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Knowledge reuse for ontology modelling in Maintenance and Industrial Asset Management

Maintenance and Industrial Asset Management (AM) are fundamental business processes in guaranteeing the availability of physical assets at minimum risk and cost, while balancing the interests of several stakeholders. To reach operational excellence, intra- and inter-enterprise interoperability of systems is needed to support information management and integration between several involved parties. To this end, ontology engineering is relevant since it supports interoperability at technical and semantic levels. However, ontology modelling methodologies are varied, and several best practices exist, among which knowledge reuse. Nevertheless, reusing extant knowledge is not completely exploited so far, causing a heterogeneous ensemble of ontologies that are not orchestrated. The present work aims at promoting the adoption of knowledge reuse for ontology modelling in maintenance and AM. Therefore, an extensive review of existing ontologies for the two targeted business processes is performed with a twofold objective: firstly, to realise a cross-industrial ontological compendium, and secondly to understand the state of art of ontology modelling in maintenance and AM. To support the adoption of knowledge reuse, this practice is framed in AMODO (Asset Management Ontology Development methOdology). Finally, a laboratory-sized showcase is provided to prove the usefulness of relying on knowledge reuse during the ontology development. The results show that the developed ontology is realised faster and is inherently aligned with established ontologies, towards enterprise systems interoperability. Consequently, maintenance and AM business processes may rely on information management and integration to pursue operational excellence.

Keywords: ontology, knowledge reuse, interoperability, maintenance, Asset Management

Highlights

- Knowledge reuse is relevant to guarantee interoperability
- Ontological resources reuse allows to extend previous knowledge
- Foundational ontologies must be considered to enable proper reuse
- A cross-industrial compendium of ontologies is realised for maintenance and AM

1. Introduction

The current industrial scenario is making intra- and inter-enterprise interoperability of systems mandatory to reach operational excellence since it guarantees proper data sharing and valorisation [1]. Interoperability could be seen as a first step towards integration, since the latter implies functional dependence between systems [2]. This, in tun, promotes the collaborative and distributed settings that are today vital to foster the digital transformation for improved productivity and sustainability [3,4]. Therefore, given the relevance of the Industrial Information Integration discipline in the current industrial context to exploit at maximum the business processes [5,6], moving the first steps by addressing interoperability is mandatory and challenging in smart factories [7]. To this end, ontology engineering is becoming central to foster interoperability at both semantic and technical levels: at semantic level, ontologies allow creating shared concepts and related meanings between different stakeholders [8]; at technical level, ontologies guarantee consistent data formats among systems for advanced data management [9]. Reasoning and inference making capabilities over small and large repositories make ontologies even more powerful since they are able to augment the data stored in traditional relational database and deduce conclusions based on available dispersed information [10]. All in all, companies are looking with interests towards ontologies, due to the centrality of enhanced information management and integration [11,12], which is relevant in the current industrial scenario to generate business value [13].

Among those business processes that benefit from the application of ontologies, maintenance and AM are seeing an increasing interest: their processes are more and more interlaced with other company processes and data from different sources need to be integrated [14]. The usefulness of ontology adoption is unclosed across industries, including manufacturing, construction, and process industries. In manufacturing, companies are seeking for the use of ontologies to manage the increase in number of data sources [15]; this is due to the intensive digitalization manufacturing companies are undertaking [16]. The process industry, in which Oil&Gas plays a central role, is open to the use of ontologies to manage and coordinate all participants involved in AM, considering the complex structure of the system [17]. Also, in process industry the ISO 15926 was released with a strong ontological commitment [18], which is a sign of relevance given to ontologies. Similarly, due to system complexity and multi-stakeholders management needs, ontologies are also bringing advantages to the construction industry [19]. Herein ontologies are fully exploited thanks to BIM (Building Information Modelling), which is a structured repository of data to be shared among interested parties for different purposes, from idealisation, to design, realisation, and maintenance [20], thus covering the entire asset lifecycle [21].

This wide and diversified use brings to a heterogeneous ensemble of ontologies being developed so far. This occurs because best practices in ontology modelling, like the usage of a foundational ontology and knowledge reuse, and structured ontology modelling methodologies are often not considered [22]. Thus, beneficial effects of interoperability are not completely unclosed if each process or system is based on its own ontology that is not aligned with the other ones. Especially, there is also a loss of opportunities in regard to knowledge reuse, which could be promoted building on the modular reuse of ontological knowledge [23]. Reusing already existing ontologies reveals to have several benefits during the ontology conceptualisation phase, e.g. reduced workload and increased quality [24]. Further on, avoiding a deep exploration of related works looking for knowledge reuse [25], leads to new ontologies that overlap with already existing ones, in terms of concepts, not consistent as meaning and semantics; it finally slows down the knowledge extension process [26].

The goal of this research is to promote knowledge reuse of ontological resources for maintenance and Asset Management as relevant business processes in today industrial context. Although, knowledge reuse is not intended as a solo practice, but it should be integrated in an ontology methodology to support the entire ontological modelling process. Therefore, the steps followed in this work, also reflecting the structure of the paper, are:

- Analysis of the centrality of knowledge reuse for optimal ontological modelling (Section 2).
- Definition of the state of art and realisation of a cross-industrial compendium of ontological resources for maintenance and AM (Section 3).
- Description of AMODO (Asset Management Ontology Development methOdology) making knowledge reuse its cornerstone (Section 4).
- Demonstration of how knowledge reuse fasters the implementation of an ontology in a laboratory showcase in manufacturing (Section 5).

2. Core role of knowledge reuse for ontology modelling

Ontology is defined as *"an explicit specification of a conceptualisation"* [27]. Recently, "computational ontologies" term comes to light, underlying the current interest towards knowledge-based models empowered by reasoning and inference capabilities for computational purposes: "*computational ontologies are those models that formally represent the structure of a system, usually with a pragmatic approach"* [28]. On the whole, ontologies have been explored in both scientific literature and industry as means to support semantic and technical interoperability between enterprise information systems [2,12].

Over the years, several best practices emerged with the aim to guarantee consistent ontological modelling among different scientific domains and industries, like the selection of a reference ontology and the definition of competency questions [29]. Moreover, ontological and non-ontological knowledge reuse is seen as a valuable practice for this aim [30]. Indeed, reusing extant knowledge is nowadays fundamental and represents a structural ontology characteristics that may bring an ontology to be considered as reliable [31]. Therefore, reusing ontological resources, which means both ontologies themselves as well as ontological taxonomies, is a well-mentioned practice [23,32] with many recognised advantages [25]:

1. Reduced workload in formalising new concepts in ontologies from scratch.
2. Increased quality since the reused parts of the new ontology have already been tested.
3. Improved mapping between ontologies sharing the same concepts.

4. Reduced maintenance overhead since common and shared concepts are updated once.

Thus, the reusing practice is guaranteeing knowledge improvement or extension in the discipline by relying on previously tested and verified ontological parts. The reused or imported concepts (classes, properties, axioms, etc.) should have been already tested and assessed; as such, they may not undertake a new verification process, but could be directly implemented and the modeller could focus on new concepts, only.

Before analysing the practice of ontological knowledge reuse, in the process of ontology building, non-ontological resources serve as a fundamental knowledge basis, too [33]. Non-ontological resources include everything that helps to scheme out concepts, providing definitions, insights, and examples of application for the domain of discourse. Among these resources it is worth mentioning international and national standards and normative, taxonomies, data models, reports, theoretical contributions, handbooks, and many others. They represent an entire body of knowledge that must be considered while developing a new ontology. Especially, international standards (ISO/IEC) represent an already established consensus about concepts that may serve as a fundamental basis in formalising concepts in ontologies.

2.1 Knowledge reuse as the basis for enhanced interoperability

Ontologies may serve for several needs, from high-level conceptualisation of terms to connection between different information systems. Ontologies allow to implement collaborative knowledge management for improved decision-making [34]. There is no consensus on the kinds of ontologies that could be developed and one of the first conceptualisation is by Guarino [35], which identified four kinds. In this work, the “ontological pyramid” of the IOF (Industrial Ontologies Foundry) [36] is adopted, as depicted in Figure 1.

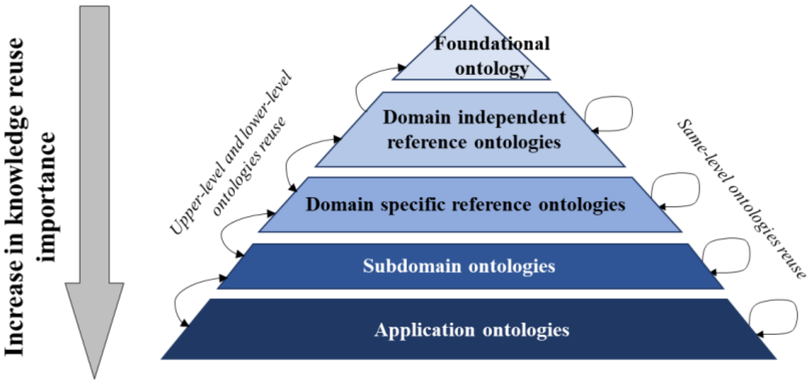

Figure 1 – Knowledge reuse practice.

This pyramid includes five ontology kinds that are (from the top, the most general concepts, to the bottom, the more application-oriented): i) foundational ontology, like BFO[1] [37] or DOLCE[2] [38]; ii) domain independent reference ontologies, like time, geospatial, or unit of measure ontologies; iii) domain specific reference ontologies, like maintenance or product ontologies [29,39]; iv) subdomain ontologies, like prognostics or maintenance planning; finally, v) application ontologies, like ontologies for machine tools prognostics in manufacturing. Ontological knowledge reuse may happen both between different levels as well as within the same level. Hereinafter an explanation of how the ontological knowledge reuse applies is reported, completed with some examples:

- Knowledge reuse between levels implies that the ontology could gather knowledge from upper and lower levels ontologies; two relevant examples are:
    - ROMAIN [40]: it is a domain specific reference ontology, which reuses ontological resources from domain independent reference ontologies, namely, IAO (Information Artifact Ontology) [41] and CCO (Common Core Ontology) [42].

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[1] Basic Formal Ontology (BFO) - https://basic-formal-ontology.org/

[2] Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) - http://www.loa.istc.cnr.it/dolce/overview.html

    - Time and place ontologies: they are domain independent reference ontologies, which reuses and extends from the *site* concepts of BFO, including new relationships to univocally define an event in time and space.
- Knowledge reuse within the same level implies that the on-development ontology could gather relevant knowledge from same-level ontologies. Important examples of this practice could be found in the domain independent ontology collection CCO [42]: unit of measure ontology reuses concepts from the information entity ontology, which in turn derives from the time ontology, extending from the class *Measurement unit*, all being domain independent reference ontologies.

For the sake of completeness, considering an ontology in its entirety (like Time ontology with all its concepts, or ROMAIN with all its concepts), a foundational ontology cannot reuse itself or any other ontology. It encapsulates the ontological commitment and as such must be unique. The upper block of the pyramid is so filled by one ontology only, which is “passive” to the reuse practice.

Leveraging on knowledge reuse, ontology compliance may be supported since some parts of the ontology share concepts with ontologies that are already recognised as common knowledge base from different stakeholders in academia and industry. Finally, reusing ontological knowledge combined with the identification of a unique foundational ontology could, in the long-term, supersede the necessity of demanding activities related to ontology integration to overcome enterprise systems interoperability issues [43]. In this regard, it is worth reminding that BFO (Basic Formal Ontology) [37] is going to become the reference foundational ontology for industry, as suggested by the ISO/IEC DIS 21838 standard [44], whose publication process is ongoing.

Referring to Figure 1, it is worth underlining that the importance of knowledge reuse increases towards the bottom of the pyramid. Lower-level ontologies must reuse upper-level ones to guarantee semantic alignment. Given that BFO is considered the reference foundational ontology, it is worth to highlight that IOF is developing also the IOF-CORE (link), which could be classified as a domain independent reference ontology based on BFO. Worth noting that knowledge reuse between ontologies not sharing the same ontological commitment may be critical because semantic alignment may not be guaranteed. In this case, ontology integration strategies may be adopted. Thus, it is foreseeable that combining a unique foundational ontology across domains and industries with an extensive knowledge reuse activity may overcome interoperability bottlenecks, promoting seamless data sharing and valorisation.

To promote this vision, section 3 realises a cross-industrial compendium to ease the collection of ontologies that already fit for maintenance and AM in manufacturing, construction and process industries.

3. Compendium of ontologies for maintenance and Asset Management

As anticipated in section 2, knowledge reuse is relevant to foster compliant ontology modelling towards interoperability. As such, both non-ontological and ontological resources should be recovered. Nonetheless, retrieving any form of knowledge but ontologies may be unfeasible and neither useful since it is highly case-dependent. Therefore, ontology modellers need to refer to domain experts to ground their ontology on solid non-ontological basis, like normative and industrial standards. In this section 3, the focus is on supporting the development of maintenance and Asset Management-related ontologies by collecting all relevant ontological resources developed so far in the scientific literature. The realised compendium acts as a repository from which interested modellers may find knowledge to reuse to ease and speed up their modelling activity, inherently pointing towards enhanced interoperability. The literature review allows also to define the state of art on the use of ontologies in the field of maintenance and Asset Management. Thus, in combination with the realised compendium, research opportunities and suggestions for future works are identified.

Hence, a systematic literature review (SLR) methodology is applied, which allows to span the scientific literature to retrieve information on available ontologies for maintenance and Asset Management. The documents are recovered by Scopus, Web of Science, and IEEE Xplore.

3.1 Research process

The retrieval of relevant documents from the databases passes through the definition of a suitable research protocol. To span the ontology-related literature for maintenance and AM, a two-layer structure of the keywords (KWs) is used. The first layer aims at restricting the literature to documents dealing with ontologies (KW: *ontolog**) and maintenance/Asset Management (KWs: *maintenance* OR *Asset Management*). The second layer is devoted to discerning the findings from the first layer considering manufacturing, construction, and process industries. The last industry has been restricted to Oil&Gas, power/energy generation/distribution and water treatment.

In the research process, the following eligibility criteria are applied:

1. Limitation to engineering-related documents.
2. Only peer-reviewed journal papers.
3. Only papers including an ontology implementation and/or application, excluding those that are general research on the topic, frameworks, or literature reviews.

The first two eligibility criteria are applied leveraging on the database searching engines' options while the last one has been performed manually. The final list of eligible papers underwent a content analysis to collect relevant variables. After this process, a consistency checking of the results should be performed since some KWs, like *production*, may be transversal to the industries and may be allocated to one whereas they should belong to the other. Figure 3 summarises and provides details on the whole research process.

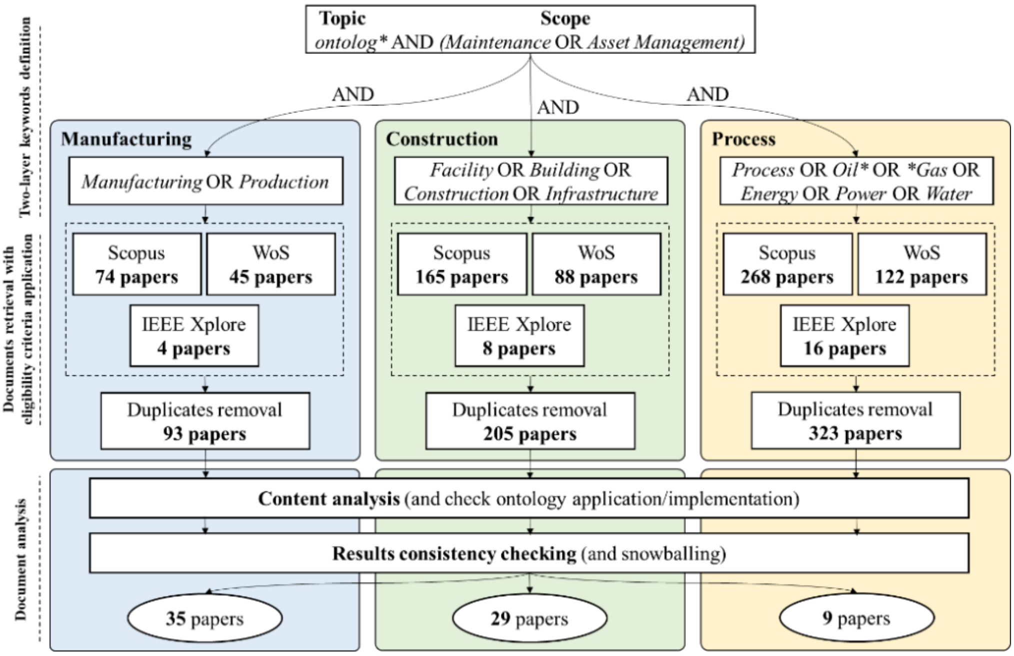


Figure 3 – Research process and results.

The non-duplicated papers (before content analysis) span from 1993 to 2020. Nevertheless, eligible papers, thus filtered for consistency with the research scope, are almost all confined in the last ten years. This demonstrates the growing interest in the application of ontologies for maintenance and AM purposes. The eligible papers allow to create the compendium of ontologies to ease and speed up the knowledge reuse practice.

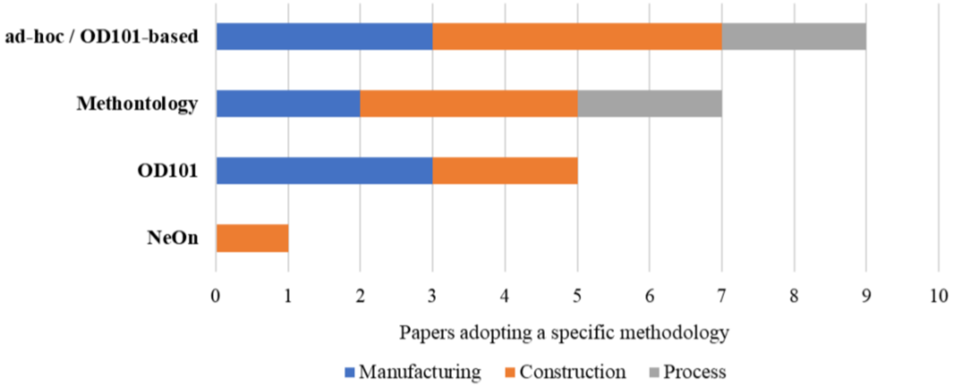
3.2 Compendium for ontological knowledge reuse

Before realising the compendium, the eligible papers underwent a content analysis, which may help further applications. Not all documents provide details for the variables in the meta-analysis.

The content analysis of the papers is based on six variables. For the sake of conciseness, the detailed results of the content analysis are not shown. Please refer to the Supplemental material for a throughout summary of the eligible papers and the complete meta-analysis. Overall, some conclusions can be drawn from the literature findings:

1. **Methodology**. The predominant adopted methodology is Ontology Development 101. The methodology is adopted as such, either customised for the specific application but adhering to the main structure. Methontology is well used, while NeOn finds only one application in construction, which is the industry more prone to use structured methodologies.
2. **Formalism**. OWL is the most widespread formalism, independently from the industry. It should be highlighted that most of the documents do not specify any OWL language versions or eventual sub-language (OWL-DL, OWL Lite or others). In addition to OWL, one paper in manufacturing adopts DAML+OIL, while one paper in the process industry adopts RDFS.
3. **Reasoner**. Pellet and HermiT result to be the most used reasoners in industry. Alongside, ad-hoc reasoners are adopted, which are built upon case-based or rule-based reasoning, implemented in various languages, like SWRL (Semantic Web Rule Language). Other reasoners are occasionally adopted.
4. **Foundational ontology**. Across industries, no information is provided about the adopted foundational ontology. Only one document highlights the use of BFO and another one the use of the ISO 15926 underlying foundational ontology.
5. **Competency questions**. CQs are sporadically used across industries. They are used for ontology validation; sometimes they are complemented by interviewing experts to validate the efficiency of ontology in answering the CQs.
6. **Knowledge reuse**. It is not possible to measure the extent of knowledge reuse; anyhow we rely on how much authors stress the reuse of some other resources as a proxy to measure the reuse extent. In so doing, process industry extensively relies on knowledge reuse, construction introduces mainly normative and de-facto standards in a relevant way, while manufacturing barely introduces external resources in their ontologies. Indeed, it is important to underline that the meta-analysis shows reuse practice is increasingly adopted over time across the three industries.

Figure 4-6 report some statistics about three relevant variables, that are adopted methodology, reasoner, and competency questions.



Legend: OD101 stands for "Ontology Development 101"

Figure 4 – Statistics on adopted methodologies.

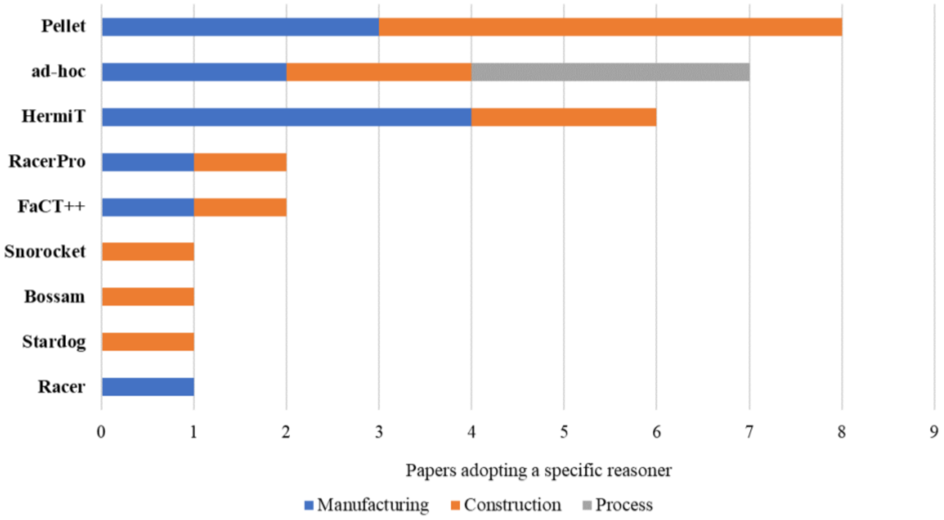


Figure 5 – Statistics on adopted reasoners.

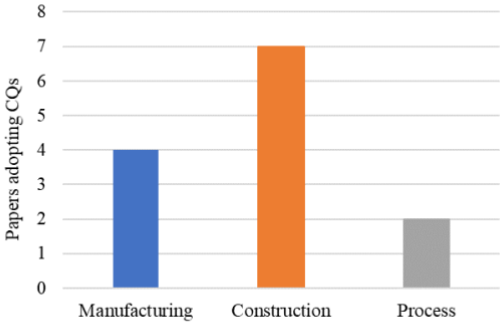
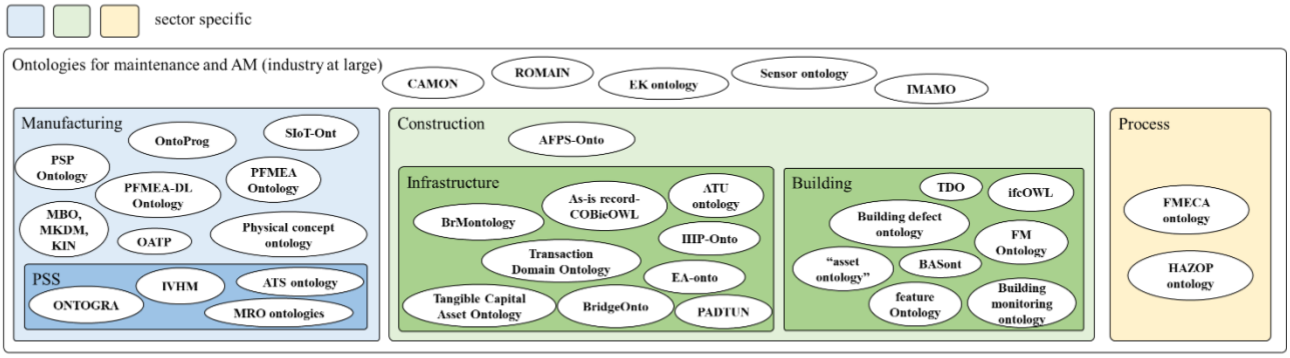


Figure 6 – Statistics on CQs adoption.

The compendium of industry-specific knowledge reuse could be finally realised, which is graphically reported in Figure 7 (refer to the Supplemental material of the interested industry). Different insights may be drawn:

1. Five ontologies, namely ROMAIN, CAMON, EK ontology, Sensor ontology and IMAMO aim at addressing maintenance and AM at large, without specialising for a specific industry.
2. Apart from the five listed in point 1., the other ontologies in the coloured boxes of Figure 7 are at the levels of subdomain ontologies and application ontologies.
3. There are specific clusters of ontologies dealing with specialised topics or applications, such as PSS (Product-Service System) in manufacturing or infrastructure and building in construction.
4. Especially in manufacturing, modellers tend not to provide name for the developed ontologies. However, naming it could favour sharing and reuse of those ontologies, also providing a unique way to identify them in repositories.



The picture reports only those ontologies whose authors provide a name/acronym. The full list of eligible articles with relative analysis is in the Supplemental material of this work.

Figure 7 – Graphical representation of the compendium.

3.3 Synthesis of literature review findings

The SLR helped in realising the compendium of ontologies as well as in getting shreds of evidence from the eligible documents. First and foremost, it must be said that ontology application in different industries is increasing, driven by the need of integrating data and information among systems and exploiting at maximum those data by considering the accompanying semantics. Secondly, despite the presence of several ontology engineering methodologies, modellers and developers are adopting world-wide recognised best practices in a more consistent way over time, as denoted in the Supplemental material. Thirdly, from the language standpoint, OWL is the current de-facto standard, besides being also a W3C recommendation. Finally, ontologies have caught up attention of industrial parties as a powerful mean of knowledge management, so that also some standards are under evaluation/publication in these years.

Nonetheless, the SLR foreshadows some criticalities that require to be faced in the future, in particular:

- Very few ontologies are transparent with respect to the adopted foundational ontology as reference, if any; consequently, an ex-ante evaluation of compatibility issues between ontologies is difficult.
- Despite being a well-recognised best practice, ontological knowledge reuse is limited in its application.
- Most of the developed ontologies do not clear out the underlying ontological commitment.

In the following Section 4, AMODO is described, which is an ontology development methodology built upon the presumption of the centrality of knowledge reuse. Indeed, it should be not considered a new methodology, rather a synthesis of already available methodologies that makes knowledge reuse as its cornerstone.

4. AMODO: Asset Management Ontology Development methOdology

The development of ontologies has been favoured by two approaches, the top-down and the bottom-up. The first one starts from the top-level ontologies to further extend the taxonomy and the relationships downwards to increase the formalised domain in a structured way. Instead, the second approach considers the already available data in diversified sources and tries to build the ontology upwards by leveraging upon machine learning algorithms [45,46]. Both top-down and bottom-up approaches have been used to describe the domain of maintenance and AM and further develop ontologies fit-for-purpose as demonstrated by recent works [47,48]. Each approach has its own advantages and disadvantages, to name a few: the top-down approach guarantees downwards semantic consistency, but it highly relies on human intervention and the meanings could be biased by the experts involved in ontology development; the bottom-up approach fasts the realisation performance and enables always up-to-date ontologies, but concepts are likely to be inconsistent and the process is not completely automated, hence incurring again in human intervention. Given the strong focus this paper has on knowledge reuse, as well as ontological commitment and downwards semantic alignment, the top-down approach is considered either when reviewing extant ontology development methodologies and when introducing the compendium for knowledge reuse. Nonetheless, the reader should be aware that this is one approach to ontology development and there is also the other way round (bottom-up).

4.1 Top-down methodologies for ontology development

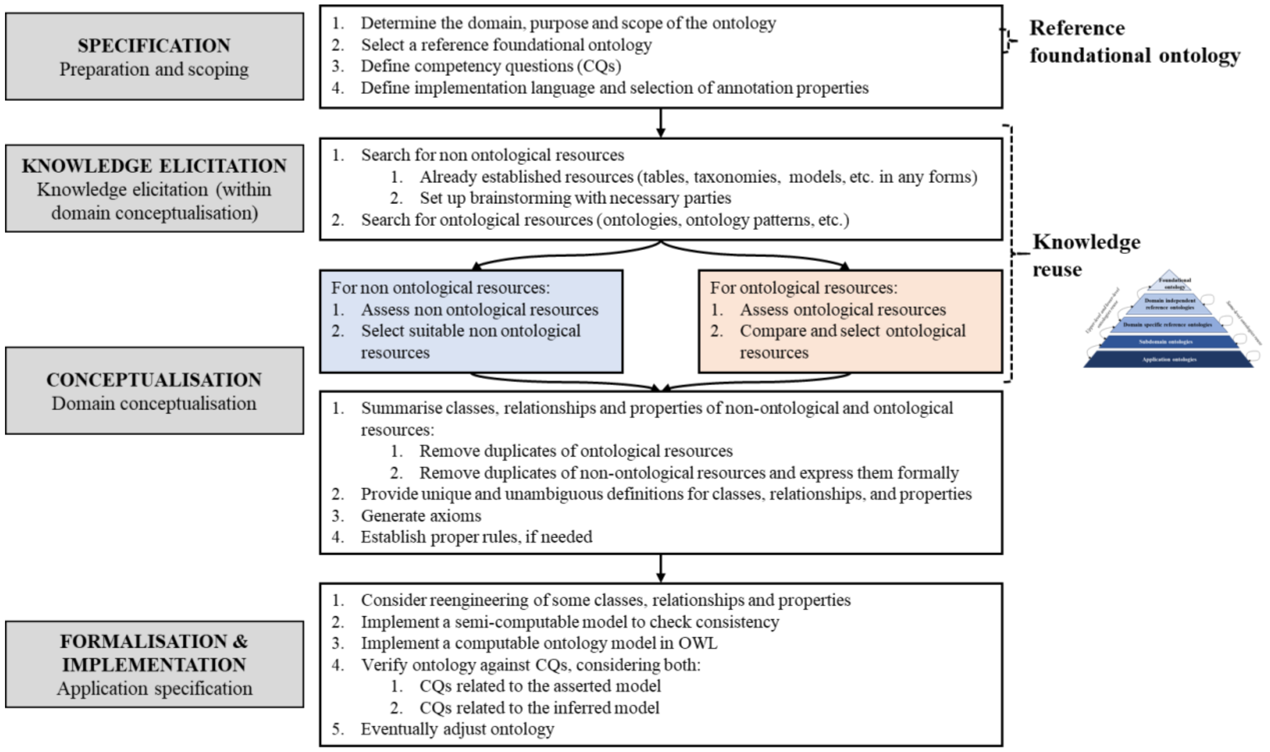
Over the years, the top-down methodologies for ontology modelling have been increasing in number and improving in complexity. From the Nineties, methodologies like the ones proposed by [49,50] and METHONTOLOGY [51] represent the very first examples of rules, best practices and activity flowcharts for ontology engineering. Then, other methodologies were developed, aiming at reproducing a more standardised way for creating, implementing and maintaining ontologies, such as: Ontology Development 101 [52], OntoClean [53] and DILIGENT [54]. Nowadays, DOGMA [55] and NeOn [56] represent two of the most enhanced methodologies for ontology engineering, even though they are thought for advanced modellers. This has brought most of the modellers, from beginners to experts too, to rely on Ontology Development 101 due to its ease of use. Examples could be found in different industries and applications, like [57] for construction, or [58] for maintenance and [59] for logistics in manufacturing. This situation may leave floor for uncompliant and incompatible ontologies. Consequently, in domains in which ontologies are today more impactful than ever, like maintenance and AM, it is possible to find several models, each representing its own view of the domain of discourse as evidence from the performed literature review (Section 3). This will finally lead to a low degree of interoperability between information-based systems.

AMODO aims at coping with this methodological gap by i) embracing the beginner-oriented philosophy of Ontology Development 101, while ii) considering advanced and recent practices embedded in DOGMA and NeOn, complemented by the industrial perspective of IOF. Built upon knowledge reuse, AMODO is fitted for application in maintenance and AM, with purpose to support the development of domain specific reference ontologies, subdomain ontologies and application ontologies. The knowledge reuse is fostered by the realised compendium (subsection 3.2). Ontologically speaking, AMODO should be not considered a new methodology, rather a synthesis of DOGMA and NeOn methodologies, where knowledge reuse, as a methodological step, is promoted by its "instantiation" for maintenance and Asset Management via the compendium.

4.2 AMODO overview

AMODO finds its roots in DOGMA and NeOn. Both ontology engineering methodologies are focused on the characterisation of the ontology lifecycle management, starting from feasibility study up to ontology maintenance. The former one provides detailed guidelines also on the documentation part of the ontology to guarantee consistency between versions, correct versioning controls and facilitate maintenance. The core steps are related to knowledge elicitation and knowledge breakdown, intended to foster the modeller in retrieving suitable knowledge stack from various sources and structuring it properly. The latter methodology is a scenario-based methodology, where, apart from a central backbone represented by the basic ontology development process, overlapping with DOGMA, different scenarios are analysed. Among them, reuse and merging of previous ontologies are recalled many times as relevant steps. Hence, AMODO makes an integration of these methodologies, providing a straightforward path to develop ontologies, with specific focus on ontologies for maintenance and AM.

Figure 2 reports the entire methodology, while in the remainder each macro-phase (grey boxes of the Figure 2) is described in more details. In the grey boxes, the name (bold and capital letters) of the macro-phase, adopted from NeOn terminology, comes with a (almost) synonymous from DOGMA.



1. Determine the domain, purpose and scope of the ontology
2. Select a reference foundational ontology
3. Define competency questions (CQs)
4. Define implementation language and selection of annotation properties

1. Search for non ontological resources
    1. Already established resources (tables, taxonomies, models, etc. in any forms)
    2. Set up brainstorming with necessary parties
2. Search for ontological resources (ontologies, ontology patterns, etc.)

For non ontological resources:
1. Assess non ontological resources
2. Select suitable non ontological resources

For ontological resources:
1. Assess ontological resources
2. Compare and select ontological resources

1. Summarise classes, relationships and properties of non-ontological and ontological resources:
    1. Remove duplicates of ontological resources
    2. Remove duplicates of non-ontological resources and express them formally
2. Provide unique and unambiguous definitions for classes, relationships, and properties
3. Generate axioms
4. Establish proper rules, if needed

1. Consider reengineering of some classes, relationships and properties
2. Implement a semi-computable model to check consistency
3. Implement a computable ontology model in OWL
4. Verify ontology against CQs, considering both:
    1. CQs related to the asserted model
    2. CQs related to the inferred model
5. Eventually adjust ontology

Figure 2 – AMODO methodology for ontology modelling.

4.3 AMODO methodological macro-phases

AMODO is composed by four macro-phases, each further specified in some steps.

Specification. The first macro-phase of AMODO is the specification and provides the ground for subsequent ontology development. Going more in details, the specific steps of specification are:

1. Define the domain in which the ontology must move, the purpose for which it is developed and the scope the ontology must absolve.
2. Select a reference foundational ontology to guarantee that the developed ontology has a predefined ontological commitment.
3. Define competency questions (CQs), which are questions to which the ontology must answer. They force modellers to formalise ontologies capable to answer to these questions upfront. The CQs must be selected and defined in accordance with the needs of the final stakeholder/s of the ontology.
4. Define a proper implementation language, balancing formality of the ontology and its executability. Among the various ontology languages [60], OWL is recommended by the W3C since it exploits all reasoning and inference capabilities and has the maximum expressivity. Also, the annotation properties should be selected, which will serve to complete the description of each entity in the ontology. Generally, there is not a common set of annotation properties [61].

During specification, the only retrieved ontology is the foundational one that includes the ontological commitment to comply with during the development. The retrieval of additional ontologies useful to rapidly introduce already development knowledge is done in the next macro-phase, called knowledge elicitation.
Nonetheless, before moving to the next macro-phase, it is worth digressing on foundational ontology and CQs. The ontological commitment is the basis for a correct formalisation and modelling of the domain of interest [62]. It is defined as an agreement *"to use the shared vocabulary in a coherent and consistent manner"* [27]. It is not only related to the selection of a reference foundational (also called formal, top level or generic) ontology, but this selection is crucial [63]. In fact, a certain foundational ontology already implies its perspective of the reality to be modelled; for example the adoption of a 3D (space) or 4D (space and time) perspective and the assumption of possible worlds [18]. Stating the foundational ontology taken as reference thus provides the modeller as well as the user the lens he or she must adopt when looking at the (sub)reality (intended as the things modelled in the ontology).
Nowadays numerous are the foundational ontologies that may be adopted, such as DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) [64], BFO (Basic Formal Ontology) [37], and SUMO (Standard Upper Merged Ontology). Each has different commitment, conciseness and also intended use [65]. The selection of the foundational ontology guarantees, or at least allows to evaluate, interoperability between information systems [66]. If they share the same foundational ontology as reference, the concepts they need to share (e.g. data about a certain asset) not only are technically but also semantically aligned. As such, foundational ontologies represent the backbone of ontology engineering, fostering ontologies interoperability. Among the foundational ontologies so far developed, BFO is the most concise [67], intended as number of modelled concepts, and it is going to become a normative for ontology engineering in industry. Further information about the importance of foundational ontologies may be found in [17,68,69].

On the other side, CQs represent tasks that the ontology must be able to address and solve [70]. As such, they are "*typical query that an expert might want to submit to a knowledge base of its target domain, for a certain task"* [71]. CQs could be classified in three types [72]:

1. Selection questions, where the ontology must answer by retrieving classes or values respecting a set of constraints.
2. Binary questions, where the ontology must answer with a binary (Boolean) value, such as *true* or *false*, or *yes* or *no*.
3. Counting questions, where the ontology must respond with the number of all different answers for a selection question.

As such, CQs are relevant in both the conceptualisation phase of the ontology and in the validation phase [40]. In the former case, they help in narrowing the ultimate goal of the ontology, defining all the relevant tasks that the ontology must accomplish within the domain of interest; in a sense, they are the actual ontology requirements [73]. In the latter case, CQs serve also as validation since the developed ontology must be able to answer to them [74], both considering the asserted as well as the inferred ontological model.

Knowledge elicitation. The second macro-phase is knowledge elicitation, which aims at retrieving useful domain-related knowledge to be included in the ontology. This knowledge may derive from different sources, that could be explicit knowledge that has been already formalised in some models, or tacit knowledge, to be extrapolated from experts in the field [75]. Therefore, knowledge reuse plays a central role in this macro-phase, with focus on both non-ontological and ontological resources.

Especially for maintenance and AM, international standards, data models, taxonomies, technical reports, and scientific literature represent relevant non-ontological resources. Moreover, interviews to domain experts and interested/necessary parties may be of advantage. Brainstorming may be one sort of methods to extract tacit knowledge from persons. On the other side, existing ontology patterns and ontology models must be considered while implementing the new ontology. Thus, within knowledge elicitation, the steps are related to searching for non-ontological resources (already established or to be recovered through stakeholder's involvement) or ontological resources. Nevertheless, retrieving all the relevant knowledge could be cumbersome and modellers may not be aware of the entire body of knowledge that fits its ontology. For this reason, the cross-industrial compendium is proposed in section 3. Thus, a modeller willing to develop maintenance or AM-related ontologies, could refer to AMODO as overarching pathway and on the compendium to start with for collection ontological resources.

The final output of knowledge elicitation is a list of natural language definitions of each class as well as identification of already established relationships between classes. Definitions and relationships will be then assessed in the conceptualisation macro-phase to make them unique and consistent.

Conceptualisation. The conceptualisation macro-phase is the core part of every ontology development methodology. This step brings the idea of ontology to its formal representation, with concept definitions (including classes, relationships, and properties) and axioms.

Stemming from the identified non-ontological and ontological resources, an assessment is required (coloured blue and red boxes in Figure 2):

- The assessment of non-ontological resources implies the verification of how the concepts in the domain of interest are described, to identify those relevant for the current purposes.
- The assessment of ontological resources is more demanding since it requires not only the investigation of the concepts formalised in the found ontologies, but mainly the verification of the adherence of the ontological commitment with the choice made during specification.

Once available all resources, the next steps are:

1. Summarise classes, relationships, and properties of non-ontological and ontological resources as well as new ones needed. In this step an unstructured list of concepts should be created. It serves as the source of domain-related knowledge that must be then arranged properly. During this step:
    1. Remove duplicates between ontological resources that may overlap.
    2. Remove duplicates of non-ontological resources and express them formally.
2. Provide unique and unambiguous definitions for classes, relationships, and properties. Definitions could be provided in various ways, such as natural language definitions and First Order Logic (FOL) definitions. The former ones point towards a better comprehension of the entity and readability, also for maintaining the ontology in the long term [76]. FOL definitions are more formal and based on mathematical terms that ease the understanding independently from the used language and with explicit reference to higher-level ontologies. In IOF, also semi-formal natural language definitions are present; they allow an easy "transition" between the two above since they are expressed in natural

language but with ontological terms that links with FOL. For all of them, the structure of the definition could be provided in an Aristotelian fashion, that is *genus* + *differentia/e* [77]. Moreover, along with definitions, it is also useful to provide:

    1. Elucidations, for more insights on the concept and its usage.
    2. List of possible synonymous that may be used to label those concepts in the real practice.

3. Generate axioms for the identified classes. Axioms could be of two types [78]: "schemata axioms" are facts that are always true, whereas "domain axioms" are true in a specific domain. Axioms allow to empower reasoning capability of ontologies and to support consistency checking by unveiling possible erroneous modelling of classes [79].
4. Establish proper rules, if needed. Rules complement and empower the knowledge stored in the ontological model [80]. They are particularly useful to improve assertion inferences. Among the various rule languages, like OWL2 RL, SPIN, SHACL Rules [81], SWRL is widely adopted as an established language through which it is possible to create rules with both built-in (swrlb) and customised functions.

Until this step, the ontology has not been yet implemented. However, it could be useful to sketch out the classes, properties, and relationships, for example using object-oriented schemes.

Formalisation and Implementation. The last macro-phase of the methodology implies the formalisation and implementation of the model in the selected language, such as OWL. An ontology reengineering should be taken into consideration since retrieved ontologies may not be reused directly, but they need to be reengineered to be fully compatible with the new one. As suggested by NeOn, it is a best practice to implement a first semi-computable model to check consistencies of various concepts and axioms. Only then, the entire computable model may be developed, which of course must be checked against consistency again.

Finally, the ontology must be tested versus CQs, i.e., ontology verification. The ontological model must be able to answer to the CQs defined in the first macro-phase (specification) since they represent the ultimate goal of the ontology. If the ontology is verified, it could be deployed, leveraging on available semantic web technologies frameworks, like Apache Jena-Fuseki [82] or Virtuoso [83]. The deployment for extensive use is not in the scope of AMODO.

The following section 5 describes the application of AMODO in a laboratory-sized application, where the compendium of ontologies for maintenance and AM developed in section 3 is used.

5. Laboratory-sized showcase in manufacturing

The showcase at laboratory scale is used to demonstrate the usefulness of the knowledge reuse, and so the realised compendium. The AMODO methodology is so applied since it represents the skeleton of ontology modelling.

The system at hand is an automated FML (Flexible Manufacturing Line) aimed at producing dummy cellular phones by assembling different components. It develops in 7 stations; each station had already come with sensors for controlling purposes at automation level, e.g., product placed correctly in the station or not. Moreover, all stations have sensors for energy monitoring, related to the compressed air (flow and pressure) used as main mean for operations to take place. Finally, additional sensors have been installed to favour Prognostics and Health Management (PHM) research, thus the drilling station has three accelerometers measuring vibrations over the three axes. Figure 8 reports an overview of the laboratory, showing the layout, the sensors and their types, and the flow of products (for the sake of shortness, sensors whose purpose is restricted to automated controlling of product flow are not listed).

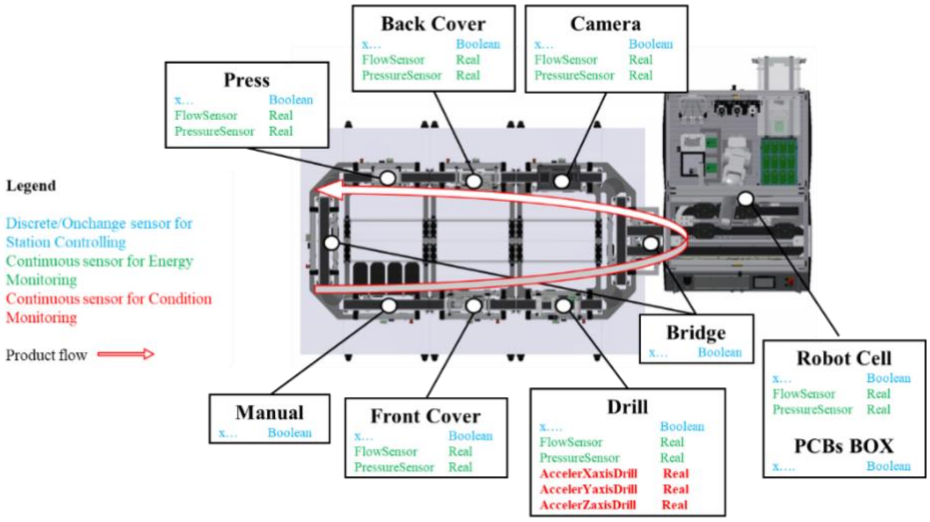


Figure 8 – Laboratory layout with indications on sensors installation.

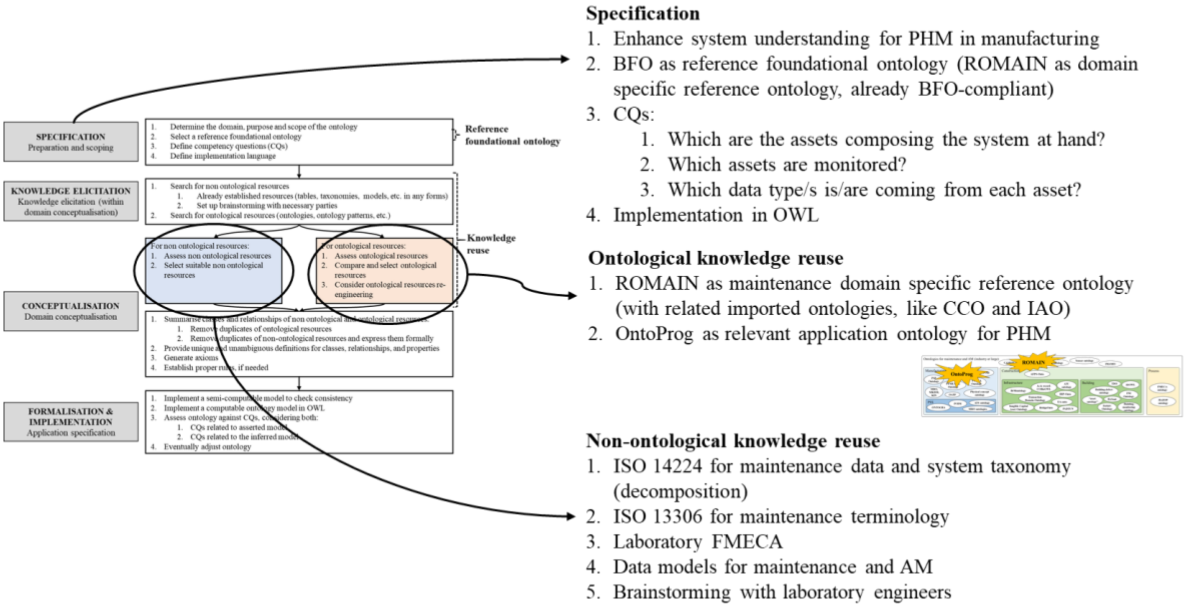
In the remainder of this section 5, an ontology to support PHM-related activities is developed, considering the laboratory as scope of work. The ontology is then verified through competency questions.

5.1 Application of AMODO for ontology modelling to support PHM

The ontology is implemented taking as a reference the FML. The ontology is named ORMA (Ontology for Reliability-centred MAintenance). The development of ORMA follows AMODO and, for this showcase, it is intended to support the fundamental activities of engineers to start a PHM process, mainly related to the comprehension of the system at hand, like the assets composing the system, the assets that are also monitored and the type/s of data coming from each asset [84].

The reference foundational ontology is BFO, even though ROMAIN [40] (a BFO-compliant domain specific reference ontology for maintenance) is selected as major reference. BFO is based on the distinction between continuants (entities that exist through time) and occurrents (entities that occur). In the current showcase, the focus is on continuants given their relevance to PHM; nonetheless, some insights on occurrents will be provided. The formalism adopted is OWL and Protégé editor [85] is used to develop the ontology. For the sake of simplicity, in this showcase, annotation properties will not be adopted.

According to AMODO, most of the knowledge is reused, both ontological and non-ontological. For the former, needed additional concepts complement already established ontologies, like OntoProg [58], that, according to the compendium of already existing ontologies in Figure 7, represent a relevant ontological knowledge for PHM applications in manufacturing. However, OntoProg is not BFO-compliant and so a re-engineering process is needed to realise ORMA. For non-ontological resources, mainly ISO standards are used, as well as previous data models and expert knowledge of the laboratory engineers. Figure 9 details better the resources and provides further insights on the AMODO macro-phases.



Specification

1. Enhance system understanding for PHM in manufacturing
2. BFO as reference foundational ontology (ROMAIN as domain specific reference ontology, already BFO-compliant)
3. CQs:
    1. Which are the assets composing the system at hand?
    2. Which assets are monitored?
    3. Which data type/s is/are coming from each asset?
4. Implementation in OWL

Ontological knowledge reuse

1. ROMAIN as maintenance domain specific reference ontology (with related imported ontologies, like CCO and IAO)
2. OntoProg as relevant application ontology for PHM

Non-ontological knowledge reuse

1. ISO 14224 for maintenance data and system taxonomy (decomposition)
2. ISO 13306 for maintenance terminology
3. Laboratory FMECA
4. Data models for maintenance and AM
5. Brainstorming with laboratory engineers

Figure 9 – AMODO as applied in the laboratory-sized showcase.

Non-ontological resources are important knowledge repositories, but the developed ontology need to be framed with respect to the already existing ontologies. This allows to understand where the current new developed knowledge is going to be placed. Figure 10 reports the hierarchy of ontologies in total, from the foundational to the domain ones, up to the application ontology reused. It encompasses also some domain-independent reference ontologies, that are CCO (Common Core Ontologies) [42] and IAO (Information Artifact Ontology) [41]. These are already imported in ROMAIN, but they could be used also directly, as the arrows show.

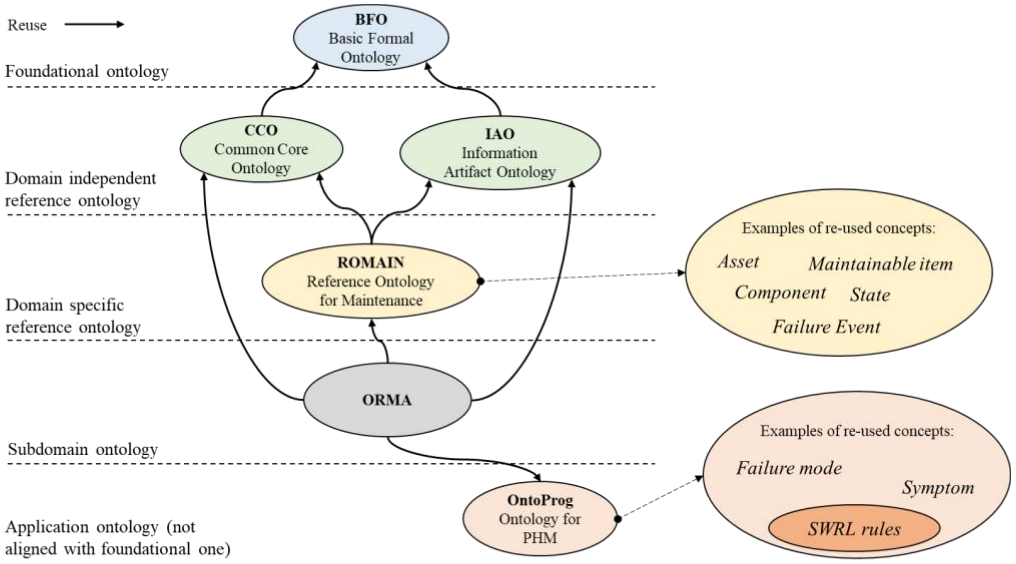
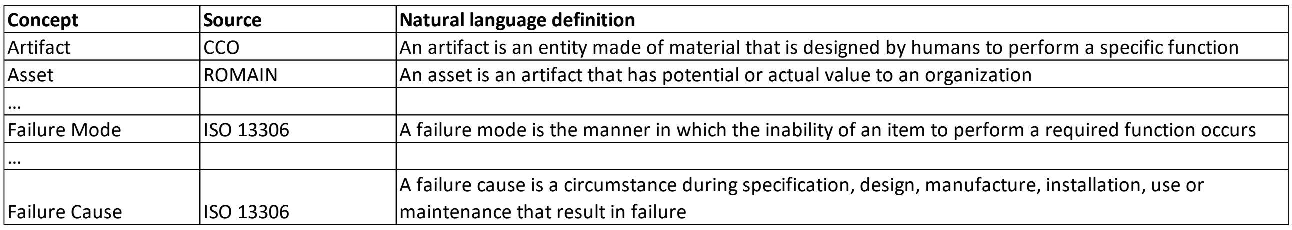


Figure 10 – Hierarchies of ontologies with focus on what is reused in ORMA.

The output of the knowledge elicitation is a list of definitions in natural languages (for those concepts reuse as such it is worth to keep also a formal definition if available, as for *CCO:Artifact*). Figure 11 reports a screenshot of a spreadsheet realised to this end.



Concept	Source	Natural language definition
Artifact	CCO	An artifact is an entity made of material that is designed by humans to perform a specific function
Asset	ROMAIN	An asset is an artifact that has potential or actual value to an organization
…		
Failure Mode	ISO 13306	A failure mode is the manner in which the inability of an item to perform a required function occurs
…		
Failure Cause	ISO 13306	A failure cause is a circumstance during specification, design, manufacture, installation, use or maintenance that result in failure

Figure 11 – Screenshot of the definitions in natural language, output of the knowledge elicitation.

Relying on already established ontologies speeds up the conceptualisation and implementation of ORMA, but the knowledge must be completed in the conceptualisation macro-phase of AMODO, in order to adhere in scope with the goal of the current ontology and provide concrete improvement to the field of ontology engineering for PHM in manufacturing. As such, as an example of knowledge extension, the introduction of physical decomposition relationships is necessary, to let the final user selecting the most appropriate indenture level according to the analysis to be performed.

To this end, the taxonomy proposed in the ISO 14224 [86] is taken as reference. This brings to the identification of another relevant artifact to be added, that is *Functional Unit*, which is (physically) in the middle between *Asset* and *Component*.

Even though this decomposition may not fit every situation, for the case at hand it represents the best way, as demonstrated by the FMECA previously developed on the FML, which identifies, as relevant levels: "machine or equipment", "sub-equipment functional group", and "item". Thus, in the ontology, we maintain the three-level structure, but rename each level according to already established label in other ontologies, that are *Asset*, *Functional Unit*, and *Component*, respectively. As from ROMAIN and IOF, the practice of relating object (independent continuant) to role (specifically dependent continuant) allows to better specify what we intend as *Asset* or *Maintainable Item*. In the laboratory case for example, the *Maintainable Item Role* is also taken by the *Component*, thus *Maintainable Item* is inferred as its subclass. Figure 12 proposes a simplified conceptualisation, where also the OntoGraf view of Protégé is reported.

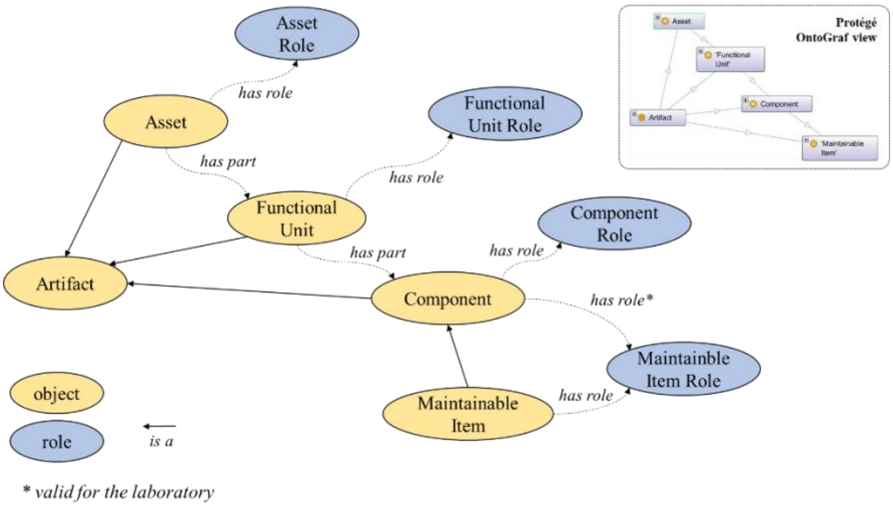


Figure 12 – Extract of the ontology model: focus on physical decomposition.

To univocally define the concepts, it is worth adding axiom/s to each already defined concept. For example, *Asset* in ROMAIN has the following axiomatic expression, involving reuse of CCO:

CCO:Artifact AND (hasRole SOME 'Asset Role')

Since the goal of the current ontology is to support PHM-related activities, beforehand it is mandatory for any modeller/engineer to understand which assets are monitored. For this reason, the class *Monitoring process* is introduced as a *BFO:process* (occurrent). Therefore, the following equivalent class axiom for *Monitored Component* is defined (involving reuse of ROMAIN):

ROMAIN:Component AND (participates_in SOME 'Monitoring process')

Also, an additional relationship *participates_in* is introduced so to define a *Sensor* as a *Transducer* that *participates_in* a *Monitoring process*, either *Continuous monitoring process* or *Discrete monitoring process.*

As relevant digression, the *Monitoring process* class is classified as a *BFO:process*; it may be argued that a better classification may see it as subclass of *Planned process* by IOF-CORE. However, the *Planned process* does include an *Agent* (person or organisation) carrying out that process. Instead, the *Monitoring process* may be carried out automatically by the *Asset* itself via sensors. In this first formalisation, it is preferred to maintain the *Monitored process* class under *BFO:process* and leave a better classification to future research works.

In ORMA, the main adopted relationship between occurrent and continuant is *participates_in* (namely between *Artifact* and *Process*). When scaling up to also consider maintenance strategies and so on, additional occurrents should be formalised as done in the current release by IOF.

After the generation of axioms, the conceptualization macro-phase of AMODO entails the identification of rules that may support reasoning. The rules are mainly related to reasoning above failure modes, causes and mechanisms and are retrieved by OntoProg. After an adaptation to be consistent with the current ontology terminology, they allow to establish direct links between concepts exploiting already available engineering knowledge. Indeed, the FMECA analysis results a core repository of domain-related knowledge also in this case. The language adopted for rule-based reasoning is SWRL and an example is the following, in which [58] relates *PotentialCause* to *Component* through *FailureMode*:

FailureMode(?FailMode) ^ Component(?Comp) ^ PotentialCause(?PotCause) ^ hasMode(?Comp, ?FailMod) ^ hasCause(?FailMode, ?PotCause) -> hasCause(?Comp, ?PotCause)

the implementation is carried out in SWRLTab Protégé plug-in, while the assessment of the rules is performed through SQWRLTab Protégé plug-in, which allows querying over SWRL rules. Thus, SQWRL allows to test the rules before for them being part of the ontology itself. At this stage of the ontology development no *swrlb* (SWRL built-in) functions are used.

Last but not least, each of the concept should have its own definitions. Various types of definition are available. As lesson learnt from the showcase, it is suggested not to select a specific type of definition for all concepts, but to change the type according to how "mature" is the concepts in the domain of discourse. For example:

- The artifact is a "mature" concept since it comes from CCO. For this concept it is possible to report all the three types of definitions (natural language, semi-formal, and formal in FOL, respectively):
    - An artifact is an entity made of material that is designed by humans to perform a specific function.
    - An artifact is an object (independent continuant) that is designed by some agent to realise a certain function.
    - Artifact(x) ≡ object(x) ∧ ∃y(Agent(y) ∧ is_designed(x,y))
- The failure mode is not a "mature" concept. This because its definition changes from standards to scientific literature and even in some already proposed ontologies. For this concept, a natural language and semi-formal definitions could be enough to elucidate the meaning in the developed ontology:
    - A failure mode is the manner in which the inability of an item to perform a required function occurs (according to ISO 13306 [87]).
    - A failure mode is a realizable entity of a failure mechanism through which a (state of) failure occurs (adapted from IOF).

In the following sub-section 5.2, the implementation of the model is carried out, and later tested against defined CQs.

5.2 Ontology verification through competency questions

The developed ontology (ORMA) must be able to answer to CQs considering both the asserted model as well as the inferred knowledge (HermiT reasoner is used). Protégé offers the possibility to check both using two different plug-ins: SPARQL Query (SPARQL Protocol and RDF Query Language) could be used to query the asserted model, while DL Query (Description Logic Query) allows to also query the inferred model. It is also possible to use Snap SPARQL Query plug-in that can query both asserted and inferred knowledge. Even though it provides the same results of SPARQL Query for the asserted model, it could be more powerful than DL Query (i.e., the queries could be more complex). Table 1 reports CQs numbered 1, 2 and 3, while Figure 13 reports the CQ numbered as 4; all CQs are used for the current ontology verification. For the sake of completeness, the first lines of SPARQL code are reported here (common to all queries). Note that reusing/importing ontologies mean to retrieve their IRI (Internationalized Resource Identifier) so to identify them univocally.

```
PREFIX rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
PREFIX owl: <http://www.w3.org/2002/07/owl#>
PREFIX rdfs: <http://www.w3.org/2000/01/rdf-schema#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX ao: <http://www.ontologylibrary.mil/CommonCore/Mid/ArtifactOntology#>
PREFIX ro: <http://www.obofoundry.org/ro/ro.owl#>
PREFIX ORMA: <http://www.semanticweb.org/user/ontologies/2020/5/ORMA#>
```

Asserted model

CQs | *SPARQL Query* | *Answer*

CQ1
Which are the assets composing the system at hand?

```
SELECT ?asset
        WHERE { ?asset rdf:type onto:Asset }
```

- DrillStation
- FrontCoverStation
- ManualStation
- BridgeRobot
- BridgePress
- RobotCell
- CameraStation
- BackCoverStation
- PressStation

CQ2
Which are the components of the Drilling Station?

```
SELECT ?component
        WHERE { ?asset rdf:type onto:Asset ;
                onto:has_name "Drilling Station" .
                ?asset onto:has_part ?funUnit .
                ?funUnit onto:has_part ?component .
}
```

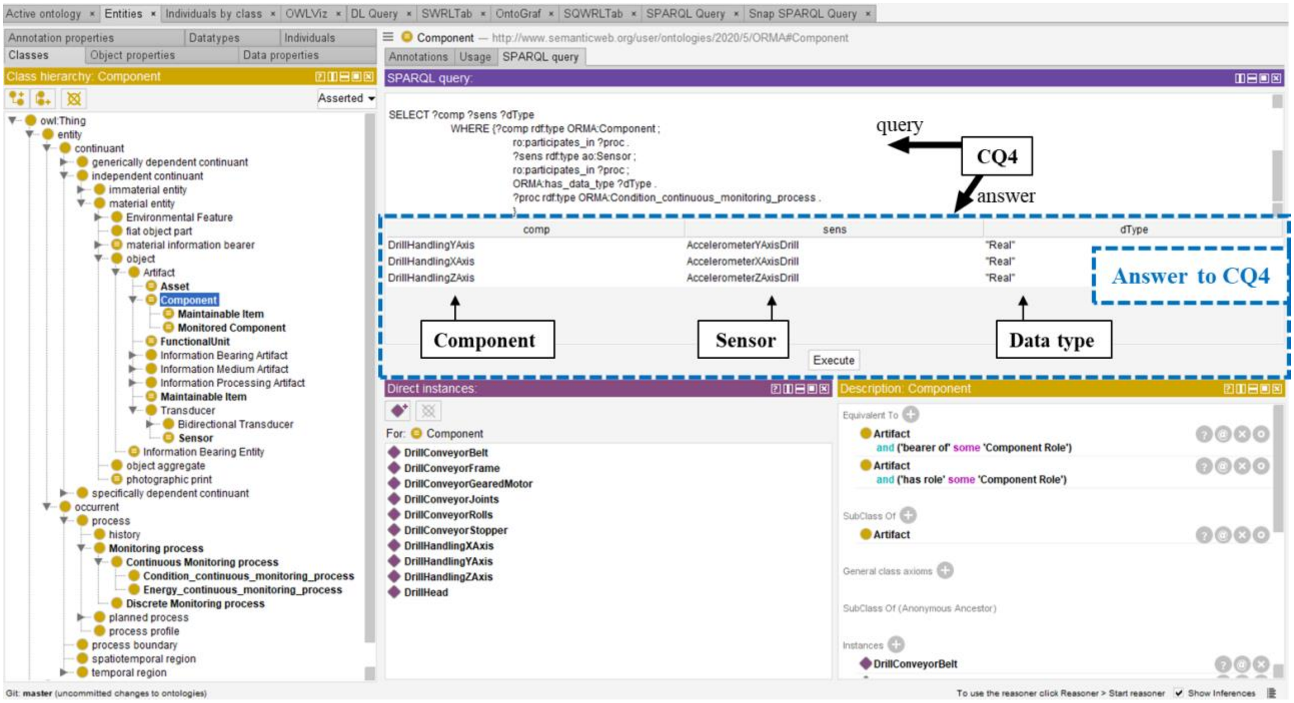
- DrillConveyorRolls
- DrillHandlingYAxis
- DrillConveyorJoints
- DrillConveyorGearedMotor
- DrillConveyorStopper
- DrillHandlingZAxis
- DrillConveyorFrame
- DrillHead
- DrillHandlingXAxis
- DrillConveyorBelt

Inferred model

CQ	*DL Query*	*Answer*
CQ3 Which assets are monitored?	Asset and ('has part' some 'Monitored Component')	DrillStation

Table 1 – Some competency questions for the asserted and inferred model.

Top right part of Figure 13 reports the screenshot of the answer to CQ4 *Which data type/s is/are coming from condition monitoring process?* Moreover, on the left-hand side it is also possible to see the hierarchy, which starts from BFO and goes down to the leaf classes related to PHM. In the hierarchy, *Component* is highlighted and details about its instances and axioms are shown in the bottom right part.



```
SELECT ?comp ?sens ?dType
        WHERE {?comp rdf:type ORMA:Component ;
                ro:participates_in ?proc .
                ?sens rdf:type ao:Sensor ;
                ro:participates_in ?proc ;
                ORMA:has_data_type ?dType .
                ?proc rdf:type ORMA:Condition_continuous_monitoring_process .
                }
```

comp	sens	dType
DrillHandlingYAxis	AccelerometerYAxisDrill	"Real"
DrillHandlingXAxis	AccelerometerXAxisDrill	"Real"
DrillHandlingZAxis	AccelerometerZAxisDrill	"Real"

For: Component
- DrillConveyorBelt
- DrillConveyorFrame
- DrillConveyorGearedMotor
- DrillConveyorJoints
- DrillConveyorRolls
- DrillConveyorStopper
- DrillHandlingXAxis
- DrillHandlingYAxis
- DrillHandlingZAxis
- DrillHead

Equivalent To
Artifact and ('bearer of' some 'Component Role')
Artifact and ('has role' some 'Component Role')

SubClass Of
Artifact

General class axioms

SubClass Of (Anonymous Ancestor)

Instances
DrillConveyorBelt

Figure 13 – Screenshots of Protégé while answering to specific queries (CQs).

The defined queries can suitably interrogate the ontologies and retrieve the correct responses. Note that CQ4 could be combined with CQ2 to retrieve information about which asset those components belong to. Thus, the answers the ontology provides to the CQs, being known completely the system, verify ORMA.

The current ontology has not been already deployed, but this implementation already shows the potentialities when scaled up. For example, through the already defined CQs it is possible to understand the physical structure of the system at different indenture levels; even more, it is possible to know which are the assets under monitoring and identify them as targets of PoCs (Proof of Concepts) for a complete PHM programme aligned with the ISO 13374 [88], to be then further extended to the entire assets portfolio.

5.3 Implications from the showcase

The use of AMODO, centred on knowledge reuse, in the laboratory for starting a PHM programme shows some implications. Recalling the two levels of technical and semantic levels, the implications could be summarised as follows:

1. **Technical level**:
    a. *Reduced time to implementation*. The extensive reuse of extant knowledge allows to speed up the ontological modelling by importing ontologies or, in case of non-ontological knowledge, though a re-engineering process. For example, reused relationships between potential failure cause with failure mode, expressed in SWRL, are rapidly introduced in the ontology since the formalisation effort has been previously done and the concepts were already tested.
    b. *Reduced interoperability shortfalls*. Connected also to point 1., the use of shared and "certified" knowledge allows to make the developed ontology easily integrable with systems with the same ontological commitment. Even though not immediately provable, it could be assumed that it will be easy the integration of other ontologies, through several strategies [43].
2. **Semantic level**:
    a. *Fostered semantic alignment*. The selection of a foundational ontology that is on the path to become an international standard (ISO 21838) allows to guarantee that the terms have a unique and precise definitions, and their meaning is not confused. For example, the *asset* intended as a physical entity used to operate on a product to finalise it, could be recognised by *is-a* chain *artifact/object/material entity* [40] in BFO. The definitions provided by BFO for *object* and *material entity* clear out that the *asset* must not be confused with an *immaterial entity*, for

example because thinking about *information* as the *asset*. Therefore, it must represent at least, aligned with BFO [37], something that exists in reality through time (*independent continuant*), and that has some matter as part *(material entity*), which is three-dimensional extended[3] (*object*) and is built on purpose to do something (*artifact*).

b. *Improved knowledge base*. The extension of the knowledge provided by the new ontology, based on reused/imported ontologies, improves the current knowledge base in the domain of discourse. Therefore, future research must not concentrate on exploring already developed knowledge but could rely on it to extend the domain knowledge, towards a complete description of the world the ontology is willing to represent, i.e., PHM.

Therefore, adopting knowledge reuse and, in general, AMODO, it is possible to support ontological modelling towards enhanced intra- and inter-enterprise interoperability at technical and semantic levels.

6. Conclusions and future research

Open challenges in industrial information integration are still open and should be addressed from various perspective, including standardisation that is seen as a cornerstone on which smart factories are built upon [89]. Collaborative and distributed settings are today vital to embrace the digital transformation and improve productivity in manufacturing, construction, and process industry, by aligning business processes, and information systems accordingly. Hence, this research work faces interoperability as a first step towards the integration of information systems, even geographically dispersed, which is much more difficult to solve given the presence of organisational issues [90]. Specifically, it is analysed and highlighted how reusing both ontological and non-ontological knowledge is relevant to guarantee compliance with already existing ontologies, towards interoperability, as well as to promote knowledge extension. The performed scientific literature review reveals that knowledge reuse is not systematically adopted while developing new ontologies, causing an heterogenous ensemble of ontological models. Nonetheless, extant scientific literature agrees upon the fact that methodologies and best practices are essential to guarantee the development of ontologies that are interoperable. Stemming from this background, knowledge reuse is investigated in the scope of ontology engineering for maintenance and AM. This is due to the considerable requirements of integrating information between several stakeholders to optimise the decision-making process towards operational excellence. The goal of this research is to promote the adoption of ontological knowledge reuse practice, which is not intended as a solo practice and, for this reason, it is integrated as cornerstone in AMODO. AMODO is a methodology for ontology modelling specifically fitting maintenance and AM needs and it aims at the realisation of domain specific reference ontologies, subdomain ontologies and application ontologies in the maintenance and AM domains. Knowledge reuse is promoted by the realisation of a cross-industrial compendium, which groups together ontologies for maintenance and AM in manufacturing, construction, and process industries. The showcase in the laboratory demonstrates that the reuse practice and AMODO as a whole, allow to speed up the conceptualisation, acknowledging about existing ontological resources. Even though AMODO is thought to support knowledge reuse practice in maintenance and AM-related applications, the methodology may have a wider adoption, also beyond the scope/domains of this work. This is in the scope of future research.

The AMODO methodology and the realised compendium promote the integration of information by collecting and systematising extant knowledge about maintenance and AM. Specifically, the compendium enables a fast realisation of ontologies by integrating knowledge from various and dispersed sources that have been already summarised and classified. Then, AMODO allows a structured approach to ontology development that fits also for beginners. Particularly, AMODO fosters the selection of the foundational ontology that guarantees consistency in the development and easiness in the integration of ontologies sharing the same ontological

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[3] As a matter of fact, a *BFO:object* has also other “differentiae” that must be listed, namely casually unified (all the parts are tied each other and share the same destiny, or *common fate*) and maximally self-connected (all the parts are tied together and if another part is connected to the whole in the same way, then it is part of the object itself). However, in this work we try to focus on a more engineering and pragmatic approach, thus investigating, dwelling, and analysing only those facets of ontologies that may be clear at the first round. The reader may refer to other documents for a careful analysis of ontologies also involving philosophy as background (some of them are in the reference list of this work).

commitment. As such, this research work advances the use of top-down approaches for ontology development for maintenance and Asset Management in multiple industries.

In the long-term, leveraging upon standardised ontology engineering methodologies, intra-, and inter-enterprise enhanced interoperability could be established, with information systems more ready to be connected, with less work aimed at solving integration problems, at least at semantic level. In so doing, in-house business processes cooperation and operations integration along the value chain will be boosted. However, the journey towards a complete interoperable intra- and inter-enterprise ecosystem requires further research and studies. The open questions are summarised hereinafter, driven by the results of the literature review (1 and 2) and our experience in industry (3 and 4).

1. *How to evaluate the compatibility of ontologies with respect to the ontological commitment and eventually integrate them in a homogenous knowledge base?*

Not fixing a foundational ontology, and not stating which is adopted, limit the possibly to evaluate ex-ante if two ontologies are compatible or some ontology re-engineering is needed. Nonetheless, this evaluation needs to be further investigated to identify those dimensions that allows an a-priori understanding of integration issues that may arise towards the realisation of a homogenous knowledge base. Moreover, even though BFO is going to be the major reference for foundational ontologies, most knowledge have already been modelled. This knowledge must not be discarded since it represents an entire knowledge stack that has also been already tested, validated, and implemented. Thus, additional works should be focused on enhancing the reuse of this knowledge, even under re-engineering activities, by mapping extant ontologies.

2. *How to make ontologies dynamic and self-update with respect to data change?*

Most of the identified ontologies are fixed and static in nature. It means that concepts are not allowed to be added/changed once the ontology is deployed, and most of the instantiated knowledge is not updated, at least not in real time. However, in the current shop-floor context, asset data introduce dynamics to which ontology must cope with. For example, asset health state must be classified with ex-ante defined features' boundaries, but pre-determined asserted knowledge may fail to classify all possible future and unforecastable cases. This is also the pathways for future development for ORMA.

3. *How to aid the extensive interlacement of business processes with ontologies?*

Today more than ever, business processes are interlaced, inside and outside the company. More disciplines, like PLM (Product Lifecycle Management) and AM, are making cross-functional integration of data and information central to optimise their decision-making processes. Here ontology engineering may play the lion's share. Semantic alignment must be pursued at first and conceptualisation must be strengthened to guarantee linguistic and logic consistency between interested parties.

4. *How to support knowledge and data-driven decision-making processes?*

The increasing use of (big) data analytics towards the maximum exploitation of the data content are making decision-making processes more robust by providing insights on interesting phenomena. Nonetheless, to actively support (big) data-driven decision-making, several research streams are present where ontologies could be a breakthrough. Thus, open questions relate to: i) how to introduce semantics underneath big data so to improve the information content they provide; ii) how to use ontologies to improve explainability of artificial intelligence algorithms; iii) how to position ontologies with respect to data lakes. Specifically, point iii) is challenging since data lakes represent a massive storage of structured and unstructured data that are fed into big data algorithms; as such, an open question relates to if the data lakes should be semantically empowered through ontologies or data lakes play the "passive" role of repositories from which ontologies gather useful data and only then add semantics. The selection of the best configuration of data lakes and ontologies could drastically change the way big data are used and perceived by adding semantics that is so far not introduced in conventional data analytics, mainly focused on non-symbolic artificial intelligence.

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Supplemental Material

For each industry, the analysis of the eligible documents is reported in a tabular form. The meta-analysis includes the following variables: objective, used ontology, methodology, language, reasoner, foundational ontology, competency questions CQs (does the paper use CQs? *extensive*, *yes*, - *(not)*), reuse resources (does the paper practice reuse? *extensive*, *yes*, - *(not)*).

Since foundational ontology is an empty field for almost all papers, for the sake of simplicity it is not included as column in the following table, but the references are listed in the following. At the end, the reference list for the cited documents is reported.

About the use of foundational ontology, the following references have to be mentioned:

- Ref. [1] uses BFO as foundational ontology;
- Ref. [2] adopts the ISO 15926 as foundational ontology.

Eligible documents analysis for the manufacturing industry

Reference	**Objective**	**Ontology**	**Methodology**	**Language**	**Reasoner**	**CQs**	**Reuse**
[3]	Develop an ontology building process for CPS-based systems to enable information exchange	-	ad-hoc	OWL 2	-	Yes	Ext.
[4]	Design a communication ontology for data exchange in a logistic system to support HMI visualisation for maintenance operator	-	-	-	-	-	-
[5]	Develop an ontology-based model for enhancing maintenance planning in production companies	-	-	-	-	-	-
[6]	Automatically build ontologies based on data from different sources in production plants	-	-	-	-	-	Yes
[7]	Develop an ontology-based system to manage disruption with automatic responses	-	-	OWL	-	-	-
[8]	Propose an ontology-based architecture to exploit and enhance Social Internet of Things	SIoIT-Ont	-	OWL	-	-	Yes
[9]	Realise an information sharing system between stakeholders involved in CNC machine maintenance	-	-	OWL DL	ad-hoc	-	Yes
[10]	Develop an ontology-based intelligent condition monitoring system	-	Ontology Development 101	OWL	ad-hoc	-	-
[11]	Develop an ontology-based architecture to enhance knowledge retrieval for operation optimisation	-	-	-	-	-	-

Reference	**Objective**	**Ontology**	**Methodology**	**Language**	**Reasoner**	**CQs**	**Reuse**
[12]	Develop an ontology to support Prognostics and Health Management	OntoProg	*somehow aligned with* Ontology Development 101	OWL	Pellet	Yes	Ext.
[13]	Propose a foundational ontology for modelling manufacturing environments	-	-	-	-	Yes	Yes
[14]	Propose an ontology to favour human-CPPS cooperation to solve problems	PSP ontology	*somehow aligned with* Ontology Development 101	-	-	Yes	-
[15]	Develop an ontology-based method for fault diagnosis for efficient knowledge utilization	-	-	OWL	Pellet, HemiT, and FaCT++	-	Yes
[16]	Support Prognostics and Health Management trough ontology-based standardisation of concepts and data collection	-	Methontology	OWL 2	HermiT	-	Yes
[17]	Support decision-making in product design phase based on ontology	ONTOGRA	OWL	-	-	-	-
[18]	Define a FMEA ontology to support knowledge sharing and reuse of natural language expression	PFMEA ontology	-	OWL	HermiT	-	Yes
[19]	Develop an ontology-based simulation experiment to support production and maintenance	-	-	OWL	-	-	Yes
[20]	Support assembly operators through an ontology-based system	OATP	-	OWL	Pellet	-	-
[21]	Develop a cloud-scalable system for maintenance knowledge sharing through ontology-based representation	-	-	OWL	HermiT	-	-
[22]	Guarantee digital continuity between real and virtual factory through ontologies	-	-	OWL	-	-	Yes
[23]	Support automobile services through knowledge-based systems	ATS ontology	-	OWL	-	-	-
[24]	Propose an ontology-based knowledge framework to support remote and collaborative maintenance	MBO, MKDM, KIN	-	OWL	-	-	-
[25]	Develop an ontology-based architecture for self-adaptive production systems	-	-	OWL	-	-	-
[26]	Propose an ontology-driven collection of data for guaranteeing its quality to support business functions	IVHM ontology	ad-hoc (from [27])	-	-	-	Yes

Reference	**Objective**	**Ontology**	**Methodology**	**Language**	**Reasoner**	**CQs**	**Reuse**
[27]	Foster unambiguous reuse of knowledge for MRO (Maintenance, Repair, Overhaul) process based on ontology	MRO ontologies	-	OWL	-	-	-
[28]	Support knowledge transfer and sharing over distributed resources from FMEA to get insights on manufacturing processes	PFMEA-DL ontology	Methontology	OWL	RacerPro	-	-
[29]	Develop an ontology-based service-oriented architecture to support production system lifecycle decision	-	-	-	-	-	-
[30]	Develop and ontology-based agent communication mechanism to support collaborative maintenance tasks	-	-	DAML	-	-	-
[31]				+OIL			
[32]	Support knowledge reuse in the design phase through ontology-based Virtual Reality	-	-	OWL	-	-	Yes
[33]	Integrate semantic web and grid computing for efficient collaborative solutions	-	-	OWL	-	-	Yes
[34]	Enable manufacturing knowledge spread through ontological knowledge formalisation and multi-perspective modelling	-	ad-hoc	OWL	Racer	-	-
[35]	Foster lifecycle engineering design by integrating and making available diversified knowledge based on ontology	-	-	-	-	-	-
[36]	Support effective ontology-based sharing between enterprise for enhanced innovation	-	-	-	-	-	-
[37]	Foster integration and sharing of engineering knowledge stored in CAD-CAE systems for diversified application, such as design, maintenance, and recycling	Physical concept ontology	-	-	-	-	-

Eligible documents analysis for the construction industry

Reference	Objective	Ontology	Methodology	Language	Reasoner	CQs	Reuse
[38]	Design an ontology-based decision support system for asset management of infrastructure considering different stakeholders' knowledge	ATU ontology	NeOn	OWL 2	-	Yes	Ext.
[39]	Realise a knowledge-integrated (semantically) framework to favour building information re-use for BIM	as-is record-COBieOWL	*somehow aligned with* Ontology Development 101	OWL 2	-	-	Ext.
[40]	Support pathology diagnosis and assessment of tunnels using an ontology-based decision support system	PADTUN	Methontology	OWL	ad-hoc	Yes	-
[41]	Ease the transferring of BIM data in AM-related application based on ontology	-	Ontology Development 101	OWL	HermiT	Yes	Ext.
[42]	Implement a mapping between ontology and BIM based of FMEA for historical building management	-	-	OWL	-	-	Yes.
[43]	Develop of an ontology for pavement assets of highway to manage process planning	IHP-Onto	Methontology	OWL	Pellet	Yes	Ext.
[44]	Develop an ontology-based method to support bridge management	BrMontology	Ontology Development 101	OWL	Pellet	Yes	Yes
[45]	Develop an ifcOWL-based rule-based system for creating building views	-	-	OWL	Stardog	-	Yes
[46]	Support the transfer of construction to asset management through an ontology for database update	“asset ontology”	-	OWL	-	-	Ext.
[47]	Develop an ontology-based facility management system to enhance the integration of BIM and historical data	FM ontology	-	OWL	Bossam	-	Ext.
[48]	Develop an ontology-based BIM for faults analysis in building automation systems	-	-	OWL	Pellet	-	-
[49]	Enhance building monitoring through data ontological representation for advanced support systems	Building monitoring ontology	-	-	-	-	Yes
[50]	Support integration of geometric data models via a common building defect ontology and framework	Building defect ontology	-	-	-	-	Yes
[51]	Develop a knowledge-based system for the design and selection of active fall protection systems for risky operations	-	-	-	-	-	Ext.
[52]	Enhance information extraction from reports for bridge maintenance	-	-	-	-	-	-

Reference	**Objective**	**Ontology**	**Methodology**	**Language**	**Reasoner**	**CQs**	**Reuse**
[53]	Propose an ontology-based BIM for model-based fault diagnosis with propagation effects	BASont	-	OWL	-	-	Yes
[54]	Support knowledge understanding and sharing for eco or natural assets	EA-Onto	*somehow aligned with* Ontology Development 101	OWL	FaCT++, HermiT, Pellet, RacerPro, Snorocket	-	Yes
[55]	Develop an ontology for active fall protection system design	AFPS-Onto	Methontology	OWL	Pellet	Yes	Yes
[56]	Formalise domain-related knowledge for different design conditions of buildings	Feature ontology	-	OWL	-	-	Yes
[57]	Foster structured transaction management through ontology	Trans_Dom_Onto	*somehow aligned with* Ontology Development 101	OWL	-	-	Ext.
[58]	Develop an ontology-based integrator system of asset information for asset inventory and condition assessment	Transaction Domain Ontology, Tangible Capital Asset Ontology	*somehow aligned with* Ontology Development 101	-	-	Yes	Yes
[59]	Propose a system to integrate energy data from different sources using a shared ontology model	-	-	-	-	-	-
[60]	Use domain ontologies and graph-based reasoning for information sharing and re-use	-	-	-	-	-	-
[61]	Support maintenance schedule of buildings through combination and validation of multi-source data	-	-	-	ad-hoc	-	Yes
[62]	Develop an ontology for multi-layered data inferencing for bridge maintenance	-	-	-	-	-	Ext.
[63]	Develop an ontology model to support information retrieval for healthcare facility-related decisions	-	-	-	-	-	-
[64]	Develop and ontology-based building navigation system for health diagnosis	-	-	-	-	-	-
[65]	Enhance knowledge reuse to support risk management activities	project risk ontology	-	-	-	-	Yes
[66]	Develop a knowledge management system for context awareness about project task execution	Process-centered enterprise ontology	-	-	-	-	-

Eligible documents analysis for the process industry

Reference	Objective	Ontology	Methodology	Language	Reasoner	CQs	Reuse
[67]	Develop an ontology-based system to support water supply network through linked data	Water Supply Network Management Ontology	-	OWL	-	-	Yes
[68]	Mediate signals from sensors through ontologies for advanced rule-based diagnostics	-	-	OWL 2	ad-hoc	-	Ext.
[2]	Support energy efficiency and operations sustainability through integration of plant data and human expertise by relying on ontology inference engine and data mining	-	*somehow aligned with* Ontology Development 101	OWL	-	-	Yes
[69]	Extend diagnostics knowledge of wind farms and wind turbines leveraging on ontology and FMECA to support new maintenance personnel	FMECA ontology	-	OWL	ad-hoc	Yes	-
[70]	Support maintenance activity through ontology collecting operational data from monitoring systems and information from work order histories	-	*somehow aligned with* Ontology Development 101	-	-	-	-
[71]	Monitor the plant shutdown to retrieve cause and effects of alarm for further decisions	-	-	-	-	-	-
[72]	Show how domain ontology supports knowledge-based system but needs review over time	-	Methontology	OWL	-	-	-
[73]	Develop and evaluate an ontology for knowledge management in an energy utility	-	Methontology	RDFS	-	Yes	Ext.
[74]	Facilitate HAZOP through an ontology-based information system especially in non-standard analyses	HAZOP Ontology	-	OWL	ad-hoc	-	Yes

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