level, i.e. semantic interoperability. To achieve semantic interoperability, it is necessary to understand the formal conceptualization behind the terms used in each domain and to integrate them. To achieve this, a standardized data format is a prerequisite, that is to say, an appropriate consensus of the term's formalization is needed. The use of standards seems to be an appropriate option, however, in practice industries employ different families of standards with different vocabularies, so causing new semantic discrepancies. This means that the use of standards for semantic interoperability is not as useful as may be expected. Although ontologies have been proposed by academia to deal with this type of interoperability, it is still unclear whether they have been applied in manufacturing industries. For that reason, this article aims to explore research works in academia to review the combined use of standards and ontologies applied to the design and implementation of product lifecycle management systems that support semantic interoperability. Reaching this type of integration allows PLM systems to achieve effective and efficient collaborative product development across geographically distributed enterprises.

To reflect the aforementioned scope and issues, we formulated the following research questions:

1. Which technologies are employed by ontology-based solutions already implemented in industrial environments?
2. What types of problems do ontology-based systems in industries solve or tackle?
3. How are the ontology-based proposals presented? Are they mature enough to be implemented in industry?
4. Which standards or family of standards are considered to solve semantic interoperability problems in industry?
   4a. Have these standards been formalized or adapted as ontologies?
   4b. Have these ontologies been used in the development of an ontology-based system?
5. Which additional models, other than the standard formalizations or the ad-hoc ontologies, has academia used to develop a knowledge base for product lifecycle management systems?

The primary focus of this SLR is to understand the technology used to build ontology-based systems that act as mediators to accomplish a collaborative production process between industries. That is to say, it is a qualitative systematic review which emphasizes the specific use of technology in a domain. The following section introduces the search strategy that has guided our review.

4.2. Search Strategy

The study presented in this article was conducted using four different databases: Scopus, IEEExplore, ScienceDirect, and SpringerLink. The generic search string was defined as: "standard*" AND ("OWL" OR "ontolog*" OR "semantic interoperability") AND ("product *" OR "CAX" OR "plm" OR "computer-aided *") AND ("manufactur*" OR "enterprise*" OR "industr*"). In order to select additional relevant studies, the snowballing technique [45] was employed. This technique is also mentioned by Kitcheman [21] as a source of alternative inputs to research. In addition, inclusion and exclusion criteria were defined in order to select which research studies should be included, or not, in the review.

The defined inclusion criteria are:

1. Studies from 2009 to 2018. This date was defined because 2009 was the year of Ontology Web language 2.0 release;
2. Studies in the English language;
3. Studies related to the search string defined in title, keywords and abstract;
4. Primary studies.

The exclusion criteria are:

1. The primary study is not labelled as a paper published in journal or conference proceedings;
2. Duplicated papers;
3. Secondary studies;
4. Non-English written papers;
5. Specific Domain papers;
6. The redundant papers of the same author.

4.3. Quality Assessment

The quality assessment criteria are an essential part of a systematic literature review. They provide a filter to identify and enhance the value of the research studies [21]. We reused some questions from the published literature [21], [46], [47] to outline seven closed-ended questions, stated in Table 3. Every article must be tested with the aforementioned questions and when a negative answer is found the work must be excluded from the review, due to a minimum threshold.

Table 3. Quality Assessment checklist

Item	Answer
QA1: Did the study review previous research on the topic?	Yes/No
QA2: Did the study mention a base technology for its proposal?	Yes/No
QA3: Was the article refereed?	Yes/No
QA4: Was there a clear statement of the aims of the research?	Yes/No
QA5. Was there an adequate description of the context in which the research was carried out?	Yes/No
QA6. Is there a complete description of the methodology carried out and the limitations in arriving at the conclusion presented by its authors?	Yes/No
QA7. Is the conference or journal ranked by any important reference site? (Scimago, ERA, Qualis, MSRA)	Yes/No

4.4. Data Extraction

The data schema plan is designed to record the most relevant data from the studies, in order to facilitate the analysis and answer every research question. The data schema is shown in Table 4. For every study the data collected were: title, authors, year, publication type, publication source, database, the used technology, standard formalization, the domain of application and where the proposal evaluation was carried out (academia or industry).

Table 4. Data extraction schema

Field	Description

Study ID	Identification number
Title	The paper title given by the authors
Authors	Authors of the study
Year	Year of the publication
Publication type	Event type where the paper was published
Publication source	Name of the event where the paper was published
Database	Scientific search engine where the paper was indexed
Used technology	Name of the technology used to achieve interoperability
Standard formalization or ad hoc approach	If the study employs a standard formalization, is based on a standard, or employs an ad hoc approach
Domain of application	The industry that the proposal covers
Implementation	Academia, industry or conceptual

5. Results

This section presents the results that were obtained after the execution of the conducting phase of this study, following the aforementioned search strategy. As Fig. 2 shows, this phase involved the following tasks: i) the identification of papers from the database or search engine; ii) the selection of studies, the deletion of duplicate articles and the application of inclusion and exclusion criteria; iii) data extraction and quality assessment filtering, and finally, iv) the analysis and synthesis of the remaining studies, enabling us to answer the research questions.

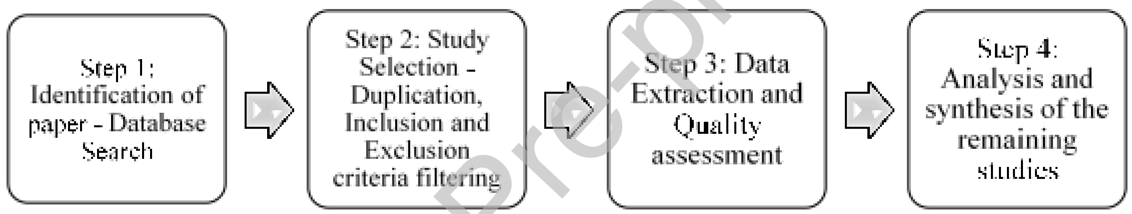

Fig. 2. Conducting Review Process

5.1 Search Results

Once the search engine had been queried, the selection process was performed to identify the relevant papers for the systematic review. It is important to highlight that the search string mentioned in the previous section was too general and this generality may have influenced the search results, since each selected engine uses a different syntax for expressing the string. So, this general search string was manually rewritten using the particular syntax of each engine. Once the results of the query executions were obtained, they were merged. Table 5 presents the papers that were retrieved from the search engines by executing the queries. The first column of the table indicates the knowledge base in which the search was carried out. The second column shows the number of studies retrieved by the query execution in each source. The third column indicates the quantity of papers left after removing the duplicate studies and filtering by the inclusion and exclusion criteria. Finally, the fourth column represents the number of studies that were excluded from the systematic review. A total of 116 studies were retained after this step. The SpringerLink search engine did not perform an effective search based on the search string, retrieving a lot of unrelated papers. ScienceDirect retrieved few studies, while, Scopus returned 194 studies of which 60% were excluded. IEEE retrieved 64 studies and approximately 36% were included. It is important to note that in the cases of duplicate studies, the article from Scopus is included and the ones from other sources are omitted from the study.

Table 5. Quantity of papers selected during the first filtering process

Source	Retrieved	Included	Excluded
IEEE	64	23	41
Scopus	194	77	117
SpringerLink	271	12	259
ScienceDirect	16	4	12
Total	545	116	429

Table 6 shows the papers finally included in our analysis, after being filtered once more by the quality assessment criteria. This table shows in the second column the same values as the third column in Table 5. Additionally, the snowballing backward technique was applied in this step and several studies, i.e. 54 research works, were added using the reference section from the 116 papers left by the previous filtering process. The fifth column, i.e. the one named “Selected after reading”, presents the studies selected for further analysis after having been read. Fig. 3 summarizes the selection process from the search engine and the snowballing technique.

Fig. 4 shows the percentage of studies finally selected from the search engines, where Scopus represents around 52% of the remaining papers thus proving to be the most effective search engine, and IEEExplorer the second most effective with 22%.

All the articles included in the review are listed in the Appendix A. In order to have a clear separation between the studies analyzed for the systematic review and those that did not participate in the review but are cited in this article, we have identified the selected articles with a code and have used this code to cite them in the text. For example, the article identified as S1 corresponds to the study entitled "Retrieval of CAD model data based on Web Services for collaborative product development in a distributed environment”, whose detailed reference is labeled as [64]. The link between the S1 code and the number in the reference list (64 in the mentioned example) is shown in the second column of the table that lists the selected articles in Appendix A. We have adopted the method of identifying the selected articles following [48].

Table 6. Quantity of papers selected during the final filtering process

Source	Remained	Excluded	Included due to QA	Selected after reading
IEEE	23	6	17	10
Scopus	77	27	50	25
SpringerLink	12	1	11	5
ScienceDirect	4	0	4	1
Subtotal	**116**	**34**	**82**	**41**
Snowballing backward	54	18	36	13
Total	170	52	118	54

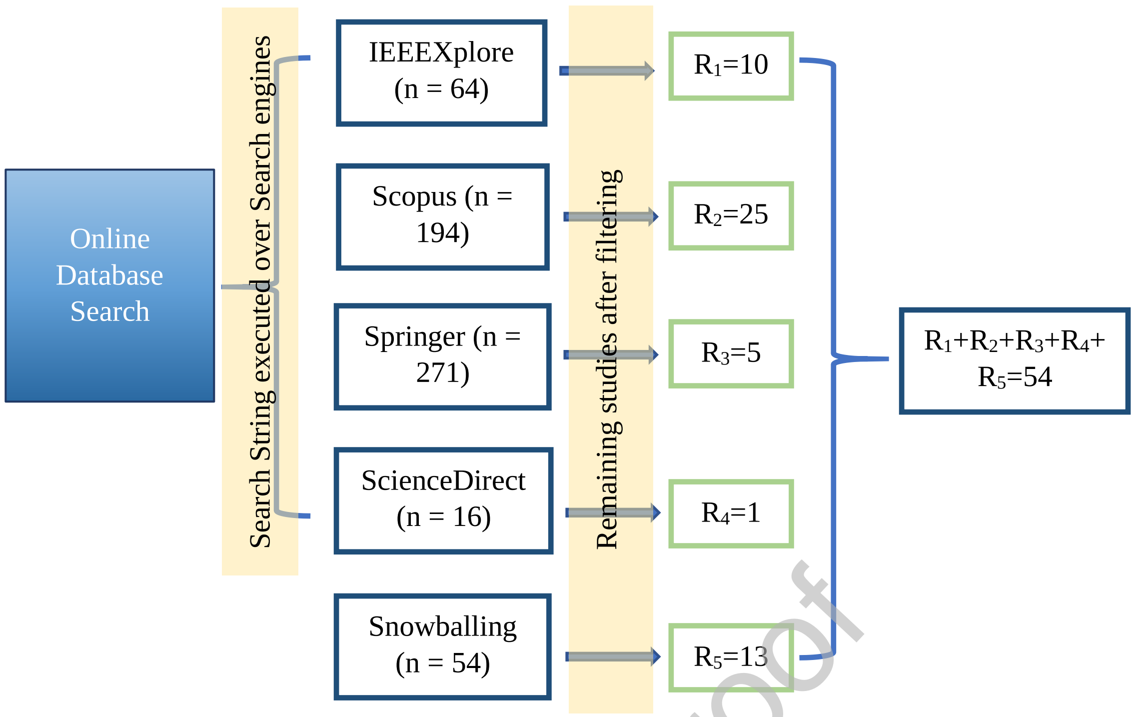

Fig. 3. Paper selection summary

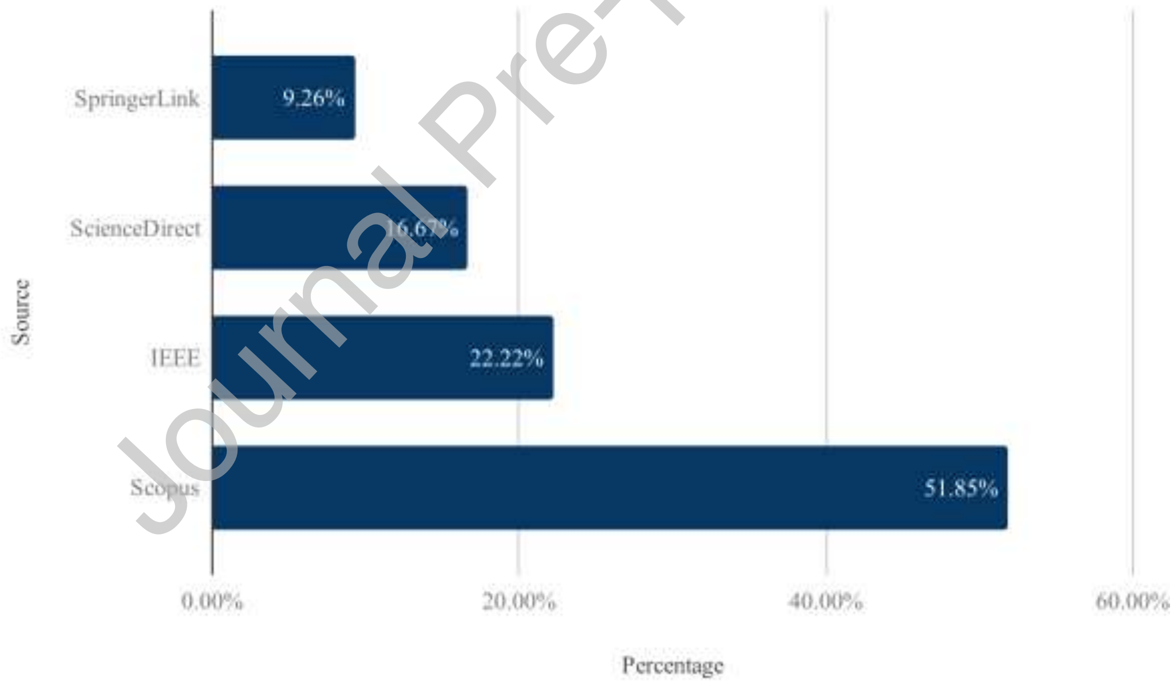

Fig. 4. Percentage of selected papers from each search engine

5.2 Overview of the selected papers

Regarding the publication in which the selected studies appeared, Fig. 5 shows the most popular journals and conferences chosen by authors in the field. The figure shows that the *Computers in Industry* journal and the *International Conference on Industrial Informatics*, holding 6 and 3 studies respectively, are preferred among the journals and conferences after the filtering process. Of the 54 research works, 39 studies (72.22%) were published in journals and 15 articles in conference proceedings. The journals in which 72,22% of the studies were published are: *Computers in Industry, The International Journal of Advanced Manufacturing Technology, Advanced Engineering Informatics, Automation in Construction, CAD Computer Aided Design, International Journal of Advanced Manufacturing Technology, International Journal of Product Lifecycle Management, International Journal of Production Research, Journal of Intelligent Manufacturing, Expert Systems with Applications, Food Control, IEEE Transactions on Automation Science and Engineering, International Journal of Circuits, Systems and Signal Processing, International Journal of Computer Integrated Manufacturing, International Journal of Manufacturing Research, International Journal on Interactive Design and Manufacturing, Journal of Ambient Intelligence and Humanized Computing, Journal of Cleaner Production, Journal of Industrial Information Integration, Key Engineering Materials, Lecture Notes in Business Information Processing and Zhejiang Daxue Xuebao (Gongxue Ban) / Journal of Zhejiang University*. In turn, the conferences at which the rest of the articles were presented are: *International Conference on Industrial Informatics, Conference on Emerging Technologies & Factory Automation, International Conference on Enterprise Information Systems, Annual Conference of the Industrial Electronics Society, International Conference on Emerging Technologies and Factory Automation, International Federation of Automatic Control, International Conference on Advanced Learning Technologies, International Conference on Automation Science and Engineering, International Conference on Electrical and Information Technologies, International Conference on P2P, Parallel, Grid, Cloud and Internet Computing, International Symposium on Industrial Electronics, International Conference on Service-Oriented Computing and Applications, International Conference on Industrial Technology*.

Fig. 6 illustrates the publication year of the selected papers. Although we have discarded similar works by the same authors, it can be observed in this graph that there is interest in the subject as new related projects emerge. The interest in semantic interoperability among industrial informatics systems is increasing but the community still does not have complete knowledge and understanding of how to implement full ontology-based systems. Moreover, the articles that report such solutions do not present a quantitative validation of the solutions, or the benefits of their implementation versus the previous solutions (the ones that existed prior to the application of the reported solution). However, this situation does not rule out that fully functional ontology-based solutions are indeed employed in the industry without been described or presented in a research article. The low number of publications in 2018 can be explained by the fact that our search string was executed in the middle term of the year and this probably affected the result.

5.3 RQ. 1. Which technologies are employed by ontology-based solutions implemented in an industrial environment?

To answer the first research question, we analyzed each study considering the language and the environment used for implementing the proposal. Regarding the implementation language, we looked for both programming and ontology modeling language.

Table 7 Programming Language employed in the proposals

Categories IDs	Programming Lang.	Percentage	Count	Studies IDs
C1	C++/C#	22.22%	4	S1, S5, S26, S44
C2	Java	66.67%	12	S3, S4, S19, S22, S31, S37, S38, S39, S50, S51, S52, S53
C3	Jython	5.56%	1	S43

C4	Prolog	5.56%	1	S18

To explore this question, we dealt with two main subjects. On one hand we analyzed the programming language used by the researchers, including: Java, Visual C++, C#, Python in its variant of Jython, and Prolog, outlined in Table 7. On the other hand, we looked for the semantic language employed in the research and how it interacted with the programming language to deploy a fully functional solution.

We found that the preferred programming language was Java with 12 identified studies ([S3], [S4], [S19], [S22], [S31], [S37], [S38], [S39], [S50], [S51], [S52], [S53]). In order to support ontology manipulation these articles propose the use of OWLAPI ([S12], [S19], [S29], [S39], [S51]), Jena library ([S4], [S38], [S53]) or the JSDAI library ([S12], [S37], [S43]).

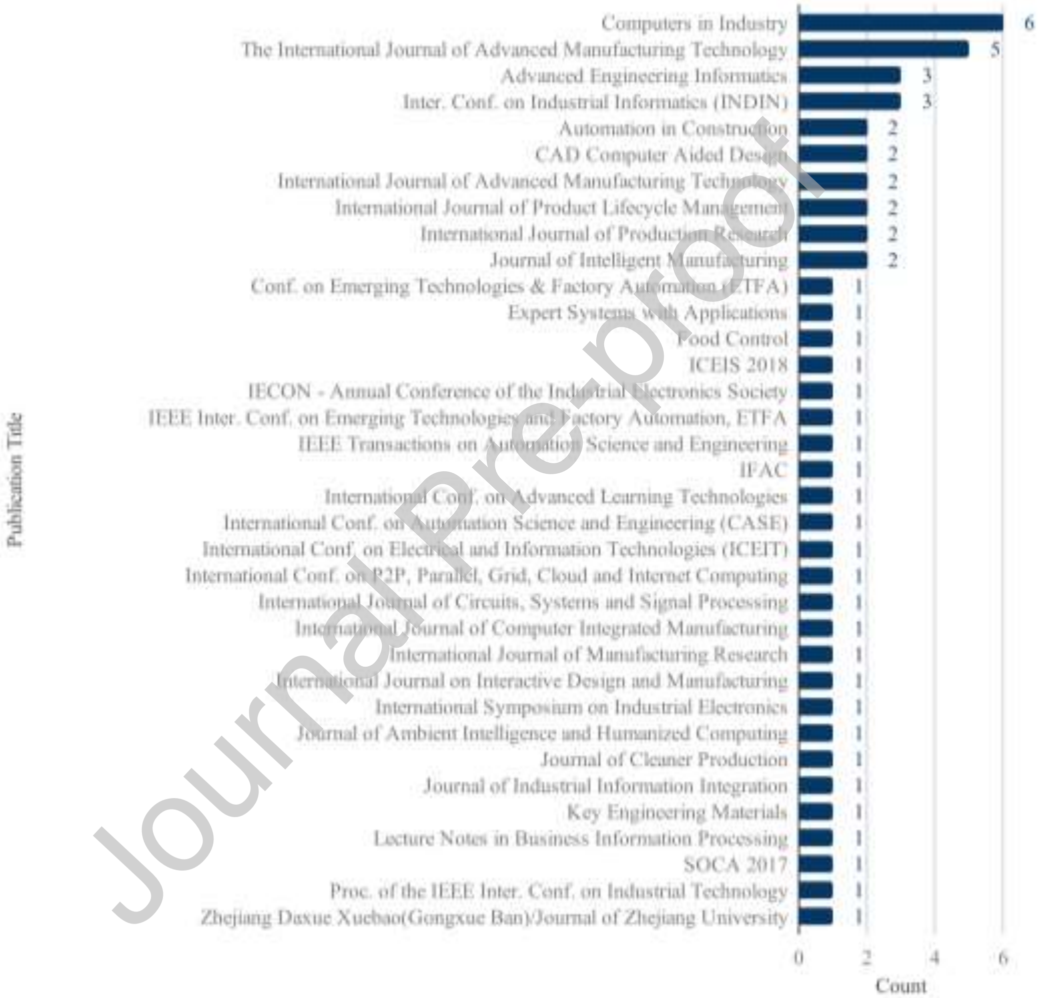

Fig. 5. Journal/Conference Publication Title

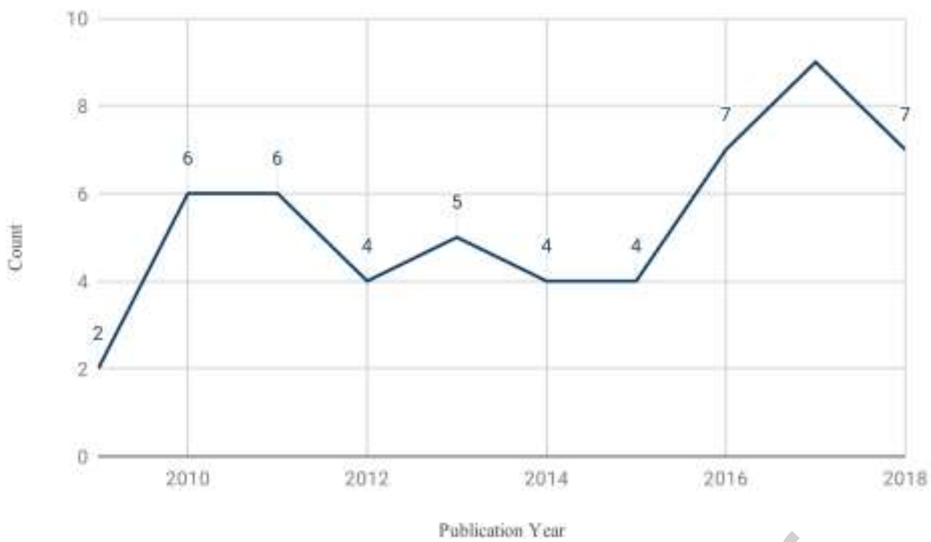

Fig. 6. Publication distribution by year

The OWLAPI is a Java API (Application Programming Interface) and reference implementation for creating, manipulating and serializing OWL ontologies, nowadays maintained by many contributors on GitHub. Meanwhile, Apache Jena (or Jena for short) [49] is a free and open source Java framework for building semantic web and Linked Data applications. The framework is composed of different APIs interacting together to process RDF data. Finally, JSDAI [50] is an API for reading, writing and runtime manipulation of object-oriented data defined by an EXPRESS based data model. Such models are widely used in STEP [51] (ISO 10303), PLIB [52] (ISO 13584) and other ISO, IEC and DIN standards a summary of this libraries and tools is presented in Table 8.

Although Java appears as the preferred programming language, we identified other programming languages as isolated cases, i.e. there are one or two studies that take them into account. For example, Visual C++ and C# were employed in [S1], [S5], [S26], [S44]. These articles propose the construction of the ontology by translating data models that are represented in Relational Database Systems or Entity framework into XML.

Table 8. Libraries or Tools employed in the proposals

Categories IDs	**Libraries or Tools employed.**	**Percentage**	**Count**	**Studies IDs**
C1	OWL	52.70%	39	S2, S3, S4, S6, S7, S8, S9, S10, S11, S12, S13, S14, S16, S17, S18, S19, S20, S21, S22, S25, S29, S30, S31, S33, S34, S35, S36, S37, S38, S39, S40, S41, S44, S45, S47, S51, S52, S53, S54
C2	Protege	29.73%	22	S2, S3, S4, S7, S12, S19, S25, S29, S33, S35, S36, S37, S38, S39, S40, S41, S45, S47, S51, S52, S53, S54
C3	OWLAPI	6.75%	5	S12, S19, S29, S39, S51
C4	Jena	4.06%	3	S4, S38, S53
C5	JSDAI	4.06%	3	S12, S37, S43
C6	IODE	2.70%	2	S50, S51

Although the studies mentioned in the previous paragraphs present the programming language used for the implementation of the proposal, several studies did not provide any information about a deployable solution. Instead, those proposals focus on presenting the ontology model, i.e. the entities, relationships, axioms, and the environment or ontology language employed by the authors.

Regarding the ontology language, we identified that Web Ontology Language (OWL) is the preferred language in the analyzed proposals. OWL is mentioned in the following articles: [S2], [S3], [S4], [S6], [S7], [S8], [S9], [S10] , [S11], [S12], [S13], [S14], [S16], [S17], [S18], [S19], [S20], [S21], [S22], [S25] ,[S29], [S30], [S31], [S33], [S34], [S35], [S36], [S37], [S38], [S39], [S40], [S41], [S44], [S45], [S47], [S51], [S52], [S53], [S54]. The Web Ontology Language was designed to build a solution that focuses on processing the information instead of presenting it to humans. OWL facilitates machine interpretability of web content and it also supports XML, RDF, and RDF Schema (RDF-S), providing additional vocabulary along with a formal semantics.

Regarding the ontology development environment, the Protégé tool [53] from Stanford University is the most common choice ([S2], [S3], [S4], [S7], [S12], [S19], [S25], [S29], [S33], [S35], [S36], [S37], [S38], [S39], [S40], [S41], [S45], [S47], [S51], [S52], [S53], [S54]). Another tool is Integrated Ontology Development Environment (IODE) [54] from Highfleet ([S50], [S51]). Imran [55] and Chungoora and Young [56] have showed that IODE offers an expressive language based on Common-Logic called Knowledge Framework Language (KFL) with the capability to write heavyweight ontologies. It also provides model validation, a library for ontological content, and tools to support visualization and sample data for testing. The particularity of this tool is that IODE is mentioned only in articles whose authors belong to a team of researchers coming from universities including the *CODATA France; Univ-Lille Nord de France; Ecole Centrale de Lille; Wolfson School of Mechanical, Electrical and Manufacturing Engineering, Loughborough University; Centre for Manufacturing, Materials and Engineering, Faculty of Engineering and Computing, Coventry University; ainia centro tecnológico, Parque tecnológico de Valencia; Instituto Tecnológico de Informática; Fraunhofer Institute for Production Systems and Design Technology; Institute for Advanced Manufacturing Engineering, Coventry University; Industrial and Systems Engineering, Pontifical Catholic University of Paraná*. Another point to mention is that all references provided by these studies to the Highfleet tool or the ontology reference are no longer accessible. So, Protégé remains the best choice when looking for an ontology development environment. In order to manipulate ontologies from a programming language like Java, Python or C#, the best tools are the Jena framework or the OWLAPI.

5.4 RQ. 2. What types of problems do ontology-based systems solve or tackle in industries?

El Kadiri and Kiritsis [37] summarized 7 key roles that ontologies play: (1) trusted source of knowledge, (2) database, (3) knowledge base, (4) bridge for multiple domains, (5) mediator for interoperability, (6) contextual search enabler, and (7) Linked Data enabler. We observe that these 7 roles are not mutually exclusive or disjointed. For example, it is not possible to deploy a mediator for interoperability without thinking of it as a synonym of a bridge for multiple domains or heterogeneous models. Also, such mediator deployment cannot be achieved if there is no knowledge base or trusted source of knowledge in which the exchanged information is stored. In addition, the contextual search enablers, which cannot be achieved without a knowledge base or a trusted source of knowledge or database, have the capability to become interoperability mediators. Hence, semantic interoperability includes several of the roles mentioned in El Kadiri and Kiritsis´s review.

Table 9. Phases covered by the proposals

Categories IDs	Phase	Percentage	Count	Studies IDs

C1	Automatic processing or configuration	6,78%	4	S2, S4, S19, S20
C2	Reusability	6,78%	4	S6, S7, S53, S54
C3	Tracing	3,39%	2	S5, S28
C4	Consistency	8,48%	5	S7, S9, S21, S29, S53
C5	Validation	1,69%	1	S13
C6	Information extraction or contextual search enabler	6,78%	4	S22, S24, S31, S39
C7	Semantic Interoperability	66,10%	39	S1, S3, S8, S10, S11, S14, S15, S16, S17, S18, S20, S23, S25, S26, S27, S28, S29, S30, S32, S33, S34, S35, S36, S37, S38, S40, S41, S42, S43, S44, S45, S46, S47, S48, S49, S50, S51, S52, S54

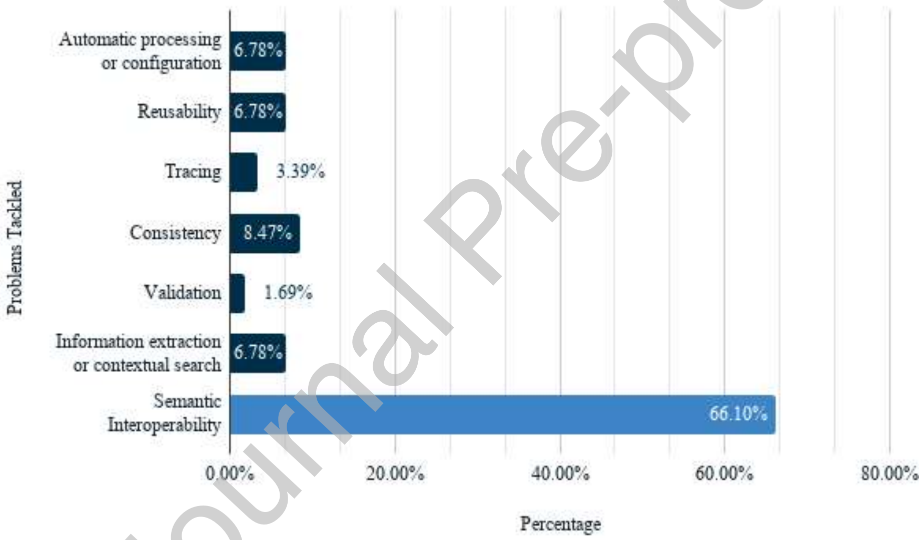

Fig. 7. Percentages of problems addressed by the proposals

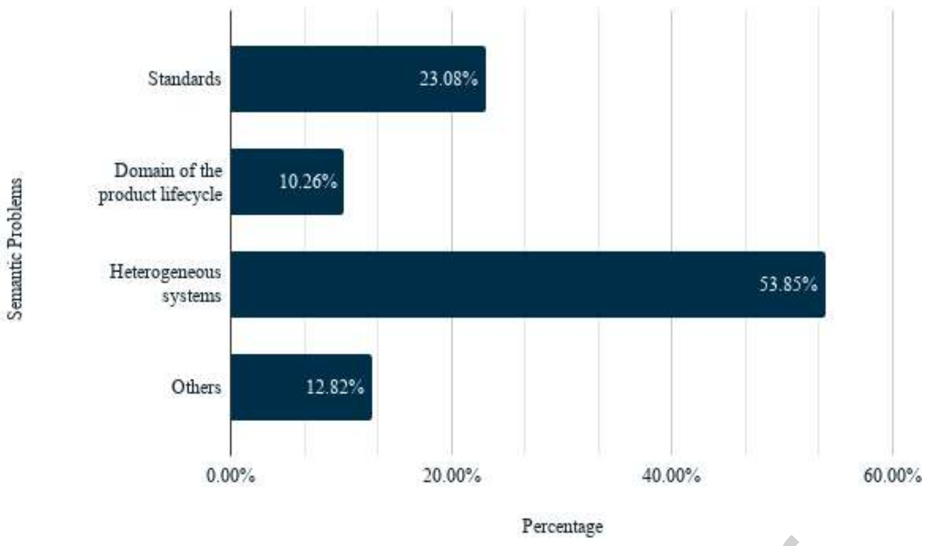

Fig. 8. Percentages of problems addressed by the proposals concerning semantic interoperability

Thirty-nine of the selected studies ([S1], [S3], [S8], [S10], [S11], [S14], [S15], [S16], [S17], [S18], [S20], [S23], [S25], [S26], [S27], [S28], [S29], [S30], [S32], [S33], [S34], [S35], [S36], [S37], [S38], [S40], [S41], [S42], [S43], [S44], [S45], [S46], [S47], [S48], [S49], [S50], [S51], [S52], [S54]) have shown that semantic interoperability, information exchange and integration rely on a consistent knowledge base. Those studies focus on the interoperability among standards ([S23], [S25], [S35], [S36], [S37], [S38], [S41], [S42], [S43], [S45]), domains of the product lifecycle ([S26], [S27], [S40], [S46]) and heterogeneous systems ([S1], [S3], [S8], [S11], [S14], [S15], [S16], [S17], [S20], [S28], [S30], [S32], [S33], [S34], [S47], [S48], [S49], [S50], [S51], [S52], [S54]) to improve production or collaboration between enterprises or areas inside a company.

Other articles propose approaches to solve problems related to: automatic processing or configuration ([S2], [S4], [S19], [S20]), reusability ([S6], [S7], [S53], [S54]), tracing ([S5], [S28]), consistency ([S7], [S9], [S21], [S29], [S53]), validation ([S13]), information extraction or contextual search enabling ([S22], [S24], [S31], [S39]).

From the analyzed studies, in Table 9 we observe that semantic interoperability among industrial information systems can be tackled with ontology-based solutions deployed as a mediator or bridge between legacy information systems, publishing web services or interfaces to handle requests from the integrated systems. These mediators can include a knowledge base to provide a method of matching different implemented vocabularies in the systems meant to interoperate with each other. Fig. 7 highlight these finding, where Semantic Interoperability represent the 66.10% of the sample, also Fig. 8 breakdown the category semantic interoperability into: i) Standards; ii) Domain of the product lifecycle; iii) Heterogeneous systems; and iv) others where it could be observed that categories “iii” and “i” are the most addressed by the authors of those proposals.

The mentioned ontology solutions are also able to provide in their specific domain: i) consistency; ii) validation; and iii) easy knowledge extraction, even though their authors do not explicitly highlight these features in their articles.

5.5 RQ. 3. How are the ontology-based proposals presented? Are they mature enough to be implemented in industry?

Regarding this question, we wanted to know how the authors of the selected papers presented the proposed solution or approach to deal with their presented challenges, i.e. if they presented a framework, a prototype, a fully installable desktop application or a web application, a middleware, a model, or a method. In Fig. 9. and Table 10, we summarize the approaches that are followed by the ontology-based solutions we have found. This figure shows that about 28% of the articles propose the development of a framework ([S1], [S2], [S3], [S4], [S14], [S18], [S29], [S30], [S31], [S33], [S35], [S43], [S45], [S46], [S49]). It is necessary to emphasize that we excluded similar proposals from the same authors. Bearing in mind that a framework can be the conjunction of methods and tools for use, the works that we have classified as such are studies in which the authors explicitly express that they are presenting a framework, which in most cases is only the definition and structure of a methodology to construct and use ontologies in a particular domain.

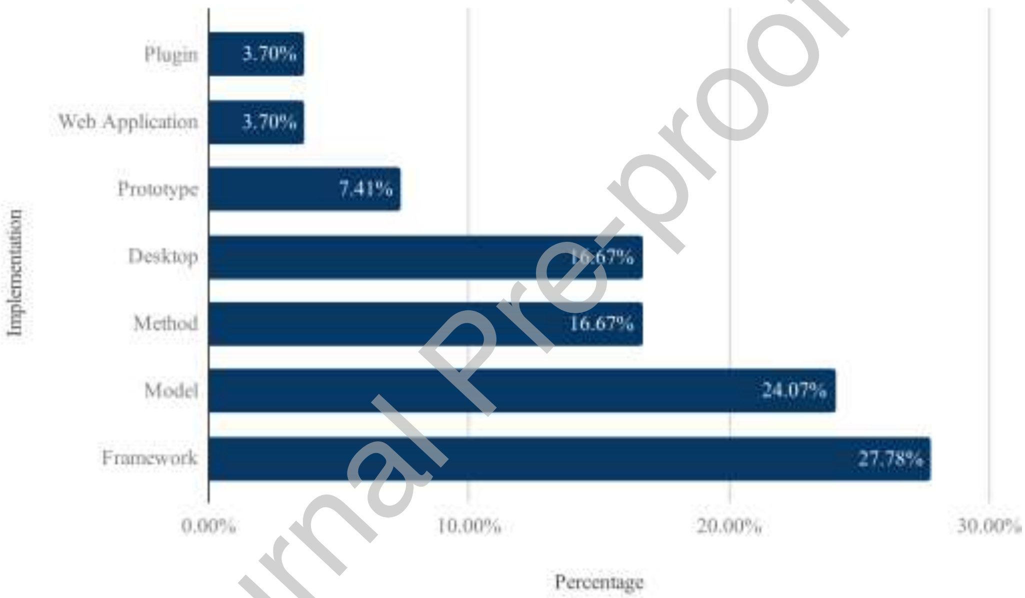

Fig. 9. Percentage of Implementation Approaches

Table 10 Implementation approaches presented in the proposals

Categories IDs	Phase	Percentage	Count	Studies IDs
C1	Framework	27,78%	15	S1, S2, S3, S4, S14, S18, S29, S30, S31, S33, S35, S43, S45, S46, S49
C2	Model	24,07%	13	S6, S7, S8, S9, S10, S11, S13, S16, S36, S37, S41, S47, S54
C3	Method	16,67%	9	S17, S23, S24, S25, S28, S32, S34, S40, S42
C4	Plugin	3,70%	2	S12, S51
C5	Web Application	3,70%	2	S27, S48
C6	Desktop	16,67%	9	S5, S15, S19, S22, S26, S38, S39, S50, S53

C7	Prototype	7,41%	4	S20, S21, S44, S52

An ontology model is the second most presented proposal, in approximately 24% of the selected studies ([S6], [S7], [S8], [S9], [S10], [S11], [S13], [S16], [S36], [S37], [S41], [S47], [S54]). Methods that use ontologies correspond to 17% of the analyzed articles ([S17], [S23], [S24], [S25], [S28], [S32], [S34], [S40], [S42]). Other categories detected are plugins ([S12], [S51]), web applications ([S27], [S48]), prototypes ([S20], [S21], [S44], [S52]) and standalone or desktop applications ([S5], [S15], [S19], [S22], [S26], [S38], [S39], [S50], [S53]). In the case of the last three categories we cannot be sure that a concrete enterprise (or enterprises) is making use of them, because despite the example of development, the solutions validations showed in the studies are based on built scenarios, without mentioning a specific floor, workshop, machinery or company involved.

There is a gap regarding proposal evaluations. Some articles propose validation through case studies or tests over controlled scenarios. Very few proposals report validation using quantitative methods. There is only one study [S49] that presents metrics. Others show partial descriptions of the number of entities but none of the selected studies present an exhaustive evaluation method of the proposed ontology model.

In addition, we catalogued the identified studies into two groups: academia and industry. The latter group contains those articles in which we were able to identify evidence of industry or enterprise collaboration. Fig. 10 shows that 93% of the articles are academic proposals, while the remaining ones ([S12], [S22], [S49]) were carried out in collaboration with industry partners.

Additionally, we analyzed which product lifecycle phases are covered by the selected research. We labelled the studies using the following categories: design, production engineering, manufacture, logistics or distribution, disposal, and the entire lifecycle. The distribution and disposal environment is managed by product information management applications and is not included in the product lifecycle management application ecosystem. In Fig.11 we summarize the percentage of studies belonging to each of these categories.

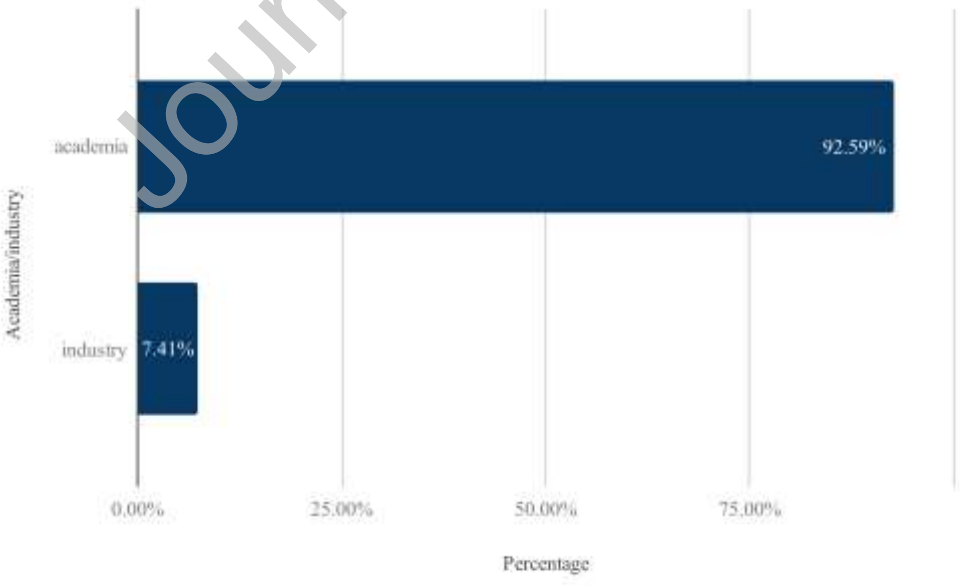

Fig. 10. Percentage of the catalogued studies that are academic proposals, or include industry collaboration

We provide Table 11 as a brief overview of this analysis. The table indicates the defined categories, their description, the studies which focus on each category, the number of studies and the overall percentage of articles in each category. Table 11 shows that the least investigated stage of the product lifecycle is disposal, with only one article ([S4]) dealing with this topic. Also, combinations of the mentioned categories have been studied, such as [S13] and [S27], articles whose proposals involve both the design and the production engineering phases, or [S15, [S19], [S25], [S26] which are focused on the production engineering and manufacture stages. Production engineering, which involves configuration, planning and simulation phases, is reflected in 5 studies ([S16], [S20], [S23], [S34], [S52]). The manufacture and design phases are tackled in 5 ([S2], [S7], [S9], [S48], [S53]) and 11 studies ([S1], [S8], [S12], [S17], [S29], [S33], [S37], [S38], [S44], [S51], [S54]) respectively. Finally, there are 13 studies ([S3], [S5], [S6], [S32], [S35], [S36], [S39], [S40], [S41], [S43], [S46], [S47], [S50]) that consider the product lifecycle as a whole. However, 8 out of the 54 studies are not focused on any stage of the product lifecycle.

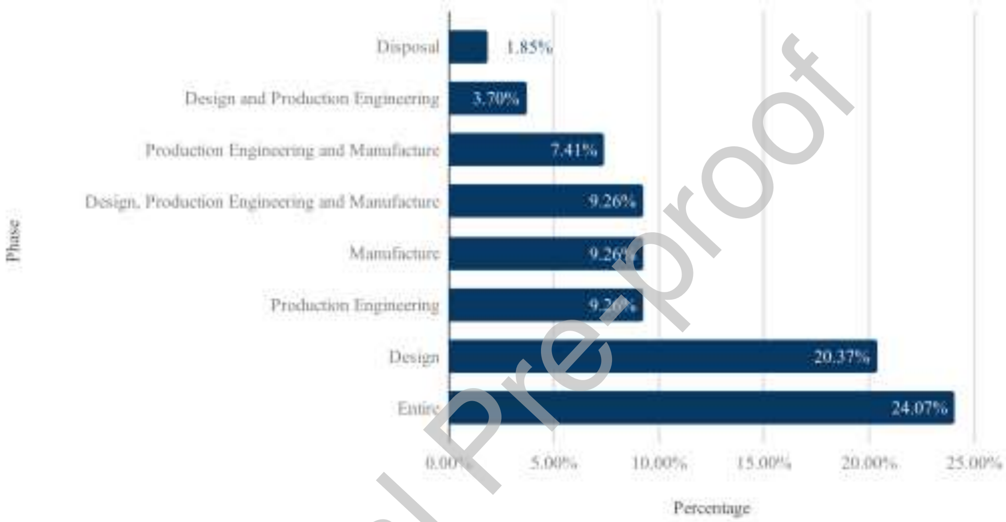

Fig. 11. Percentage of proposals focused on each Product Lifecycle phase

Table 11. Product lifecycle phase covered by selected studies

Category ID	Phase	Percentage	Count	Studies Ids
C4	Disposal	1,85%	1	S4
C6	Design and Production Engineering	3,70%	2	S13, S27
C7	Production Engineering and Manufacture	7,41%	4	S15, S19, S25, S26
C8	Design, Production Engineering and Manufacture	9,26%	5	S24, S30, S42, S45, S49
C3	Manufacture	9,26%	5	S2, S7, S9, S48, S53
C2	Production Engineering	9,26%	5	S16, S20, S23, S34, S52
C9	Not Applicable	14,81%	8	S10, S11, S14, S18, S21, S22, S28, S31
C1	Design	20,37%	11	S1, S8, S12, S17, S29, S33, S37, S38, S44, S51, S54
C5	Entire	24,07%	13	S3, S5, S6, S32, S35, S36, S39, S40, S41, S43, S46, S47, S50

The approaches that are focused on the entire product lifecycle are the most observed. In these articles we can see broad approaches focusing on the information flow and generalizations to solve knowledge management issues. Regarding the PLM stages, as shown in Table 11, the design phase is the most investigated stage. This may be due to the diversity of tools and standards, but is mainly due to the variety of the manufactured product with domain-specific terminology or terms that are outlined in standards specifically defined for such products.

5.6 RQ. 4. Which standards or standard families were considered to solve the semantic interoperability problem in industry?

During the analysis of the identified papers, we extracted the standards and models on which their proposals were based. Fig. 12 shows the percentages of the most investigated standards or models. Table 11 describes the topic tackled by each of these standards. The standards/models that appear in Fig. 12 and Table 12 are the ones that are most cited by the authors of the selected articles. The complete list of standards mentioned in the articles can be found in Table 13. As can be seen in Fig. 12, 18% of the articles deal with a standard belonging to the ISO 10303 family ([S1], [S12], [S17], [S25], [S28], [S30], [S33], [S35], [S36], [S37], [S43], [S51]), which is related to the representation of product data as well as with their exchange. 15% of the papers ([S3], [S8], [S9], [S20], [S27], [S38], [S40], [S44], [S52], [S53]) use ad-hoc models, which are inspired by standards or combine various standards formalizations or parts of them. It should be noted that no ad-hoc proposal is exempt from some foundational standard that is well-known within its own domain.
After the ISO 10303 standard family and the ad-hoc models, the IEC 62264 ([S7], [S24], [S26], [S36], [S48]), ISO 16739 ([S18], [S21], [S22], [S29]) and ISO 14649 ([S19], [S35], [S39]) standards have been mentioned in 7.46%, 5.91% and 4.48% of the articles respectively.

Table 12. Summary of the most cited standards and models from Fig. 12

Name	Specification
ISO 10303	Product data representation and exchange.
ISO 14649	Physical device control – Data model for computerized numerical controllers.
IEC 62424	Representation of process control engineering - Requests in P&I diagrams and data exchange between P&ID tools and PCE-CAE tools
IEC 62264	Enterprise-control system integration
ISO 15926	Industrial automation systems and integration -- Integration of life-cycle data for process plants including oil and gas production facilities
ISO 16739	Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering. Oriented toward capturing the ontological categories underlying natural language and human common sense.
SUMO	The Suggested Upper Merged Ontology (SUMO) and its domain ontologies form the largest formal public ontology in existence today. They are being used for research and applications in search, linguistics, and reasoning. SUMO is the only formal ontology that has been mapped to all of the WordNet lexicon.

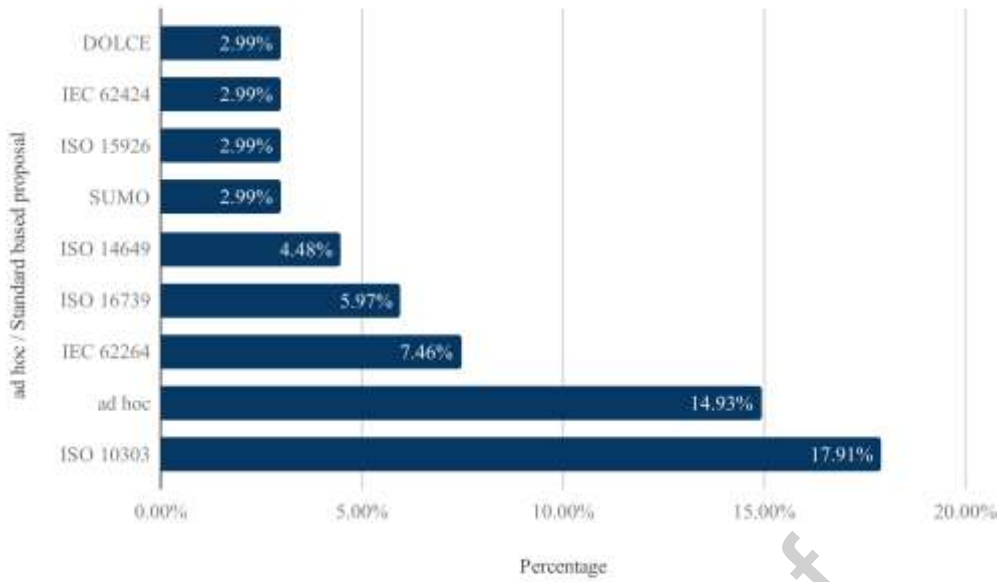

Fig. 12. The most identified standards and ad-hoc approaches by percentage

Table 13. Standards cited by selected studies

Standard formalization	Solution presented	Study ID
BPMN	NA	S25
CPM	Plugin	S51
Design Core Ontology	NA	S54
FLEXINET	NA	S49
FOAF	NA	S10
FTTO (food track and trace ontology)	NA	S16
IDM	NA	S29
IEC 1512	Desktop	S26
IEC 15944	NA	S24
IEC 81346	NA	S11
ISO 13584	NA	S42
ISO 14000	NA	S6
ISO 14044	NA	S6
ISO 15531	NA	S42
ISO 16100	NA	S3
ISO 25012	NA	S23
ISO TC184/SC4	NA	S41
Manufacturing core ontology	NA	S42
Material Core Ontology	NA	S54
OAGIS 9.2	NA	S46
ResumeRDF	NA	S10
SKOS	NA	S10
Product data and management Sematic object model	NA	S47
Tolerance Core Ontology	NA	S54
ISO 18629	NA	S42
DOLCE	NA	S14, S28
IEC 62424	Desktop	S13, S15

ISO 15926	Desktop	S26, S28
SUMO	NA	S14, S31
ISO 14649	Desktop	S19, S35, S39
ISO 16739	Prototype, Desktop	S18, S21, S22, S29
IEC 62264	Web Application,	S7, S24, S26, S36, S48
ad hoc	Web Application, Prototype, Desktop	S3, S8, S9, S20, S27, S38, S40, S44, S52, S53
ISO 10303	Plugin	S1, S12, S17, S25, S28, S30, S33, S35, S36, S37, S43, S51

There are two standards (IEC 62424 and ISO 15926) and two foundational ontologies (DOLCE and SUMO) that are selected in only 2,99% of the articles. In addition, 25 other standards and ontologies were identified that are mentioned in only one or two papers. The complete list of the standards and data models that we identified in the study can be found in Table 13. In addition, the second column of this table presents, using the proposal classification introduced in section 5.5, the type of applications that are proposed in the different articles that use each standard or model. We have used the NA acronym to point out those papers without an appropriate implementation.

5.7 RQ. 5. Which additional models, other than standards formalization or ad-hoc ontologies, has academia used to develop a knowledge base for product lifecycle management systems?

According to Brachman [57], a knowledge base involves a symbolic representation whose design is the foundation of the intentional stance in any knowledge-based system. These symbolic representations are intricately related to knowledge representation, which implies the desire to build a system.

To answer the final research question, we analyzed each study searching for descriptions of the technologies specifically used to create a knowledge base. The result of this analysis showed that there are many studies that do not mention the way they implement knowledge bases or, even worse, do not mention the existence of any base. In the studies that describe the technology used for building their knowledge base, most of the articles used OWL for developing ontology and knowledge representation in their proposals, as mentioned in Section 5.3. There are also some proposals that select the common logic language for knowledge representation. However, not every approach employs an ontology language. Instead of OWL or common-logic based languages, we have found knowledge representation through XML ([S1], [S5], [S26]) via relational databases and Entity Frameworks as mentioned in Section 5.3. Other approaches use the Prolog ([S18]) programming language and Jess ([S30], [S52]) scripting environment for the Java programming language. Prolog is a programming language whose logic is expressed in the form of relations and clauses. In turn, Jess is a rule engine and scripting environment in which Java based-solutions can be developed with reasoning capacity employing knowledge representation through declarative rules.

6. Discussion

This section firstly presents a discussion of the implications of this study (Section 6.1). Later in Section 6.2, we will discuss the technology available to develop an ontology-based solution for the manufacturing industry, taking into account the domain of application, the phases of the product lifecycle, and the current enterprise architecture. Then, a discussion about the threats to validity of the present paper is introduced in Section 6.3.

6.1 Systematic Literature Review Implication

We found that the implications from this review and those mentioned in section 2, contribute greatly to the use of ontologies. Our analysis of the articles identified the most investigated technologies and models. In this last section, the authors wish to highlight the technologies and models necessary to implement ontology-based systems in manufacturing industries, which may be a guide for future advances in this area, since the research has not found any development that has yet been faithfully implemented in a business environment.

6.2 Available technology for Ontology-based solutions

According to [58] a semantic language for a manufacturing domain must support conceptual modelling and data storage, easy use, model maintenance, interoperability, and automated reasoning. Thus, we should exclude some semantic languages like DublinCore, FLogic, KIF, Loom, OCML, OntoLingua, RDF (S), SHOE, UML, XML (S) and XOL. OWL and OWL sublanguages are the best choice as we highlight in our analysis.

OWL is an ontology language which is compatible with SHOE and DAML + OIL and is an extension of RDF(S), although it can express more semantics. It includes classes and operations on classes such as conjunction and disjunction and existentially and universally quantifiable variables. One of the significant features of the OWL language is its ability to make equality claims. OWL is able to make logical inferences and derive knowledge. Also, OWL supports reasoners which, in conjunction with rules definitions, can derive and validate the knowledge base. Moreover, these rules can be used as a mapping or alignment strategy between ontologies. The most popular way to create rules is using the semantic web rule language (SWRL). However, Jena has its own rule language. SWRL language needs a reasoner that supports its syntax. Some of the reasoners that support SWRL rules are KAON2, RacerPro, Hoolet, Pellet, Hermit, SWRL2COOL, SWRL-IQ, Bossam, and Stardog. Therefore, Protégé is a worthy candidate to build and manipulate ontologies with SWRL rules. It implements many reasoners in its environment, as well as an SWRL editor. Hence, the OWLAPI and Pellet API for Java can be used to support solution development.

Furthermore, to start research or development in this area we must highlight four important ontology projects which involve many of the greatest contributions in this area. The projects are the following: FLEXINET [59] which aims to define reference ontologies from which to base the flexible re-configuration of globalized production networks [60]; Interoperable Manufacturing Knowledge Systems (IMKS) [61], which tries to achieve semantic interoperability between the design and manufacture phases of the product lifecycle, making use of a heavyweight ontology solution taking into account many ISO standards; MSEE [62], which targets as its main result the transformation of the industrial business scenarios of Europe making new Virtual Factory Industrial Models, to provide a new collaborative ecosystem for manufacturing; and the Manufacturing Information ontological model set out by Hastilow [63], whose objective is to define a mechanism for evaluating system interoperability requirements and capability in environments which experience rapid change using ontologies.

6.3 Threats to validity of the present paper

The results of this present work might have been affected by certain limitations such as inaccuracy in data extractions, the bias in the selection of primary studies, and a misleading search string for each search engine to extract the studies. Moreover, the filtering process using the quality assessment criteria was subjective. Any discrepancies found were discussed among the authors until a consensus was met. Our present study might have also missed out other studies which have implemented an ontology-based solution that has been patented or commercialized, but have not been published for privacy or copyright reasons. We address the issue of bias in study selection via searching on the most popular search engines, using the snowballing technique, and manual search in targeted journals, conferences and authors that help to minimize the possibility of missing evidence.

7. Conclusion

In this review, different research questions have been addressed in order to emphasize how far the manufacturing environment is from the wide use of ontology-based systems, beyond the academic frontier. In this way, it is possible to solve the problems of the reuse of knowledge and semantic interoperability of multiple heterogeneous systems.

Summarizing our findings from this review, we suggest the following:

1) Regarding the technology employed, we suggest the use of Protégé as an ontology modeling tool and the Jena API to manipulate the developed ontologies. Jena can be used with .Net framework languages, Jython and Java to develop solutions that manipulate ontologies.
2) We identified that most studies employ ontology models as a knowledge base to solve ambiguities, providing a bridge, mediator or contextual search engine. Those approaches are not disjointed; we believe that they are synonyms from a systemic perspective. Therefore, ontology-based proposals pave the way to reuse knowledge, provide consistency, solve semantic ambiguities and integrate heterogeneous systems mainly in those industries whose systems implement different standards or models.
3) The main contributions from the studies are frameworks related to processes or methodologies that use raw solutions involving ontologies, without the presence of a fully implemented application that provides an interface to manage interactions with ontologies and the other systems involved. The second most identified proposals are methods and ontology models. It might be a lack of knowledge in the area of software development that encourages this kind of project, in which a software technology background is not needed, or due to patents or constraints, that industrial ontology-based systems are generally not presented in the selected studies.
4) The standards from the ISO technical committee 184, subcommittees 4 and 5, are the most investigated, especially ISO 10303 and IEC 62264. These subcommittees have put their effort into publishing standards around industrial data and interoperability, integration, and architectures for enterprise systems and automation applications, which may be the first place that researchers should go to find models and approaches for ontology-based solutions.
5) Expert systems based on rule definition through Jess, a rule engine for Java, were also found, as well as some other modelling approaches with XML-based solutions supported by relational database systems or modeling frameworks like the Entity framework from .NET framework. These present some alternatives to ontology-based solutions for integration and managing knowledge bases, but from our perspective, ontologies through OWL reasoners provide a better choice to address semantic interoperability.

We believe the findings of this study make an important contribution to practitioners and researchers as they provide them with useful information about the different projects and the choices involved in undertaking projects in the industrial ontology application domain. For practitioners, our review has highlighted the main contributors, programming languages, tools, models and standards. Also, we have categorized the level of maturity of the contributions as they have been deployed in industry up to now. For researchers, the number of selected studies indirectly indicates that the topic is a great challenge, due to its multidisciplinary nature and the information flow that needs to be orchestrated among the product lifecycle phases to enable geographically distributed companies to collaborate in the execution of their manufacture processes. Moreover, the popular publication venues identified in our searches can be useful for those who want to perform a further literature review in this area.

As to potential future work, this review lays the foundations to continue with the development of a system based on service-oriented ontologies, which allows mediation between the heterogeneous systems of geographically distributed industries and even among legacy systems that have not been properly integrated with the product lifecycle, thus solving the problem of semantic interoperability.

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9. Conflict of Interest Statement

The paper has not been submitted or published elsewhere.
There is no conflict of interest between the authors and their respective affiliations.

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Appendix A. List of studies selected for the review (primary sources)

Studies ID	Item Title	Publication Year	Publication Type	Publication Title	Source	Phase	Implementation	Problems Tackled	Standards approached
S1	Retrieval of CAD model data based on Web Services for collaborative product development in a distributed environment [64]	2010	Journal	The International Journal of Advanced Manufacturing Technology	SpringerLink	Design	Framework	Semantic Interoperability	ISO 10303
S2	Task-driven manufacturing cloud service proactive discovery and optimal configuration method [65]	2016	Journal	The International Journal of Advanced Manufacturing Technology	SpringerLink	Manufacture	Framework	Automatic processing or configuration	NA
S3	Multi-level ontology integration model for business collaboration [66]	2016	Journal	The International Journal of Advanced Manufacturing Technology	SpringerLink	Entire	Framework	Semantic Interoperability	Ad hoc | ISO 16100
S4	Ontology-based disassembly information system for enhancing disassembly planning and design [67]	2015	Journal	The International Journal of Advanced Manufacturing Technology	SpringerLink	Disposal	Framework	Automatic processing or configuration	NA
S5	Product data model for PLM system [68]	2011	Journal	The International Journal of Advanced Manufacturing Technology	SpringerLink	Entire	Desktop	Tracing	NA
S6	An information classification system for life cycle and manufacturing standards [69]	2014	Conference	International Conference on Automation Science and Engineering (CASE)	IEEE	Entire	Model	Reusability	ISO 14044 | ISO 14000
S7	An ISA-95 based Ontology for Manufacturing Systems Knowledge Description Extended with Semantic Rules [70]	2018	Conference	International Conference on Industrial Informatics (INDIN)	IEEE	Manufacture	Model	Reusability | Consistency	IEC 62264
S8	An ontology-based framework for virtual enterprise integration and interoperability [71]	2016	Conference	International Conference on Electrical and Information Technologies (ICEIT)	IEEE	Design	Model	Semantic Interoperability	Ad hoc
S9	Ensuring the consistency between assembly process planning and machine control	2017	Conference	International Conference on Industrial Informatics (INDIN)	IEEE	Manufacture	Model	Consistency	Ad hoc

	software [72]								
S10	Exploiting Semantic and Social Technologies for Competency Management [73]	2010	Conference	International Conference on Advanced Learning Technologies	IEEE	NA	Model	Semantic Interoperability	SKOS | Resume RDF | FOAF
S11	Linked data for building management [74]	2016	Conference	IECON - Annual Conference of the Industrial Electronics Society	IEEE	NA	Model	Semantic Interoperability	IEC 81346
S12	Ontology based geometry recognition for STEP [75]	2010	Conference	International Symposium on Industrial Electronics	IEEE	Design	Plugin	NA	ISO 10303
S13	Ontology-based validation of plant models [76]	2013	Conference	International Conference on Industrial Informatics (INDIN)	IEEE	Design and Production Engineering	Model	Validation	IEC 62424
S14	Secure Enterprise Interoperability Ontology for Semantic Integration of Business to Business Applications [77]	2013	Conference	International Conference on P2P, Parallel, Grid, Cloud and Internet Computing	IEEE	NA	Framework	Semantic Interoperability	SUMO | DOLCE
S15	The CAEX tool suite - User assistance for the use of standardized plant engineering data exchange [78]	2010	Conference	Conference on Emerging Technologies & Factory Automation (ETFA)	IEEE	Production Engineering and Manufacture	Desktop	Semantic Interoperability	IEC 62424
S16	MESCO (MEat Supply Chain Ontology): An ontology for supporting traceability in the meat supply chain [79]	2017	Journal	Food Control	ScienceDirect	Production Engineering	Model	Semantic Interoperability	FTTO
S17	A formal EXPRESS-to-OWL mapping algorithm [80]	2010	Journal	Key Engineering Materials	Scopus	Design	Method	Semantic Interoperability	ISO 10303
S18	A framework for integrating syntax, semantics and pragmatics for computer-aided professional practice: With application of costing in construction industry [81]	2016	Journal	Computers in Industry	Scopus	NA	Framework	Semantic Interoperability	ISO 16739
S19	A hybrid approach to energy-efficient machining for milled components via STEP-NC [82]	2018	Journal	International Journal of Computer Integrated Manufacturing	Scopus	Production Engineering and Manufacture	Desktop	Automatic processing or configuration	ISO 14649
S20	A metadata based manufacturing resource ontology modeling in cloud manufacturing systems [83]	2018	Journal	Journal of Ambient Intelligence and Humanized Computing	Scopus	Production Engineering	Prototype	Semantic Interoperability | Automatic processing or configuration	Ad hoc

S21	A query expansion method for retrieving online BIM resources based on Industry Foundation Classes [84]	2015	Journal	Automation in Construction	Scopus	NA	Prototype	Consistency	ISO 16739
S22	A rule-based methodology to extract building model views [85]	2018	Journal	Automation in Construction	Scopus	NA	Desktop	Information extraction or contextual search enabler	ISO 16739
S23	Adding quality of information to the ontological model of an enterprise [86]	2017	Journal	Lecture Notes in Business Information Processing	Scopus	Production Engineering	Method	Semantic Interoperability	ISO 25012
S24	Aligning Business Services with Production Services: The Case of REA and ISA-95 [87]	2017	Conference	Proceedings - 2017 IEEE 10th International Conference on Service-Oriented Computing and Applications, SOCA 2017	Scopus	Design, Production Engineering and Manufacture	Method	Information extraction or contextual search enabler	IEC 62264 | IEC 15944
S25	An energy efficiency focused semantic information model for manufactured assemblies [88]	2017	Journal	Journal of Cleaner Production	Scopus	Production Engineering and Manufacture	Method	Semantic Interoperability	ISO 10303 | BPMN
S26	An industry-oriented ontology-based knowledge model for batch process automation [89]	2018	Conference	Proceedings of the IEEE International Conference on Industrial Technology	Scopus	Production Engineering and Manufacture	Desktop	Semantic Interoperability	IEC 62264 | ISO 15926 | IEC 1512
S27	An integrated application for historical knowledge management with mould design navigating process [90]	2013	Journal	International Journal of Production Research	Scopus	Design and Production Engineering	Web Application	Semantic Interoperability	Ad hoc
S28	An ontological approach for reliable data integration in the industrial domain [91]	2014	Journal	Computers in Industry	Scopus	NA	Method	Semantic Interoperability | Tracing	ISO 10303 | Ad hoc | ISO 15926 | DOLCE
S29	An ontology-based approach for developing data exchange requirements and model views of building information modeling [92]	2016	Journal	Advanced Engineering Informatics	Scopus	Design	Framework	Semantic Interoperability | Consistency	ISO 16739 | IDM
S30	An ontology-based product design framework for manufacturability verification and knowledge reuse [93]	2018	Journal	International Journal of Advanced Manufacturing Technology	Scopus	Design, Production Engineering and Manufacture	Framework	Semantic Interoperability	ISO 10303
S31	An ontology-driven framework towards building enterprise	2013	Journal	Advanced Engineering Informatics	Scopus	NA	Framework	Information extraction or contextual search enabler	SUMO

	semantic information layer [94]								
S32	Closed-loop manufacturing process based on STEP-NC [95]	2017	Journal	International Journal on Interactive Design and Manufacturing	Scopus	Entire	Method	Semantic Interoperability	NA
S33	Knowledge framework for intelligent manufacturing systems [96]	2011	Journal	Journal of Intelligent Manufacturing	Scopus	Design	Framework	Semantic Interoperability	ISO 10303
S34	Manufacturing process modelling using process specification language [97]	2011	Journal	International Journal of Advanced Manufacturing Technology	Scopus	Production Engineering	Method	Semantic Interoperability	
S35	ManuService ontology: a product data model for service-oriented business interactions in a cloud manufacturing environment [98]	2016	Journal	Journal of Intelligent Manufacturing	Scopus	Entire	Framework	Semantic Interoperability	ISO 10303 | ISO 14649
S36	ONTO-PDM: Product-driven ONTOlogy for Product Data Management interoperability within manufacturing process environment [4]	2012	Journal	Advanced Engineering Informatics	Scopus	Entire	Model	Semantic Interoperability	ISO 10303 | IEC 62264
S37	Ontology based automatic feature recognition framework [99]	2014	Journal	Computers in Industry	Scopus	Design	Model	Semantic Interoperability	ISO 10303
S38	Ontology based product knowledge integration [100]	2009	Journal	Zhejiang Daxue Xuebao(Gongxue Ban)/Journal of Zhejiang University (Engineering Science)	Scopus	Design	Desktop	Semantic Interoperability	Ad hoc
S39	Ontology for manufacturing resources in a cloud environment [101]	2014	Journal	International Journal of Manufacturing Research	Scopus	Entire	Desktop	Information extraction or contextual search enabler	ISO 14649
S40	Ontology-based approach for product information exchange [102]	2015	Journal	International Journal of Product Lifecycle Management	Scopus	Entire	Method	Semantic Interoperability	Ad hoc
S41	Semantic interoperability among industrial product data standards using an ontology network [103]	2018	Conference	ICEIS 2018 - Proceedings of the 20th International Conference on Enterprise Information Systems	Scopus	Entire	Model	Semantic Interoperability	ISO TC184 / SC 4
S42	A model-driven ontology approach for manufacturing system interoperability and knowledge sharing [11]	2013	Journal	Computers in Industry	ScienceDirect	Design, Production Engineering and Manufacture	Method	Semantic Interoperability	ISO 18629 | Manufacturing Core Ontology | ISO 15531 | ISO 13584

S43	A PLCS framework for PDM/ERP interoperability framework [104]	2011	Journal	International Journal of Product Lifecycle Management	Scopus	Entire	Framework	Semantic Interoperability	ISO 10303
S44	A semantic product modeling framework and its application to behavior evaluation [105]	2012	Journal	IEEE Transactions on Automation Science and Engineering	IEEE	Design	Prototype	Semantic Interoperability	Ad hoc
S45	A semantic reconciliation view to support the interoperable information relationships in product design and manufacturing [106]	2017	Journal	IFAC	ScienceDirect	Design, Production Engineering and Manufacture	Framework	Semantic Interoperability	NA
S46	An integration framework for product lifecycle management [107]	2011	Journal	CAD Computer Aided Design	ScienceDirect	Entire	Framework	Semantic Interoperability	OAGIS 9.2
S47	An ontology-based approach for Product Lifecycle Management [108]	2010	Journal	Computers in Industry	ScienceDirect	Entire	Model	Semantic Interoperability	Product data management semantic object model
S48	Integration between MES and product lifecycle management [109]	2011	Conference	IEEE International Conference on Emerging Technologies and Factory Automation, ETFA	IEEE	Manufacture	Web Application	Semantic Interoperability	IEC 62264
S49	Interoperable manufacturing knowledge systems [110]	2017	Journal	International Journal of Production Research	Scopus	Design, Production Engineering and Manufacture	Framework	Semantic Interoperability	FLEXINET
S50	Mediation of foundation ontology-based knowledge sources [111]	2012	Journal	Computers in Industry	ScienceDirect	Entire	Desktop	Semantic Interoperability	NA
S51	OntoSTEP: Enriching product model data using ontologies [112]	2012	Journal	CAD Computer Aided Design	ScienceDirect	Design	Plugin	Semantic Interoperability	ISO 10303 | CPM
S52	Product configuration knowledge modeling using ontology web language [113]	2009	Journal	Expert Systems with Applications	ScienceDirect	Production Engineering	Prototype	Semantic Interoperability	Ad hoc
S53	Semantic organization of product lifecycle information through a modular ontology [114]	2015	Journal	International Journal of Circuits, Systems and Signal Processing	Scopus	Manufacture	Desktop	Reusability | Consistency	Ad hoc
S54	The reference view for semantic interoperability in Integrated Product Development Process: The	2017	Journal	Journal of Industrial Information Integration	ScienceDirect	Design	Model	Semantic Interoperability | Reusability	Tolerance Core Ontology | Material Core Ontology | Design Core Ontology

conceptual structure for injecting thin walled plastic products [115]