TLO/MLO Landscape Analysis Report

Grant Agreement: 958371

OntoCommons - Ontology-driven data documentation for Industry Commons, has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 958371.

Project Title	Ontology-driven data documentation for Industry Commons
Project Acronym	OntoCommons
Project Number	958371
Type of project	CSA - Coordination and support action
Topics	DT-NMBP-39-2020 - Towards Standardised Documentation of Data through taxonomies and ontologies (CSA)
Starting date of Project	01 November 2020
Duration of the project	36 months
Website	www.ontocommons.eu

TLO/MLO Landscape Analysis Report

Work Package	Top Reference Ontology
Task	TLOs/MLOs Landscape Analysis
Lead authors	Laura Ann Slaughter (UiO), Jens Otten (UiO)
Contributors	Stefano Borgo (CNR), Ana Correia (ATB), Emanuele Ghedini (UNIBO), Hedi Karray (ENIT), Claudio Masolo (CNR)
Peer reviewers	Emanuele Ghedini (UNIBO), Hedi Karray (ENIT)
Version	Final
Date	12/01/2022

Glossary of terms

Item	Description
TLO	Top-Level Ontology. A top-level ontology (or foundation ontology) is an ontology (in the sense used in information science) that consists of very general terms (such as "object", "property", "relation") that are common across all domains.
MLO	Middle-Level Ontologies. Middle-level (or mid-level) ontologies are primarily intended to extend TLO concepts towards a specific discipline (e.g. manufacturing, materials science, chemistry) with the aim to provide a core shared vocabulary for lower level modules. A MLO will provide a higher level of detail than a TLO, extending the taxonomical structure of the ontology more along on the horizontal dimension (i.e. sibling classes under the same superclass).
NMBP	Nanotechnology, Advanced Materials, Biotechnology, Advanced Manufacturing and Processing. An extended analysis of the NMBP domain is available in the „Report on existing domain ontologies in identified domains" of the OntoCommons project.

Keywords

Ontology, Top-Level Ontology (TLO), Middle-Level Ontology (MLO), NMBP, Landscape Analysis

Disclaimer

OntoCommons.eu has received funding from the European Union's Horizon 2020 research and innovation programme under the Grant Agreement no. 958371. The content of this document does not represent the opinion of the European Union, and the European Union is not responsible for any use that might be made of such content. The European Commission is not liable for any use that may be made of the information contained herein.

Executive Summary

This report summarizes the existing Top-Level Ontologies (TLOs) and Mid-Level Ontologies (MLOs) used in the NMBP work programme domains of interest. The report expands what is known about the TLOs and MLOs presented in the "Top-Level and Mid-Level Ontologies Multidisciplinary Workshop" of the OntoCommons project. In addition, it provides information about the perspectives of targeted communities and their methodological choices related to the use or development of TLOs and MLOs. The report provides an analysis of the main correspondences, similarities and differences between the identified TLOs and MLOs addressing potential NMBP domains of interest.

Table of Contents

1. Introduction 7
1.1 Methodology 7
2. Characterization of TLOs and MLOs 9
2.1 BFO 9
2.1.1 Active Use of BFO 9
2.1.2 Active Development of BFO 12
2.1.3 BFO Resources 13
2.1.4 BFO Expressiveness and Coverage 13
2.2 EMMO 14
2.2.1 Active Use of EMMO 15
2.2.2 Active Development of EMMO 21
2.2.3 EMMO Resources 21
2.2.4 EMMO Expressiveness and Coverage 21
2.3 DOLCE 21
2.3.1 Active Use of DOLCE 22
2.3.2 Active Development of DOLCE 24
2.3.3 DOLCE Resources 24
2.3.4 DOLCE Expressiveness and Coverage 24
2.4 BORO 25
2.5 ISO 15926 Parts 2 & 4 25
2.5.1 Active Use of ISO 15926 Parts 2 & 4 25
2.5.2 Active Development of ISO 15926 Parts 2 & 4 26
2.5.3 ISO 15926 Parts 2 & 4 Resources 26
2.5.4 ISO 15926 Parts 2 & 4 Expressiveness and Coverage 26
2.6 ISO 15926 Part 14 27
2.6.1 Active Use of ISO 15926 Part 14 27
2.6.2 Active Development of ISO 15926 Part 14 28
2.6.3 ISO 15926 Part 14 Expressiveness and Coverage 28
2.7 OPM 28
2.7.1 Active Use of OPM 29
2.7.2 Active Development of OPM 29
2.7.3 OPM Resources 29
2.7.4 OPM Expressiveness and Coverage 29

2.8 SUMO 30
2.8.1 Active Use of SUMO 31
2.8.2 Active Development of SUMO....32
2.8.3 UMO Resources....32
2.8.4 SUMO Expressiveness and Coverage 33
2.9 MLOs....33
3. Axiomatization and Reasoning 35
3.1 Languages and Complexity....35
3.2 Solvers, Reasoners and Provers....37
3.3 Axiomatizations of TLOs 37
3.3.1 BFO....38
3.3.2 EMMO 38
3.3.3 DOLCE 38
3.3.4 ISO 15926 Part 2 & 4....39
3.3.5 ISO 15926 Part 14....39
3.3.6 SUMO 39
Appendix A: List of TLOs (UK Survey) 40
References....45

List of Figures

Figure 1 - Import relations of BFO....10
Figure 2 - Overlap of BFO with other ontologies....11

List of Tables

Table 1 - Information gathered from experts concerning TLOs....8
Table 2 - List of MLOs reviewed in Task "MLO Development/Harmonisation" 35
Table 3 - Formal Logical Languages and Their Complexity 36
Table 4 - Automated Reasoning Tools....37
Table 5 - List of Top-Level Ontologies (UKRI Survey)....44

1. Introduction

This report is the landscape analysis of the top-level ontologies (TLOs) and mid-level ontologies (MLOs) showing potential for implementation within the NMBP (Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing) application domains. The report focuses on previous demonstrations with experience in implementing and developing ontologies for use within the Materials and the Manufacturing domains specifically. Input from these past projects brings to light previous experiences in order to inform the development of the Ontology Commons Ecosystem (OCES).

The report summarizes gathered information from a number of sources. These were individually conducted interviews with leaders in the NMBP domain specializing in ontology implementation and development, review of project reports from previous demonstrations, and a landscape review of articles and reports.

An overview of TLOs and MLOs is found in the report of the "Top-Level and Mid-Level Ontologies Multidisciplinary Workshop". These are the most relevant ontologies that were presented by interested parties in NMBP, and we expand on the features of these ontologies as they apply to potential use in OCES. Previous experience in the domain, size of their user communities, and other factors are considered. Characterisation of the TLOs in terms of perspectives, targeted communities, and methodological choices are further expanded. An analysis of the used axiomatization and considerations on automating reasoning are added that have not been previously included in any other report.

An additional focus of the report is to review previous demonstrations and use cases in NMBP. Interviews were conducted since the details of the ontology development process are often not published but held in personal experience. The goal of bridging between materials and manufacturing domains through ontology becomes clear through the interviews, the materials domain choosing to create their own ontology due to specific needs. We summarize the reasons behind specific design decisions, analyze the main correspondences, similarities and differences between the identified TLOs, and point towards further information.

1.1 Methodology

The methodology we used to gather information was based on (1) interviews, (2) information gathering from experts on each TLO, and (3) examining related literature (reports, previous landscape analyses, etc.).

According to the OntoCommon project proposal, these are the minimum (critical) requirements for selecting a top-level ontology.

1. The ontology is actually used in relevant NMBP domains,
2. it is actively developed and maintained,
3. it can provide additional resources (other than OntoCommons) for its further development,
4. and it is supported by strong communities that can facilitate stakeholder engagement.

Furthermore, as OntoCommons will provide a full syntactic alignment of ontologies, a TLO should be available in a selected set of ontology languages with different amount of expressiveness (e.g. OWL-DL, RDFS, FOL), see also Section 3.

Other criteria deemed as useful to collect for a landscape analysis includes: strengths and weaknesses of the TLO/MLO, organizational outlook, products and services surrounding the ontology, and potential for growth.

The methodology used in this landscape analysis is to collect data that covers the following about each TLO that has either 1) already been used in the NMBP domain or 2) that has expressed interest in use in the NMBP domain by participating in the workshop held as a part of Task "Networking and Consultation" in the OntoCommons project.

The questions and template used to collect information for each TLO is shown in Table 1.

1. Please complete some basic information about the TLO: • When was the TLO first developed? • Provide one to three good references describing the TLO. • Who is the person/institution/research group responsible for developing/maintaining the TLO? • Where would a reader learn more about using the TLO (e.g. tutorials, websites)?
2. Active Use/Domain Relevance of the TLO. • Describe the active use of the TLO in recent projects. • Write why the ontology is important/relevant to these projects.
3. Active Development of the TLO • Write a description about the current state of development of the TLO and where the communities involved are actively discussing issues. • Are there important working groups, etc.? Which institutions, communities are involved? Include organizational outlook and potential for growth.
4. Additional resources. • Write about any additional resources available to users of the TLO. Are there specific tools, networks available within the domain, etc.? • Are there specific products and services surrounding the TLO.
5. Expressiveness and Coverage. • Write a brief summary of the expressiveness and coverage of the TLO.
6. Implementation and Axiomatization • How has the TLO been implemented and in which language? • Is there an (implemented) axiomatization, e.g. in DL, OWL or FOL available?

Table 1 - Information gathered from experts concerning TLOs

MLOs are included in both reports "Report on OCES Disciplines of Interest" and „Report on existing domain ontologies in identified domains"of the OntoCommons project. The method for gathering information about these was through cooperation with the resulting efforts from several project partners. The definition of MLO is currently being discussed at the time of writing this landscape report and will be finalized as a part of the project efforts.

2. Characterization of TLOs and MLOs

Top-level (or upper-level) ontologies (TLO) are concerned with theories of such highly general categories as time, space, inherence, instantiation, identity, processes, events, and attributes. This chapter covers the landscape of existing TLOs and their corresponding MLOs used in NMBP and related domains, including the three ontologies that are currently in the spotlight for OntoCommons: the Basic Formal Ontology (BFO), the Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE), and the Elemental Multiperspective Material Ontology (EMMO).

The landscape analysis covers key organizations, and classification of the organizations type, audience, and mission for each TLO/MLO. In addition, we look at the overall criteria that are important for selection of a TLO/MLO by domain ontology developers.

A report produced as a part of the UK National Digital Twin (NDT) Hub covers TLOs and their assessment criteria 1. Information covered within the UK report is not repeated here.

2.1 BFO

The **Basic Formal Ontology (BFO)** was initiated in (Smith and Grenon, 2002). The goal of BFO is, similar to other TLOs, to provide a system of logical definitions for generic classes and relationships; they are subject-domain independent, e.g. processual entities. BFO incorporates both three-dimensionalist and four-dimensionalist perspectives on reality within a single framework and can deal with static/spatial and dynamic/temporal features of reality. The BFO taxonomy of entities are organized into continuants, entities existing at a given time, and occurrents, processes unfolding through time.

BFO has a history of over 19 years of research, development, and a strong community of users. Early applications have focused on the healthcare domain where the implementation of BFO is extensive. A list of 337 ontologies and the associated institutions/groups using BFO is available on the main BFO website at https://basic-formal-ontology.org. Detailed tutorials, courses, and other resources are available to help novice ontology developers build domain ontologies that extend BFO. A recommended set of tutorials is maintained on the BFO website.

Barry Smith at the State University in New York (SUNY) at Buffalo heads the development of BFO.

2.1.1 Active Use of BFO

BFO is relevant for the NMBP domains and has an active user base. The Industrial Ontology Foundry (IOF) provides resources and tools, with BFO serving as TLO for a suite of reference ontologies in IOF Core. To get an overview of the users in the NMBP domain, it is possible to check the list of BFO-based engineering ontologies.

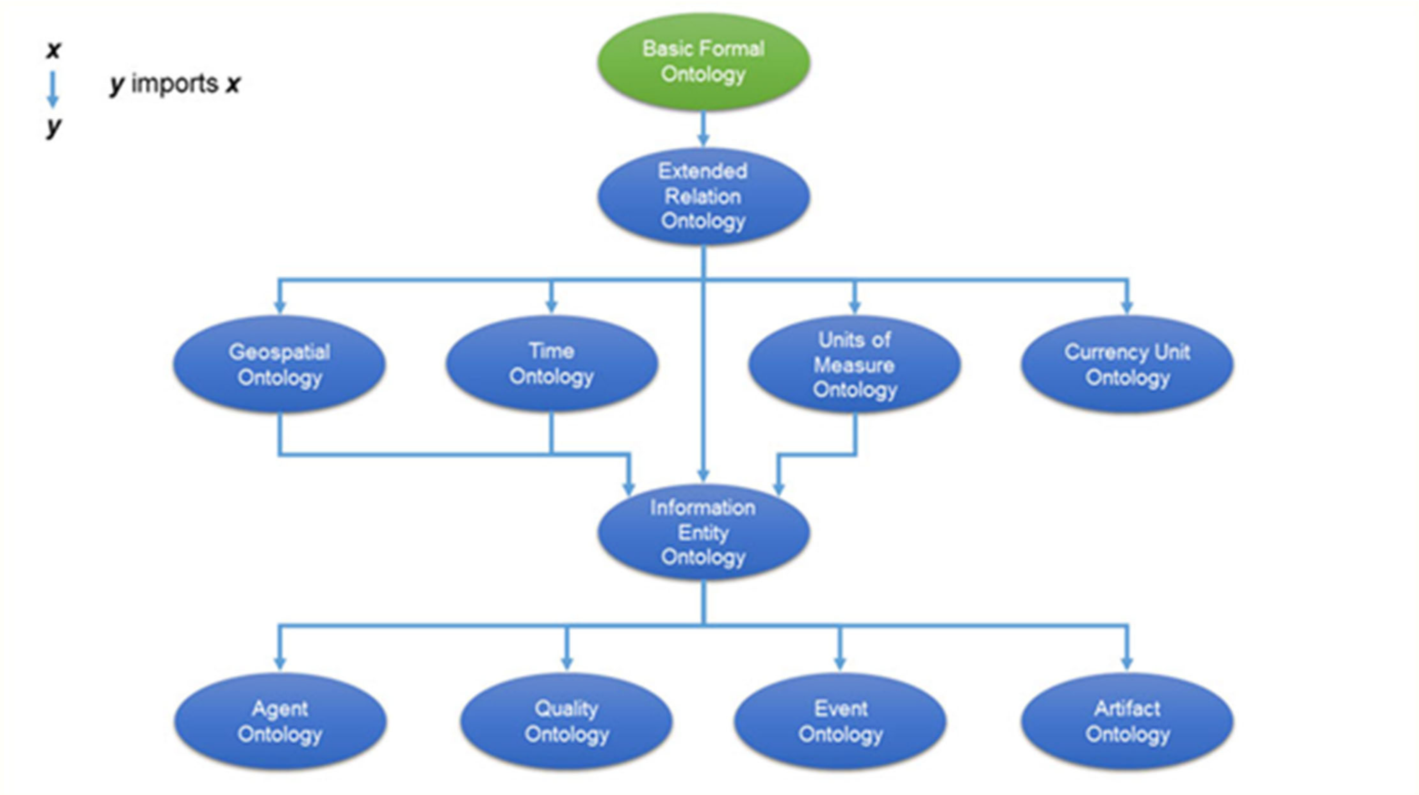

Figure 1 - Import relations of BFO

The Industrial Ontologies Foundry (IOF) was established in 2016, and has quickly become a key organization supporting development of BFO-extended ontologies within industry and engineering. There are several relevant WGs for the NMBP domain, and these are: IOF Core WG, Zero-Defect Manufacturing WG, Production Planning and Scheduling WG, System Engineering WG, MTConnect (Industrial Internet of Things) WG, Maintenance WG, Product Service System WG, and the Supply Chain WG. Each working group is focused on the development of BFO-based ontologies for use within their respective subareas. IOF's main efforts are centered on coordination and collaboration between ontology projects in the engineering domains, with the main goal of achieving interoperability and scalability.

The Common Core Ontologies (CCO) comprise eleven ontologies covering information entities, agents, qualities, events, information artifacts, time, geospatial, units of measure, currency units, extended relations and modal relations. The Data Science and Information Fusion Group's work in ontologies started in 2008. Since 2010, IARPA's Knowledge, Discovery and Dissemination program has focused on the development of the Common Core Ontologies (CCO). CCO is a mid-level extension of Basic Formal Ontology (BFO), an upper-level ontology framework widely used to structure and integrate ontologies in the biomedical domain (Arp, et al., 2015). BFO aims to represent the most generic categories of entity and the most generic types of relations that hold between them, by defining a small number of classes and relations. CCO then extends from BFO in the sense that every class in CCO is asserted to be a subclass of some class in BFO, and that CCO adopts the generic relations defined in BFO (e.g., has_part) (Smith and Grenon, 2004). The goal is to make CCO a standard mid-level ontology.

Accordingly, CCO classes and relations are heavily constrained by the BFO framework, from which it inherits much of its basic semantic relationships. Ongoing development of the CCO under projects supported by JIDO, CERDEC I2WD, ARL, AFRL Wright Patterson, AFRL Rome, and OSD have produced numerous domain-level extension ontologies, such as, Aircraft Ontology, Military Operations Ontology, Mission Planning Ontology, Sensor Ontology, and the Transportation Infrastructure Ontology.

Manufacturing x Digital (MxD) was formerly known as The Digital Manufacturing and Design Innovation Institute (DMDII). MxD is the second of the 16 institutes, known collectively as Manufacturing USA. The U.S. Department of Defense awarded the organization $80 million in seed funding in 2014, following a national competition. The CHAMP project, Coordinated Holistic Alignment of Manufacturing Processes (CHAMP) was a DMDII-funded project whose goal was to represent the Product Life Cycle in a set of mid-level ontologies that may be extended to integrate data both within industrial organizations and across them. The ontologies cover manufacturing processes, maintenance, commercial entities, services, and testing processes. Product life cycle publications resulting from CHAMP are included in the reference section of this report. The Product Life Cycle (PLC) Ontologies suite extends from the Common Core Ontologies (CCO).

MatPortal.org is a portal for all materials ontologies. Those extending BFO are Material Science and Engineering Ontology (MSEO), Matolab Tensile Test Ontology, BWMD Mid-Level Ontology (BWMD-MID), MatOnto Ontology (Bryan MIller), BWMD Domain Ontology.

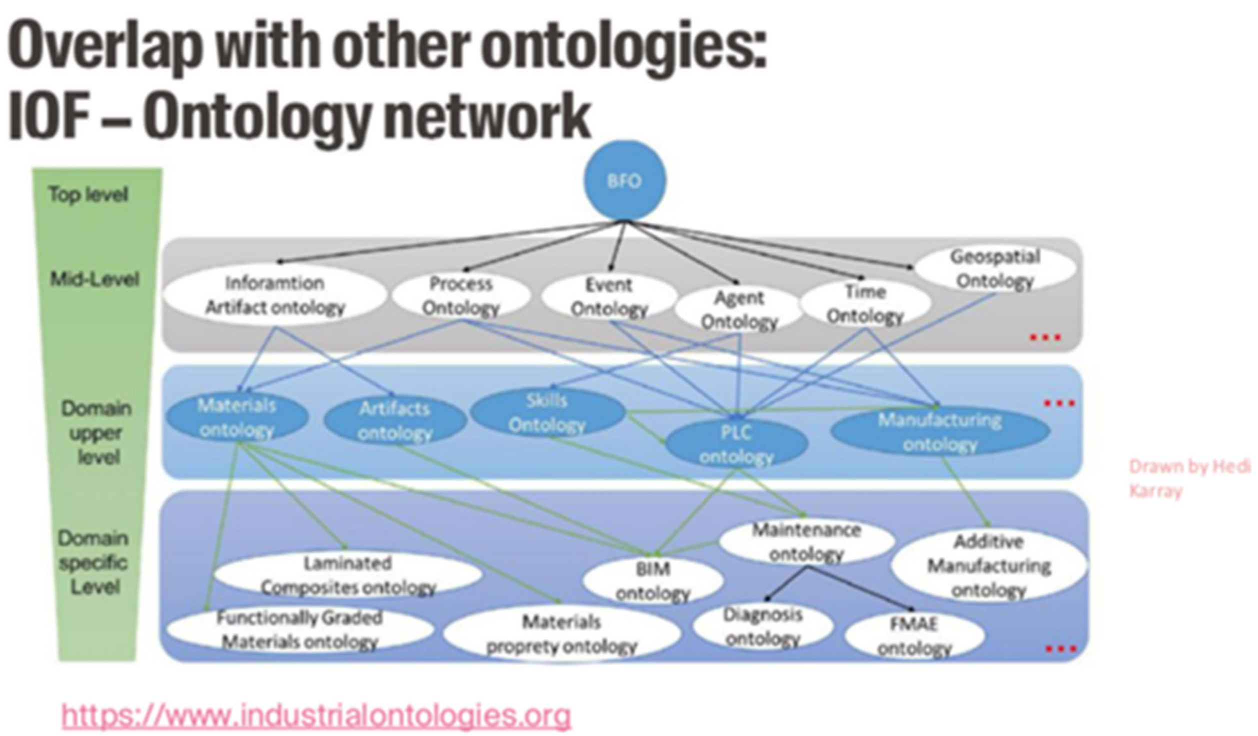

Figure 2 - Overlap of BFO with other ontologies

Domain level ontologies extend MLOs based on BFO. The z-bre4k ontologies cover the application domain of industrial maintenance and knowledge regarding components and processes. Figure 2 shows the domain and domain-specific ontologies based on BFO that are relevant to the NMBP domain. Z-Bre4k use cases demonstrate ontologies within zero-defect manufacturing of next generation automatic chassis, preventive to predictive maintenance with cold forming tooling, and predictive maintenance service for the end-user within Compression Moulding machines (see https://emmc.eu/wp-content/uploads/2021/06/Hildebrand_ECONTO2-min.pdf).

2.1.2 Active Development of BFO

The OBO (Open Biological and Biomedical Ontologies) Foundry, an ontology repository, was designed to be a community resource of public domain ontologies in the health and biological sciences. It is a collaborative experiment based on the voluntary acceptance by its participants of an evolving set of principles and designed to maximize the degree to which ontologies can support the needs of working scientists. The OBO Foundry provides models of good practice in ontology development along a number of axes, conformity to which provides a standard of evaluation for ontologies submitted to the Foundry. Foundry ontologies share a common top-level ontology—Basic Formal Ontology—which divides entities into the basic categories of continuants (which endure through time) and occurrents (which unfold themselves in time) (Grenon et al., 2004) and (Smith, Fois 2008). BFO is the upper level ontology upon which OBO Foundry ontologies are built. OBO foundry is an active community and provides issue tracking and resolution through GitHub.

Each candidate ontology for the OBO Foundry is subject to a process of peer review, the reviews being carried out by two types of editors: coordinating editors, whose primary responsibility is harmonizing interactions among ontology development projects, and associate editors, who are the editors of the ontologies already accepted for inclusion within the Foundry. In addition, ad hoc reviewers with special expertise are included in the reviewing process as occasion demands. There are 14 principles that guide the quality of ontology development, access and maintenance.

The OBO Foundry has been a successful venture in the bioinformatics domain, and its approach is now being copied by others. (Smith et al. 2007) provide a demonstration of the utility of the Foundry methodology in the neurophysiological, neuroanatomical, and biomedical domains. The United Nations Environmental Program (UNEP) is developing an ontology for use in their knowledge management platform—the Sustainable Development Goals Interface Ontology (SDGIO). The UNEP approach to achieving interoperability is modelled on the OBO Foundry. OBO Foundry principles for ontology development, are now being used by ontology developers also in other areas, including manufacturing, geology, transport, and security.

The first IOF workshop was organized in December 2016 at the National Institute of Standards and Technology (NIST), Gaithersburg, USA. Thereafter, the community has had weekly conference calls and yearly workshops. Following the workshop in 2017, the IOF charter has been drafted and became available on its web site as a community draft. The community has devised three kinds of committees: a governance board (GB), a technical oversight board (TOB), and working groups (WGs). The primary role of the GB is to maintain the health and effective operation of the IOF organization. It sets the overall policy and manages legal aspects of the business. The other important role for the GB is to resolve conflicts unresolvable by the TOB. TOB members are responsible for setting ontology principles and design guidelines used across the WGs. They have an important role to ensure that modules of the IOF ontologies developed by each WG are interoperable and consistent. Each WG develops an ontology or a suite of ontologies of the IOF ontologies vetted by the TOB. Some WGs may be responsible for developing or adapting cross-cutting, domain independent ontologies such as for time or units of measurement. BFO was adopted in the spring of 2019 to be the top-level ontology of the Industrial Ontologies Foundry (IOF), an ecosystem of ontology resources designed to promote interoperability in digital manufacturing and related fields. Recently, The Open Application Group (OAGi) and the Industrial Ontologies Foundry (IOF) have signed an agreement to produce industrial ontologies. OAGi will establish an IOF membership category, accept ownership of ontology artifacts developed by the IOF, and release them under MIT and CC BY 4.0 (or similar) licenses. Further ontology development will occur in the context of OAGi and ontology artifacts released by OAGi (see https://oagiscore.atlassian.net/wiki/spaces/IOF/overview).

More recently, BFO has also become an ISO standard:
see https://standards.incits.org/apps/group_public/project/details.php?project_id=3037.

2.1.3 BFO Resources

The National Center for Ontological Research (NCOR) was established in Buffalo in 2005 with the goal of advancing the quality of ontological research and development and of establishing tools and measures for ontology evaluation and quality assurance. NCOR draws on the expertise of ontologists associated with the University at Buffalo and of their collaborators in scientific, commercial and government institutions throughout the world. NCOR serves as a vehicle to coordinate, enhance, publicize, and seek funding for ontological research activities. It provides coordination, infrastructure, and independent review to organizations employing ontologies in fields such as defense and intelligence, management, healthcare and biomedical sciences.

Ontobee (http://www.ontobee.org/) is a linked data server designed for ontologies. Ontobee is aimed to facilitate ontology data sharing, visualization, query, integration, and analysis. Ontobee dynamically dereferences and presents individual ontology term URIs to (i) HTML web pages for user-friendly web browsing and navigation, and to (ii) RDF source code for Semantic Web applications. Ontobee is the default linked data server for most OBO Foundry library ontologies. Ontobee has also been used for many non-OBO ontologies.

Ontobeep (http://www.ontobee.org/ontobeep) is a relatively independent tool in Ontobee. Ontobeep is targeted for ontology alignment and comparison of ontologies that are listed in Ontobee. Ontobee is able to display the similarities and differences among selected ontologies. Ontobeep also provides a page to summarize statistical numbers out of the ontologies' alignment and comparison.

2.1.4 BFO Expressiveness and Coverage

For the formal axiomatization of BFO see Section 3.3.1 of this report and a paper by Smith et al. 2019 (http://ceur-ws.org/Vol-2518/paper-FOMI6.pdf). An overview of CCO is found in another report published by NIST (https://www.nist.gov/system/files/documents/2019/05/30/nist-ai-rfi-cubrc_inc_004.pdf).

2.2 EMMO

The **Elemental Multiperspective Material Ontology (EMMO)**, formerly known as the European Materials Modelling Ontology, is the result of a multidisciplinary effort within the European Materials Modelling Council (EMMC), aimed at the development of a standard representational ontology framework based on current materials modelling and characterization knowledge. Instead of starting from general upper-level concepts, as done by other ontologies, the EMMO development started from the very bottom level, using the actual picture of the physical world coming from applied sciences, and in particular from physics and material sciences.

The EMMO has grown from the bottom (i.e., scientific application field) to the top (i.e., conceptualization), staying focused on the original scope while at the same time maintaining an approach as general as possible. The ontological framework has been built around concepts like elementary particles, wave-particle dualism, finiteness of space and time intervals coming from the perspective for experimental physics. The development of the mid and upper layers of the ontology has been functional to the respect of these low-level concepts, to facilitate the understanding of the high-level concepts to users with limited or no philosophical background.

The form of knowledge generated by this approach has been formally expressed using methods of analytical philosophy (e.g., mereology, topology, semiotics) and by means of languages and technologies (e.g., OWL) in a strong multidisciplinary approach. In this sense the EMMO is more an ontology for applications than an applied ontology.

EMMO has the objective of becoming a practical tool to achieve interoperability in the areas of describing, processing, characterising and modelling of materials and of their properties. Once being established in an electronically readable form, such an ontology, together with its extensions, also provide formal categorisation schemes to complement machine learning, to facilitate digitalisation of industrial materials technologies, and to help with the integration of artificial intelligence (AI) and Big Data approaches.

The EMMO top level is the group of fundamental axioms that constitute the philosophical foundation of the EMMO. Adopting a physicalist and nominalist perspective, the EMMO defines real world objects as 4D objects that are always extended in space and time (i.e., real world objects cannot be spaceless nor timeless). For this reason, abstract objects, i.e. objects that do not extend in space and time, are forbidden in the EMMO. It has been instigated by materials science and provides the connection between the physical world, the experimental world (materials characterisation) and the simulation world (materials modelling).

In contrast to most of the existing TLO, in EMMO, everything is of material nature and there is no representation of abstract entities. The semiotic approach of the EMMO provides a means to deal with more than one single approach to represent the same domain, which is usually the case on applied sciences and engineering, where more than one standard may define a real world object in different ways. This enables EMMO to easily deal with e.g. multiple measurements, uncertainty, models. Furthermore, some aspects, such as granularity of materials and multiscale modelling, spanning from continuum to atomic level are easily represented by this TLO. The lack of immediate availability of such features in the actual TLO community was the main motivation behind the development of EMMO.

To support the pluralistic representation of the world, EMMO supports a number of so-called Perspectives, The Perspective class collects the different ways to represent the objects that populate the conceptual region between the elementary and universe levels, i.e. it acts as a root to middle-level ontologies which in turn act as roots for extending the EMMO towards specific application domains. The main perspectives are:

- *Holistic*: considers the importance and role of the whole as well as its parts without specific granularity hierarchy, with subclasses Whole (based on some criterion) and Part (as it appears in relation to the Whole, also regarding its role, hence Role is an alternative label for Part, as also used e.g. in theatre).

- *Persistence*: considering the persistence in time (process) or space (object). This perspective also enables mapping the widely used 3D ontologies BFO and DOLCE which are based on a similar high-level categorisation.

- *Physicalistic*: uses applied science concepts to provide meaning to objects (e.g. a material as a scientific object, interrogated by scientific means).

- *Reductionistic*: focusses on a strict hierarchy of objects in terms of granularity levels (in space and/or time). Also useful for a "Systems of systems" view on engineering.

- *Perceptual*: includes recognisable patters in space and/or time such as sounds, languages, alphabets symbols, mathematics, graphics.

EMMO was initially released in 2019 by five core developers:

- Emanuele Ghedini (main developer), Università di Bologna, Italy
- Gerhard Goldbeck, Goldbeck Consulting LTD, UK
- Jesper Friis, SINTEF, Norway
- Adham Hashibon, UCL, UK
- Georg Schmitz, ACCESS, Germany

More information is available at https://emmc.eu/news/emmo-new-name-and-logo/. See also https://materialsmodelling.com/2019/06/14/european-materials-modelling-ontology-emmo-release/.

2.2.1 Active Use of EMMO

As EMMO was developed within the EMMC project, its current use has a strong focus on the material science domain. Hence, it is also of particular interest in the target NMBP domain of the OntoCommons project. European stakeholders include manufacturing industries and software owners. The EMMC enjoyed wide community support from all stakeholders including substantial participation of numerous Small and Medium as well as Large European Enterprises.

Projects that use the EMMO ontology:

- **SimDOME** aims to develop an industry-ready software framework for materials modelling interoperability, based on EU/EMMC standards on materials modelling, by combining, further developing and adapting existing software developed within previous EU FP7-NMP projects SimPhoNy and MoDeNa, the H2020-NMBP project NanoDome and the FP7 ERC-AdG STRATUS. [https://simdome.eu/

- **OntoTrans** project aims to introduce an ontology-based open translation environment. Using AI, the project will make it possible for end users to represent their manufacturing process challenges in a standard ontological form. It will also enable them to connect these challenges with relevant information sources and materials modelling solutions that can support optimal materials and process design. OntoTrans is providing important contributions to EMMO, especially in the field of conceptualising and ontologising manufacturing cases. [https://ontotrans.eu/, https://cordis.europa.eu/project/id/862136]

- The EU-funded **Digital Open Marketplace Ecosystem (DOME) 4.0** project aims to develop a comprehensive industrial data ecosystem that enables sharing of business-to-business data for the purpose of value generation and creation of new or enhanced products, processes and services. The project will be aligned with the Open Science and Open Innovation objectives. The DOME 4.0 ecosystem will be accessible to all providers and users of data, using ontology-driven semantic data interoperability and modern data processing technologies adopted from the fields of machine learning and artificial intelligence to facilitate maximum knowledge extraction. DOME 4.0 will focus on data-driven knowledge generation within the materials and manufacturing sectors, but the proposed ecosystem will be scalable to any sector of the economy.

  [https://dome40.eu/, https://cordis.europa.eu/project/id/953163]

- **OpenModel** aims to design, create, provide, and maintain a sustainable integrated open platform for innovation which delivers predictable, validated, and traceable simulation workflows integrating seamlessly third-party physics-based models, solvers, post-processors and databases. OpenModel thus bridges the gap from industry challenge via translation to actionable results that enable well informed business decisions. Six use cases (Success Stories) show the applicability to a wide range of materials and their related processing technologies and demonstrate how OpenModel facilitates setting up experiments, reducing error and enhancing development efficiency.
  [https://www.open-model.eu/, https://cordis.europa.eu/project/id/953167]

- **INTERSECT** wants to leverage European leadership in materials' modelling software and infrastructure, as embodied in track record of the team, to provide industry-ready integrated solutions that are fully compliant with a vision of semantic interoperability driven by standardized ontologies. The resulting IM2D framework – an interoperable material-to-device simulation platform – will integrate some of the most used open-source materials modelling codes (Quantum ESPRESSO and SIESTA) with models and modelling software for emerging devices (GinestraTM) via the SimPhoNy infrastructure for semantic interoperability and ontologies, powered by the AiiDA workflow engine, and its data-on-demand capabilities and apps interface. [https://intersect-project.eu]

- The EU-funded **ReaxPro** project has identified a set of academic software tools (EON, Zacros, CatalyticFOAM) which will be upscaled into easy-to-learn, user-friendly, interoperable software that is supported and well documented. These tools will be further integrated with commercial software (Amsterdam Modeling Suite) into an industry-ready solution for modelling and design of catalytic materials and reactive processes. To fully reach the target technology readiness level of 7, ReaxPro has partnered with translators and industry for validation and demonstration in pilot- and industrial-scale use cases. [https://www.reaxpro.eu/]

- The **MarketPlace** consortium will utilise state of the art information technologies to build an open web-based integrated Materials Modelling and Collaboration platform that acts as one-stop-shop and open Marketplace for providing all determining components that need to be interwoven for successful and accelerated deployment of materials modelling in industry. This includes linking various activities and databases on models, information on simulation tools, communities, expertise exchange, course and training materials, lectures, seminars and tutorials. [https://cordis.europa.eu/project/id/760173]

- The **Virtual Materials Market Place (VIMMP)** facilitates and promotes the exchange between all materials modelling stakeholders for the benefit of increased innovation in European manufacturing industry. VIMMP will establish an open-source, user-friendly, powerful web-based marketplace linking beneficiaries from different manufacturing industry sectors with relevant materials modelling activities and resources. To enable a seamless and fully integrated environment, VIMMP is built on solid taxonomy and metadata foundations, including those centered on materials models, software tools, communities, translation expertise and training materials.

  [https://www.vimmp.eu/, https://link.springer.com/article/10.1007/s13218-020-00648-9]

- **Oyster** is an open characterisation and modelling environment to drive innovation in advanced nano-architectured and bio-inspired hard/soft interfaces OYSTER uses contact mechanics to bridge adhesion data at multiple length scales and link interfacial adhesion to physicochemical properties. OYSTER brings Europe's first-class laboratories and SMEs to take existing nanoscale characterisation technologies towards widespread utilisation in process optimisation and model validation. OYSTER achieves this by sharing metadata in an Open Innovation Environment (OIE), where new paradigms of multi-scale contact mechanics are validated on selected application oriented reference materials through continuous interaction with the European Materials Characterisation Council (EMCC).

- The **Battery Interface Genome – Materials Acceleration Platform (BIG-MAP)** project is part of the large-scale and long-term European research initiative BATTERY 2030+. Here, we propose a radical paradigm shift in battery innovation, which will lead to a dramatic speed-up in the battery discovery and innovation time; reaching a 5-10 fold increase relative to the current rate of discovery within the next 5-10 years. BIG-MAP relies on the development of a unique R&D infrastructure and accelerated methodology that unites and integrates insights from leading experts, competences and data across the entire battery (discovery) value chain with Artificial Intelligence (AI), High Performance Computing (HPC), large-scale and high-throughput characterization and autonomous synthesis robotics. In short, BIG-MAP aims to reinvent the way we invent batteries and to develop core modules and Key Demonstrators of a Materials Acceleration Platform specifically designed for accelerated discovery of battery materials and interfaces.

  [https://www.big-map.eu/, https://cordis.europa.eu/project/id/957189]

- The **Formulations and Computational Engineering (FORCE)** consortium is a 10 pan-European expert partnership with the objective to develop an integrated Business Decision Support System (BDSS) based on open standards for industries engaged in formulating chemical ingredients. The generic BDSS is an open framework that connects any existing or future materials models at various levels of complexity and discretion (electronic, atomistic, mesoscopic, continuum and empirical), experimental data sets, and structured and unstructured commercial information (e.g. on cost, forecasting, intellectual property). The project has a generic focus but targets three specific important industrial sectors as main demonstrators, namely Personal Care (liquid detergents), Insulating Rigid PolyUrethane (PU) based Foams and Industrial Inks (PU-based) for the purpose of focus and generating a real ready to use BDSS available to large, medium and small enterprises alike.

- The mission of **COMPOSELECTOR** is to develop a Business Decision Support System (BDSS), which integrates materials modelling, business tools and databases into a single workflow to support the complex decision process involved in the selection and design of polymer-matrix composites (PMCs). This will be achieved by means of an open integration platform which enables interoperability and information management of materials models and data and connects a rich material modelling layer with industry standard business process models.

- The focus of **NanoMECommons** is to employ innovative nano-scale mechanical testing procedures in real industrial environments, by developing harmonised and widely accepted characterisation method., To achieve this goal, NanoMECommons will offer protocols for multi-technique, multi-scale characterisations of mechanical properties in a range of industrially relevant sectors, together with novel tools for data sharing and wider applicability across NMBP domain: reference materials, specific ontologies and standardised data documentation.

- The goal of the EU-funded **VIPCOAT** project is to create an open innovation platform that should assist engineers in developing coating materials and constructing accelerated life test scenarios to assess their durability. Initially, the platform will target the aeronautic industry. However, it will later host interoperable applications, based on standardized ontologies as extensions of the European Materials Modelling Ontology that should enable to transfer methods and insights to other industries. The VIPCOAT platform will open the door to new production concepts with reduced process steps, lower energy consumption and reduced use of natural resources. [https://vipcoat.eu/, https://cordis.europa.eu/project/id/952903]

- The goal of the project **ZEOCAT-3D** is the development of a new bi-functional (two types of active centers) structured catalysts, achieving for the first time a tetramodal pore size distribution (micro-, meso1-, meso2-, macro-porous) and high dispersion of metal active sites for the conversion of methane, coming from different sources as natural gas and biogas, into high value chemicals such as aromatics (benzene, naphthalene, among others) via methane dehydroaromatization (MDA).

- **NanoBat** aims to develop a novel RF-nanotechnology toolbox for quality testing of Li-ion and beyond Lithium batteries with the potential to redefine battery production in Europe and worldwide. A particular focus will be testing and quantifying the electrical processes at the SEI, which are responsible for battery performance and safety, but difficult to characterise and optimise. As SEI formation amounts to one third of battery production costs, the project will reduce such costs significantly and hence benefit the evolving clean energy and e-mobility transition in Europe.

- The **Centre for Sustainable and Competitive Metallurgical and Manufacturing Industry (PhysMet)** is a centre for research-based innovation (SFI) appointed by The Research Council of Norway from 2020-2028. It is a dedicated, long-term initiative designed to strengthen and further develop physical metallurgy and aims to accelerate the transformation of the national metal industry towards more sustainable and cost-efficient production and future material products, solutions and improved processing methods. One of the activities within SFI PhysMet is to develop an EMMO-based microstructure domain ontology suitable for describing metallurgical systems and enable between experiments, analysis and modelling activities within the centre. [https://www.ntnu.edu/physmet/physmet]

- **FormPlanet** is one of European Union's Open Innovation Test Beds (OITBs) for characterisation, aiming at increasing the productivity of the sheet metal forming industries through the development of new experimental and modelling methodologies to assure zero-defects production and optimise sheet material development, production and performance. FormPlanet develops unique testing methodologies for more accurate materials characterisation and modelling for high strength sheet materials, addressing processability and quality parts problems in the sheet manufacturing sector.

- i-TRIBOMAT aims at establishing the world first open test bed of tribological materials characterisation to support industrial innovations among European manufacturing industries and SMEs by upscaling materials to the mechanical components level. i-TRIBOMAT open test bed enables user-driven versatile characterisation of materials at reduced costs by also shortening the time-to-market ca. 5 times. i-TRIBOMAT will realize a unique bundle of shared tribological infrastructure and expertise consisting of >100 tribometers, materials characterisation equipment and additional tools for modelling, protocols, tribo-analytics, design of experiments and online monitoring. i-TRIBOMAT will establish an IT-platform for materials and tribological data harmonisation, management, analytics, sharing and mining. i-TRIBOMAT on its collaboration interface will supply lab-to-field upscaling tools by combining testing with computation, e.g., using AI methods, virtual work rooms and surrogate models for various stakeholders, like EUMAT-platform.

Use of EMMO in domain ontologies

Currently there are several domain ontologies in development that use EMMO as the top- and middle-level ontology. Typically they import one of the versions of EMMO listed on https://emmo-repo.github.io/. The following table lists the public EMMO-based domain ontologies.

Domain Ontology	Link
Battery Interface Ontology (BattINFO)	https://github.com/BIG-MAP/BattINFO
Crystallography	https://github.com/emmo-repo/domain-crystallography
Mechanical Testing	https://github.com/emmo-repo/domain-mechanical-testing
Microstructure domain ontology	https://github.com/emmo-repo/domain-ontology
Datamodel ontology	https://github.com/emmo-repo/datamodel-ontology
Mappings ontology	https://github.com/emmo-repo/domain-mappings
Atomistic and Electronic Modelling	https://github.com/emmo-repo/domain-atomistic
EMMO example domain ontologies	https://github.com/emmo-repo/EMMO/tree/master/domain

Table 2 - Domain Ontologies for EMMO

2.2.2 Active Development of EMMO

EMMO is actively developed and new versions are published on the GitHub portal https://github.com/emmo-repo/EMMO.

2.2.3 EMMO Resources

The **EMMOntoPy**, formerly called EMMO-python, is a generic Python package based on Owlready2 for working with ontologies, with special support for EMMO-based ontologies. It include a set of tools to simplify development, use and documentation of ontologies:

- ontograph – Visualisation of ontologies
- ontodoc – Ontology documentation generator
- ontoconvert – Converts between formats (turtle, rdf/xml); Reasoning
- emmocheck – Checks that an ontology complies with EMMO conventions and best practices

EMMOntoPy is available at https://github.com/emmo-repo/EMMO-python.

2.2.4 EMMO Expressiveness and Coverage

Within the limit of OWL-DL, EMMO provides a high degree of expressiveness. EMMO achieves this by firstly embraces pluralism and allows to describe the world according to different perspectives. The expressivity can be further increased by combining perspectives, like the Perceptual and Reductionistic perspective for describing multidimensional tensors or formal languages with multiple granularity levels, like sentences, words, and symbols. Secondly, EMMO has a narrow, but deeply nested structure of relations, with only three basic types of relations: mereological, topological and semiotical. This gives the reasoner many possibilities to infer new relations.

The EMMO top-level ontology is very small (only 6 classes) and provide the fundamental axioms and the philosophical foundation. The EMMO mid-level provides different perspectives with which the world can be describing but stays generic and domain-agnostic. On this basis, a hierarchical structure of EMMO-based domain ontologies has been developed covering different aspects of applied sciences.

2.3 DOLCE

The **Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE)** is a foundational ontology first released in 2002 and finalized in 2003. It is maintained by the ISTC-CNR Laboratory for Applied Ontology which developed it within the WonderWeb project. DOLCE was conceived as a module of the WonderWeb Foundational Ontologies Library and, among the largely used foundational ontologies, it is the only one which is stable, today it has ensured interoperability across information systems for close to 20 years. DOLCE provides general categories and relations that can be reused in different application scenarios by specializing them to the domains to be modeled, among which are the NMBP domains.

From a philosophical perspective, DOLCE adopts a descriptive (rather than referentialist) metaphysics, as its main purpose is to make explicit conceptualizations that may already exist in a domain. The categories of DOLCE are influenced by natural language, the makeup of human cognition, and socio-technical practices. At the highest level, DOLCE distinguishes four core classes: objects (called endurants), events (perdurants), qualities and abstracts. DOLCE is formally specified in first-order logic (FOL) and has versions in the OWL language and subsets of it. The consistency of DOLCE has been proved by independent researchers.

These are some of the main references and introductory texts:

- WonderWeb Deliverable 18 (Masolo, C. et al., 2003) includes the final axiomatization of DOLCE in FOL, as well as the presentation of the WonderWeb Foundational Ontologies Library. This deliverable is to be considered as the main, official documentation of DOLCE (*http://www.loa.istc.cnr.it/old/Papers/D18.pdf*).
- *DOLCE: A Descriptive Ontology for Linguistic and Cognitive Engineering, Applied Ontology journal, (to appear) (Borgo, S., et al., 2021).*

More information about the DOLCE ontology is available at the DOLCE website at http://www.loa.istc.cnr.it/index.php/dolce/.

2.3.1 Active Use of DOLCE

DOLCE has been used for 20 years across several domains including NMBP areas. Particular attention has been paid by industrial applications (including additive manufacturing) making the ontology of particular interest for the OntoCommons project.

Projects that use the DOLCE ontology:

- The **bio-zen** Project (Medical University of Vienna) is an ontology framework, which provides a sound ontological basis for the life sciences through the tailoring and integration of several existing ontologies in the Open Biomedical Ontologies repository. The ontology framework adheres to the OWL format and reuses existing foundational ontologies like DOLCE.

- The **bio-zen-plus** ontology is an ontology for biology; as the name suggests, it is an extension of the bio-zen ontology. Bio-zen plus is an OWL DL ontology for the domain of biomedical research. It incorporates several existing Semantic Web ontologies: the DOLCE foundational ontology, the Simple Knowledge Organisation System (SKOS), the Semantically Interlinked Online Communities ontology (SIOC), FOAF ontology, the Dublin Core metadata schema and the Creative Commons Metadata schema.

- The main goal of the **BulTreeBank Project** (Bulgarian Academy of Science) is to develop a high quality set (TreeBank) of syntactic trees for Bulgarian within the framework of Head-driven Phrase Structure Grammar (HPSG). [http://bultreebank.org/en/]

- The aim of this **Semantic Web Best Practices and Deployment (SWBPD)** W3C Working Group is to provide hands-on support for developers of Semantic Web applications. [https://www.w3.org/2001/sw/BestPractices/]

- The (W3C) **Semantic Sensor Network (SSN)** ontology is an ontology for describing sensors and their observations, the involved procedures, the studied features of interest, the samples used to do so, and the observed properties, as well as actuators. [https://www.w3.org/TR/vocab-ssn/]

- The (W3C) **PROV Ontology (PROV-O)** expresses the PROV Data Model [*PROV-DM*] using the OWL2 Web Ontology Language (OWL2) [*OWL2-OVERVIEW*]. It provides a set of classes, properties, and restrictions that can be used to represent and interchange provenance information generated in different systems and under different contexts. [https://www.w3.org/TR/prov-o/]

- **IEEE - 1872.2 – Standard for Autonomous Robotics (AuR) Ontology**. The purpose of the standard is to extend the CORA ontology to represent more specific concepts and axioms that are commonly used in Autonomous Robotics. The extended ontology specifies the domain knowledge needed to build autonomous systems comprised of robots that can operate in all classes of unstructured environments. The standard provides a unified way of representing Autonomous Robotics system architectures across different R&A domains, including, but not limited to, aerial, ground, surface, underwater, and space robots. [https://sagroups.ieee.org/1872-2/]

- **Pro2Evo** - Product and Process Co-Evolution Management via Modular Pallet configuration (Factory of the Future project).

- **GECKO - Generic Evolutionary Control Knowledge-based Module**. The GECKO (Factory of the Future) project proposes an adaptive control infrastructure based on control modules named GECKO, Generic Evolutionary Control Knowledge-based mOdule. The production environment is modelled as a community of autonomous, self-declaring, heterarchically collaborating GECKO modules encapsulated in the physical mechatronic equipment. [https://www.istc.cnr.it/en/project/gecko-generic-evolutionary-control-knowledge-based-module]

- **European Japanese Ontology Interaction (EUJOINT)**. The EUJOINT exchange programme conjoined two areas of research: foundational ontology and engineering design. Foundational ontology focuses on the study of the essential elements that allow to define notions of general interest. The goal of applied ontology is to study, organise and logically formalise these notions with attention to philosophical motivations. Engineering design is the area of engineering dealing with the early phases in the product life cycle. [https://cordis.europa.eu/project/id/247503/reporting/de]

- **FourByThree - Highly customizable robotic solutions for effective and safe human robot collaboration in manufacturing applications**. FourByThree proposes the development of a new generation of modular industrial robotic solutions that are suitable for efficient task execution in collaboration with humans in a safe way and are easy to use and program by the factory worker. [https://cordis.europa.eu/project/id/637095]

- Additive **Manufacturing Ontology (AMU)** was developed to address the lack of ontologies that are suited for modern manufacturing processes such as additive manufacturing . It is developed as part of the Industrial Ontologies Foundry (IOF) initiative, and is formalised using OWL and DOLCE.

- **MatOnto (Materials Ontology)** aims to represent structured knowledge about materials, their structure and properties and the processing steps involved in their composition and engineering. The primary aim of MatOnto is to provide a common, extensible model for the exchange , re-use, integration of material science data and experimentation. MatOnto 2.0 is based on BFO.

2.3.2 Active Development of DOLCE

DOLCE has attracted much attention because it has a stable organization, deep axiomatization and large coverage. Because of these features, several foundational ontologies (e.g. BFO, UFO and YAMATO) have evolved to include aspects of DOLCE.

DOLCE is actively supported via the development of application modules and theories aimed to extend or facilitate its use (e.g. for CAD modelling, manufacturing resources, maintenance services, technical devices, social roles, cultural heritage).

DOLCE is one of the foundational ontologies submitted for inclusion in the ISO/IEC 21838 standard.

2.3.3 DOLCE Resources

DOLCE does not require special software for maintenance, reasoning, or visualization.

2.3.4 DOLCE Expressiveness and Coverage

DOLCE is written in a very expressive language (first-order quantified modal logic) making it one of the most expressive foundational ontologies. In 20 years, it has been used to cover a variety of domains at the mesoscopic level (industry, robotics, economics, public services, social interactions, cognition, digital humanities etc.) always providing ways to model the domain concepts. DOLCE is not meant to cover theories that challenge usual cognitive views of the world, like quantum physics, and its use in such domains is not endorsed.

2.4 BORO

The development of the **Business Object Reference Ontology (BORO)** started in the 1980's. BORO has two closely intertwined components: a foundational ontology and a re-engineering methodology.BORO's ontology contributed to the development of the ISO 19526-2 standard. Some of BORO's clients include: Royal Dutch Shell, and Tullow Oil. The TLO is relevant to the NMBP domain.

BORO is currently not in active development. BORO provides an upper level foundational ontology containing objects and subclasses: elements, types, and tuples. The BORO team has created a product called bCLEARer [https://github.com/emmo-repo/domain-crystallography]. This is a tool based on mining ontologies from existing systems.

2.5 ISO 15926 Parts 2 & 4

The **ISO 15926 Parts 2 & 4 (ISO 15926-2 & ISO 15926-4) standard** was developed by the EPISTLE consortium of energy and engineering companies, which ran from 1993 to 2003. It was originally intended to finance an ISO 10303 application protocol (AP221) for functional data for process plants. The project identified that a STEP API was inadequate for their purpose of building a data warehouse for engineering design that could contain requirements, design and installed equipment, with changes. ISO 15926 was proposed as a complement to STEP that could meet these requirements. The project built the information model based on an ontology, with a developed formal ontology. As an ISO standard, it is not freely available, but can be purchased from ISO and national standard organizations.

The standard is described by ISO documents listed in the References section. The formal ontology used in the standard is described in Part 2 of the standard. A short introduction to the standard is given by (Leal, 2005). The ontology is expressed in Part 2 using the EXPRESS language. Implementations in OWL have been made and are published in Part 8 and Part 12.

The website https://15926.org/home/ is maintained on a voluntary basis by Hans Teijgeler and Onno Paap. This contains information about the formal ontology and how to use it.

2.5.1 Active Use of ISO 15926 Parts 2 & 4

Recent work using the ontology has been done by three groups:

- PCA maintains and develops reference data: http://data.posccaesar.org/rdl.
- A group maintains another set of reference data, http://data.15926.org/rdl, together with teaching material.
- A group of researchers and industrial users in Korea are using the standard in applications in the nuclear industry (Kim et al., 2020, Paap 2020b).
- A project led by PCA, called MRAIL (Paap, 2020) is creating a new version of reference data. This also involves the Swedish (SEIIA) and Finnish (THTH) industry consortia for process industry interoperability.
- Paap, 2020b reports corporate initiatives in Bechtel and Fluor to build interoperability systems based on ISO 15926-2.

The CFIHOS oil industry initiative (https://www.jip36-cfihos.org/cfihos-standards/) is a standard for handover of equipment data between customers and suppliers. It is based on a Shell corporate standard (linked to the EPISTLE project) that was released to USPI in the Netherlands and then to IOGP for development. CFIHOS uses ISO 15926-4 reference data, but does not adopt the ontological assumptions of ISO15926-2.

The DEXPI (Data Exchange in the Process Industry; https://dexpi.org) initiative also references ISO 15926 reference data, but does not use the ISO 15926-2 ontology.

The National Digital Twin program in the UK has evaluated foundational ontologies for use in their Information Management Framework (West, 2020, Partridge and Mitchell, 2020). Their criteria required a four-dimensionalist approach (see Section 2.5.4 below), so they conclude that the IMF will build on a new foundational ontology based on the cluster of related ontologies: BORO, IDEAS, HQDM and ISO 15926-2.

2.5.2 Active Development of ISO 15926 Parts 2 & 4

The Standard was developed and is maintained by the ISO Technical Committee ISO/TC 184, Automation Systems and integration, sub-committee SC 4.

Work on reference data is being done in a number of projects, as described in Section 2.5.1.

2.5.3 ISO 15926 Parts 2 & 4 Resources

There is site for open-source tools at https://15926.tools/#toolbox. This site offers an Excel-based tool to inspecting and modifying reference data for ISO 15926.

2.5.4 ISO 15926 Parts 2 & 4 Expressiveness and Coverage

The philosophical assumptions of ISO 15926-2 are summarized by (Batres et al., 2007): "ISO 15926-2:2003 is founded on an explicit metaphysical view of the world known as four-dimensionalism. In four-dimensionalism, objects are extended in time as well as space, rather than being wholly present at each point in time, and passing through time. In addition, ISO 15926 has an extensional basis for identity of individuals. Thus if what appears to be two objects have all of the same parts (in both space and time) then they are the same object." This four-dimensionalism follows on from a dependence on the BOFO ontology.

The formal ontology begins with a *thing*, which can be a *possible_individual* or an *abstract_object* (*class, relationship* or *multidimensional_object).* Classes are universals used to classify things. A *possible individual* is a *thing* that could exist in time and space. (Batres, 2005) presents the different overlapping subtypes of *possible individuals*: *arranged individual*, *actual individual*, *whole life individual*, *physical object*, *activity*, *period in time* and *event*. Note that only *actual individuals* need to be real things. A *physical object* can be a *functional physical object* (which corresponds to a tag, a replaceable part or an object defined by its purpose), a *materialized object* (corresponding to installed equipment, objects defined by extension of matter and/or energy as their basis of identity) a *stream* (material or energy flowing along a path) or a *spatial location*.

These types form the basis of the formal ontology. The four-dimensional approach uses the idea one *possible individual* being a *temporal part* of another.

The model was designed for describing engineered systems and is able represent these systems, in particular as-built systems.

This approach has been criticised by (Smith, 2006) for being a closed ISO document and for, in his opinion, its unnecessary complexity and inconsistency.

2.6 ISO 15926 Part 14

The **ISO 15926 Part 14** (ISO 15926-14) was first developed in the Integrated Operations in the High North project (2008—2012) as adaption of ISO 15926-2 (2003). The standard is a series with several parts. In this note, we primarily have in mind ISO 15926-14, an adaptation of the EXPRESS format data model provided in ISO 15926-2 to OWL 2 and with a considerable degree of alignment with the Basic Formal Ontology (BFO).

References are primarily from use cases:

- Martin G. Skjæveland et al., "Semantic Material Master Data Management at Aibel", ISWC 2018 Industry Track, http://ceur-ws.org/Vol-2180/paper-90.pdf.
- Melinda Hodkiewicz et al., "An ontology for reasoning over engineering textual data stored in FMEA spreadsheet tables", Computers in Industry vol. 131, Oct 2021, https://www.sciencedirect.com/journal/computers-in-industry/vol/131/suppl/C.
- The ontology is currently maintained and updated by the READI Joint Industry Project, readi-jip.org/, and published by Posc Caesar Association (PCA).
- The online version represents the latest version, as further developed in the READI project and published by PCA; the website at http://rds.posccaesar.org/ontology/lis14/ont/core provides a good starting point.

2.6.1 Active Use of ISO 15926 Part 14

ISO 15926 Part 14 is in wide use in the process industry, in particular as the schema for the PCA Reference Data Library, see http://data.posccaesar.org/. The extensive Capital Facilities HandOver Specification (CFIHOS, Joint Industry Programme 36 of the International Association of Oil & Gas Producers (IOGP)), https://www.jip36-cfihos.org/cfihos-standards/, maintains links to the PCA RDL for definitions. The same goes for the RDL of the Data Exchange in the Process Industry (DEXPI) initiative, https://dexpi.org/.

ISO 15926-14 has been used in daily operations for capital projects at engineering companies Aibel and Aker Solutions since 2015. Current efforts in the READI project aim to extend this usage to a broader community of operators and service providers in the oil & gas and energy domain.

Siemens Technology has chosen ISO 15926-14 as their upper ontology, for a wide range of applications including a Siemens ontology library, and with an emphasis on OWL reasoning.

Grundfos, the world's largest pump manufacturer, has chosen ISO 15926-14 as the upper ontology for development of an ontology of pump products, to be applied across the enterprise. OWL reasoning and modularization are main concerns.

2.6.2 Active Development of ISO 15926 Part 14

ISO 15926 Part 14 sees infrequent updates with additions of classes and properties, in response to needs discovered in new use cases.

The READI project provides the main community for development, with a current emphasis on providing a library of modelling patterns to support requirements management and asset models (as suitable for "digital twins"). Contributions are mainly from the Oil & Gas domain, but extends beyond this, with active users in other industries. This is being implemented as OTTR libraries; preliminary versions are online and in active development.

The potential for growth is considerable, with applications being explored by companies in various domains, including Oil & Gas, Energy, Manufacturing, and Maritime.

The READI project is the primary point of contact at this time.

2.6.3 ISO 15926 Part 14 Expressiveness and Coverage

ISO 15926 Part 14 provides an upper ontology suitable for industry applications. Its purpose is to

- build an enterprise library of classes and relations for the industrial asset lifecycle,
- build models of assets that are described in this language.

2.7 OPM

The **Object Process Methodology (OPM)** is a conceptual modelling language and methodology for capturing knowledge and designing systems. OPM includes a minimal universal ontology of stateful objects and processes that transform them. OPM can be used to formally specify the function, structure, and behaviour of artificial and natural systems in a large variety of domains. The ontology of OPM is influences by an ancient Hindu school of thought called Navya-Nyāya.

OPM was conceived and developed by Dov Dori at Technion Israel Institute of Technology. The ideas underlying OPM were published for the first time in 1995. Since then, OPM has evolved and developed.

These are the main references:

- Dori, Dov. 1995. "Object-Process Analysis: Maintaining the Balance Between System Structure and Behaviour." Journal of Logic and Computation 5 (2): 227–49. https://doi.org/10.1093/logcom/5.2.227.
- Dori, Dov. 2016. Model-Based Systems Engineering with OPM and SysML. New York, NY: Springer New York. https://doi.org/10.1007/978-1-4939-3295-5.
- Dori, Dov, Hanan Kohen, Ahmad Jbara, Niva Wengrowicz, Rea Lavi, Natali Levi Soskin, Kfir Bernstein, and Uri Shani. 2019. "OPCloud: An OPM Integrated Conceptual-Executable Modeling Environment for Industry 4.0." In Systems Engineering in the Fourth Industrial Revolution, 243–71. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119513957.ch11.
- Levi-Soskin, Natali, Ahmad Jbara, and Dov Dori. 2021. "The Model Fidelity Hierarchy: From Text to Conceptual, Computational, and Executable Model." IEEE Systems Journal 15 (1): 1287–98. https://doi.org/10.1109/JSYST.2020.3008857.

- Mordecai, Yaniv, Ori Orhof, and Dov Dori. 2018. "Model-Based Interoperability Engineering in Systems-of-Systems and Civil Aviation." IEEE Transactions on Systems, Man, and Cybernetics: Systems 48 (4): 637–48. https://doi.org/10.1109/TSMC.2016.2602543.
- Menshenin, Yaroslav, Yaniv Mordecai, Edward F Crawley, and Bruce G Cameron. n.d. "Model-Based System Architecting and Decision-Making," In Handb. Model. Syst. Eng., Springer, 2021. Chapter 1, 50 pages.
- Mordecai, Yaniv, Ori Orhof, and Dov Dori. 2018. "Model-Based Interoperability Engineering in Systems-of-Systems and Civil Aviation." IEEE Transactions on Systems, Man, and Cybernetics: Systems 48 (4): 637–48. https://doi.org/10.1109/TSMC.2016.2602543.

2.7.1 Active Use of OPM

OPM is actively used in the Aviation Industry. OPM has also been used in the Automotive industry, and White appliances industry. It is used by Energy companies, Space agencies, and Insurance companies.

2.7.2 Active Development of OPM

Development is on-going and further information can be found on the OPM website https://www.opcloud.tech.

OPM is available as an ISO standard: "ISO 19450 Automation systems and integration — Object-Process Methodology," International Organization for Standardization (ISO), Geneva, Switzerland, 2015. https://www.iso.org/standard/62274.html.

2.7.3 OPM Resources

There are two software tools for creating OPM models: OPCAT and OPCloud. OPCAT's development has ended, but it is still available. OPCloud is the latest tool for creating OPM models and is a cloud-based modelling studio.

- OPCloud is accessible on-line at https://opcloud-trial.firebaseapp.com/
- OPCAT can be downloaded for free from http://esml.iem.technion.ac.il

2.7.4 OPM Expressiveness and Coverage

OPM's vocabulary includes approximately 20 terms. OPM is said to rely on the minimal universal ontology principle, whereby stateful objects (things that exist), processes (things that occur), and relations among them constitute a necessary and sufficient ontology for describing any conceivable system in the universe (in Dori, 2016).

OPM's visual representation is a set of Object-Process Diagrams (OPDs). OPM's textual representation consists of sentences in Object-Process Language, OPL.

OPM's modelling statements can be exported as RDF.

2.8 SUMO

The **Suggested Upper Merged Ontology (SUMO)** was first developed and released open source in the year 2000. Adam Pease has led the project since its inception and continues its active development today.

These are the main references:

- the original paper about SUMO: (Niles&Pease, 2000)
- textbook about SUMO and its tools: (Pease, 2011)
- papers at https://www.adampease.org
- videos: https://www.youtube.com/user/peaseadam
- web site: https://www.ontologyportal.org
- GitHub: https://github.com/ontologyportal

Two key aspects of SUMO that are not shared by other ontology efforts, and which have been crucial in the success of SUMO applications are: (1) SUMO is defined in an expressive language – a higher order logic. Graphs, description logics and even first-order logic (FOL) have more limited expressiveness and therefore necessarily omit knowledge about concepts that is not expressible in those languages (expressions of belief, numeric calculations etc.). The purpose of an ontology is to have an explicit and shared conceptualization. Recent work (Pease, 2021) quantified what logics are sufficient to represent a percentage of sentences in a balanced corpus. Approximately 50% of randomly chosen sentences require FOL and above. An ontology that can't handle the expressiveness of human language fails to embody a shared conceptualization because it must instead rely on implicit intuitions about concepts as interpreted by humans. An expressive ontology can also be validated with modern theorem proving, unlike a terminological system. SUMO is regularly tested with Vampire and EProver (Schulz et al, 2017). (2) SUMO is large and comprehensive, with some 20,000 concepts and 80,000 human-authored logical expressions. As with any modern software library, reuse comes from having a large library. Software engineers can't do their jobs effectively without large and reusable libraries of code. The same is true with ontology. To take an analogy to language, a dictionary of a single page is not very useful, and yet some popular ontologies have only a few dozen concepts.

The following list contains some key references:

- Benzmüller, C., & Pease, A., (2010). Progress in automating higher-order ontology reasoning. In Boris Konev, Renate Schmidt, and Stephan Schulz, editors, Workshop on Practical Aspects of Automated Reasoning (PAAR-2010). CEUR Workshop Proceedings, Edinburgh, UK.
- Niles, I., & Pease, A., (2001). Toward a Standard Upper Ontology. In Chris Welty and Barry Smith, editors, Proceedings of the 2nd International Conference on Formal Ontology in Information Systems (FOIS-2001), pages 2–9.
- Niles, I., & Pease, A. (2003). Linking lexicons and ontologies: Mapping WordNet to the Suggested Upper Merged Ontology. *Proceedings of the IEEE International Conference on Information and Knowledge Engineering*, 412-416.

- Pease, A., Sutcliffe, G., Siegel, N., and Trac, S., (2008) The Annual SUMO Reasoning Prizes at CASC. Proceedings of IJCAR '08 Workshop on Practical Aspects of Automated Reasoning (PAAR-2008). Volume 373 of the CEUR Workshop Proceedings.
- Pease, A., Sutcliffe, G., Siegel, N., & Trac, S. (2010). Large reasoning with SUMO at CASC. *AI Communications, 23*, 137-144.
- Pease, A. (2011). *Ontology: A Practical Guide*. Angwin, CA: Articulate Software Press ISBN 978-1-889455-10-5.
- Pease, A., Schulz, S., (2014). Knowledge Engineering for Large Ontologies with Sigma KEE 3.0, in Proceedings of IJCAR-2014.
- Pease, A., (2019). Arithmetic and inference in a large theory. In AI in Theorem Proving.
- Schulz, S., Sutcliffe, G., Urban, J., Pease, A., (2017). Detecting Inconsistencies in Large First-Order Knowledge Bases, Proceedings of CADE 26, pp310-325, Springer.
- Trac, S., Sutcliffe, G., and Pease, A., (2008) Integration of the TPTPWorld into SigmaKEE. Proceedings of IJCAR '08 Workshop on Practical Aspects of Automated Reasoning (PAAR-2008). Volume 373 of the CEUR Workshop Proceedings.

2.8.1 Active Use of SUMO

SUMO has been under active use and development for 21 years. Most recently it has been applied in a commercial project for text mining about COVID19. Another recent commercial effort was in developing metadata for a large database of construction and manufacturing supplies where the metadata was defined in SUMO and validated with the Vampire theorem prover, then the relational content of SUMO implemented in an RDBMS. A past project was defining metadata for A/B site testing experiments at eBay. Since 2007, most projects undertaken by its author have been commercially funded. Prior to that time most projects were government-funded research projects.

SUMO is also the only open source ontology that has been mapped by hand, one word sense at a time, to all 117,000 word senses in WordNet (which is in turn linked to the Global Wordnet containing some 25 different languages). This is a significant resource for NLP. SigmaNLP is an open source experimental system for language processing with SUMO that has been applied in commercial efforts in sentiment analysis and intent recognition.

Projects that use the SUMO ontology:

- Developed an ontology of planning for a military; simulation including theorem proving support for determining appropriate courses of action in response to the tactical situation.
- Developed an advanced NLP prototype that converts language to logical expressions and answers questions through deductive logical inference. The system is built on SUMO and Stanford CoreNLP.
- Delivered a prototype system that performed question answering and social chat based around the Stanford CoreNLP system and SUMO.
- Developed a natural language interpreter for mobile app execution. The system converts spoken commands into formal logic using dependency parsing, word sense disambiguation, named entity recognition and specifies actions using SUMO terms.

- Helped an analytics and machine learning group at eBay capture their experimental results and product taxonomy in formal ontology to improve in-house search and retrieval. This consisted of developing formal ontology content in higher-order logic to describe automobiles and automobile parts, user interface components (menus, buttons, etc.) and observables such as page views and revenue.
- For a travel company, designed and coded a Java-based hotel search application that parsed reviews of 100,000 hotels from TripAdvisor, performing word sense disambiguation, sentiment analysis and extraction of concepts linked to SUMO. Developed an ontology of the hotel amenities that extended the SUMO ontology and linked it with the WordNet English lexical database. Created an ontology of user types that allowed the system to match traveller types to amenities that were of greatest interest, allowing hotel suggestions that were targeted to distinct types of travellers.
- Developed ontology and Java code for a digital rights management company. Developed Java code that integrated RDF, SQL and spreadsheet-based data on music sales and artist payments. Developed an extensive ontology of digital media delivered in OWL, Turtle and SUO-KIF formats with SPARQL query infrastructure.
- Developed an Arabic lexicon, linked to WordNet and SUMO. Linked tens of thousands of word senses to the ontology by hand. Extended the Java-based Sigma tool to analyse and compare the lexicons and report errors.
- Developed an ontology-based government personnel training systems. Developed a Java dialog agent the responded to natural language questions and analysed student answers to provide feedback on cultural sensitivity training scenarios. Developed an extensive ontology of human actions and behaviour.
- Developed a Java-based group decision-making tool that implements the Delphi method and uses SUMO to support semantic search.

2.8.2 Active Development of SUMO

Most public discussion takes place on GitHub, where SUMO has been hosted since roughly 2015. Recent large domain ontology efforts include medicine, construction and manufacturing, and weather phenomena. Significant recent efforts in tool support include development of a programmer's text editor for SUMO, based on jEdit (open source on GitHub) and development of a TF0 language translator for first-order logic with arithmetic, supported by the Vampire theorem prover, among others. SUMO has been successfully applied in several dozen projects, commercially and in government, on large and small projects, for over two decades. Further growth and application of these resources seems likely.

2.8.3 UMO Resources

SUMO has a comprehensive development and application environment called Sigma that includes (1) theorem proving that integrates Vampire and EProver, (2) browsing, editing and debugging with the SUMOjEdit editor and web-based SigmaKEE system, SigmaKEE has a number of different deployment options including a RESTful interface, (3) linguistic applications with SigmaNLP that integrates the Stanford CoreNLP system

2.8.4 SUMO Expressiveness and Coverage

As mentioned above, SUMO is written in a higher-order logic, which is significantly more expressive than other open source ontologies. It is also much larger than most ontologies by several orders of magnitude (other than terminological products like some knowledge graphs). SUMO includes some two dozen domain ontologies which are all mutually logically consistent. Other than the ones mentioned above, they include ontologies of computer software and user interfaces, government, economy and finance. A full list is at https://github.com/ontologyportal/sumo.

2.9 MLOs

The definition for "mid-level ontology" (MLO) will be resolved over the course of the OntoCommons project. We currently have two definitions. In the case of MLOs, their classification depends on the reviewer's perspective. Some ontologies fall under either TLO or MLO (e.g. SUMO and ISO 15926). Other ontologies can be considered as a domain ontology or as an MLO (e.g. Allotrope Ontology).

- A mid-level ontology is one that adds general content to the structure outlined in the upper-level ontology by identifying types of entities which directly specialize the upper-level types, but which are also common to many domains of interest. Classes that appear in mid-level ontologies are still fairly basic with respect to particular knowledge domains and often require further specialization to be useful for data modelling (e.g., Person, Act of Communication, and Geopolitical Entity).
- Mid-level ontologies are primarily intended to extend those concepts towards a specific discipline (e.g. manufacturing, materials science, chemistry) with the aim to provide a core shared vocabulary for lower level modules. A MLO will provide a higher level of detail than a TLO, extending the taxonomical structure of the ontology more along on the horizontal dimension (i.e. sibling classes under the same superclass).

A number of ontologies that could be considered as MLOs have been reviewed already in the report for domain ontologies. These are the BWMD Mid-Level Ontology, CheBI, eNanoMapper, OntoCAPE, and the IOF Core. The D3.2 "Report on existing domain ontologies in identified domains" has an overview of NMBP domain-relevant ontologies, and includes the following: domain coverage, FAIR assessments, alignment with TLOs, serialisation format, and topological analysis.

An MLO review was produced as part of the OntoCommons project. This task reviewed MLO ontologies with further results covering "Middle-level ontology terms for industry" and a list of topics covered by TLOs and MLOs. This review included ontologies listed in Table 2.

Notes:

(1) SUMO and ISO 15926 were formerly reviewed as MLOs, but in the "TLO/MLO landscape Analysis Report" they are listed as TLOs.
(2) The ontologies covered in the report on "Exisitng domain ontologies in identified domains" domain analysis that overlap with the Task "MLO Development/Harmonisation" MLOs reviewed are: Allotrope Ontology, BWMD, and IOF Core.
(3) The Common Core Ontologies are included in this report "TLO/MLO landscape Analysis Report" under their relevant TLO in section 2.1 BFO.

(4) There have been suggestions for other ontologies to consider as MLOs, e.g., AFO, The Ontology of Time and Process, and QUDT.

MLO	Related TLO	Additional Info
Industrial Ontology Foundry - Core (IOF Core)	BFO	Also contains terms of IAO and CCO. In formats: owl, ttl. https://github.com/NCOR-US/IOF-BFO/tree/IOF-Core-2020
Common Core Ontology (CCO)	BFO	Composed of 12 ontologies: Agent, Artifact, Currency Unit, Event, Extended Relation, Facility, Geospatial, Information Entity, Modal Relation, Quality, Time, and Units of Measure
Virtual Materials MarketPlace Ontology (VIMMP)	EMMO	Composed of 9 ontologies: VICO, VIVO, MACRO, OTRAS, MMTO, OSMO, VISO, VOV, EVMPO & EVI DOI: 10.5281/zenodo.4411422
Baden Württemberg Material Digital Ontology (BWMD Ontology)	BFO	Composed of 3 modules: BFO 2.0, BWMD_ontology_mid, BWMD_ontology_domain
Digital Construction Ontologies	BFO	An ontology suite consists of 12 ontologies and 11 external ontologies used in all stages of construction lifecycle
Building Information Modelling Project BIMERR Ontology	BIMERR Interoper-ability Framework (BIF)	The BIMERR ontology network represents the semantic models that describe the different aspects of building renovation processes (e.g. energy efficiency, occupancy, building information models, etc.). Composed of 9 modules: KPI, Renovation process, Annotations, Information object, Building, Material properties, Occupancy profile, Sensor data, and weather.
Data Collection Ontology (DCO)	BFO	Suitable for data collection. Has components: Subjects, Processes, Data qualities, Classifiers, and Metadata

Allotrope Foundation Ontologies (AFO)		The AFO is an ontology suite that provides a standard vocabulary and semantic model for the representation of (bio and pharma-) laboratory analytical processes. https://www.allotrope.org/ontologies

Table 2 - List of MLOs reviewed in Task "MLO Development/Harmonisation"

3. Axiomatization and Reasoning

Ontologies do not only allow a formal representation of knowledge, they also allow us to reason about the represented knowledge. Reasoning on ontologies is important and essential for the design, maintenance and deployment of ontologies.

Reasoning on ontologies requires the axiomatization of the ontology in a formal (ontology) language. The choice of the (ontology) language determines the computational complexity of reasoning about the knowledge expressed in this language. Automating reasoning is a main challenge in the field of Automated Reasoning and in Artificial Intelligence (AI) in general.

Indeed, these are two of the main challenges in AI:

- transforming human knowledge into a machine-processable form (also called *knowledge acquisition bottleneck*), and
- the computational complexity of reasoning about this knowledge (also called *reasoning bottleneck*).

A solution to these challenges with respect to a certain application domain depend significantly on the choice of the formal language used to represent the given knowledge.

3.1 Languages and Complexity

In order to reason about an ontology it has to be axiomatized in a formal language. In general, there is a trade-off between the expressiveness of an ontology/language and its computational complexity, i.e., the complexity of reasoning within this language. The more expressive an ontology/language is, the higher its computational complexity of reasoning within it.

The following reasoning problems can be distinguished:

- entailment (i.e. does a conjecture C follow from the axioms/knowledge A1,...,An?),
- class hierarchy, subclass relationships (i.e. does a class/set C subsume a class/set D?),
- (class) inconsistency (i.e. is a class/set C empty?),
- consistency of an ontology,
- inferring implicit knowledge.

These reasoning problems are not completely independent but can partly be reduced onto each other. For example, an ontology expressed by a set of axiom A1,...,An is *inconsistent*, if A1,...,An entails "false" (⊥).

More specifically, the entailment and the consistency check can be reduced to the problem of determining if a (logical) formula is valid.

a) A formula/conjecture C is entailed by a set of axioms A1,...,An (representing the knowledge base) if, and only if, the formula A1 ∧ ... ∧ An → C is valid. (Note that for, e.g., modal logic there exist more than one entailment relation.)
b) A set of axioms A1,...,An is inconsistent if, and only if, the formula A1 ∧ ... ∧ An → ⊥ is valid.

Table 3 summarizes some of the main formal ontology/logical languages and their decidability and computational complexity with respect to determine logical entailment or validity.

Language/Logic	Decidability / Time Complexity
OWL 2 EL/QL/RL	decidable / P
RDF(S)	decidable / NP-complete
Propositional Logic	decidable / NP-complete
Propositional Modal Logic	decidable / PSpace-complete
OWL Lite (DL SHIF(D))	decidable / ExpTime
OWL DL (DL SHOIN(D))	decidable / NexpTime
OWL 2 DL (DL SROIQ(D))	decidable / 2NExpTime=AExpSpace
OWL Full (> DL)	Semidecidable
First-order Logic (FOL)	Semidecidable
First-order Modal Logic (FOML)	Semidecidable
Higher-order Logic (HOL)	Undecidable

Table 3 - Formal Logical Languages and Their Complexity

Propositional (modal) logic, first-order logic (FOL), first-order modal logic (FOML) and higher-order logic (HOL) are well-known and established formal languages in Mathematics and (Theoretical) Computer Science.

The Web Ontology Language (OWL) is a family of knowledge representation languages especially developed for specifying ontologies. OWL 2 EL/QL/RL, OWL Lite, OWL DL and OWL 2 DL are all decidable, but provide different levels of expressiveness and, hence, have different computational time complexities. The OWL languages are based on Description Logics (DLs), a family of formal knowledge representation languages. As for OWL, there are a large variety of DLs providing different levels of expressiveness.

OWL is less expressive than FOL due to the following restrictions:

- constructors mainly for classes (unary predicates),
- no higher arity predicates,

- no complex data types or built in predicates (e.g., arithmetic),
- no variables.

First-order (classical) logic is less expressive than first-order modal logic, which is less expressive than higher-order logic. Whereas a less expressive language might have a lower reasoning complexity, it might be more difficult or impossible to express certain knowledge in a simple and natural way, leading again to a higher reasoning complexity. A more expressive language, such as HOL might allow a simple knowledge representation at the cost of a higher reasoning complexity.

3.2 Solvers, Reasoners and Provers

For each of the formal languages/logics there exist software tools that automate reasoning within this languages. Depending on the used languages they are called "solvers" (SAT/propositional logic), "reasoners" (OWL/DL) or "(theorem) provers" (first- and higher-order logic).

The following table contains an (incomplete) list of automated reasoning tools.

Language/Logic	Reasoning Tools
Propositional Logic	MiniSat, PicoSAT Kissat, Zchaff
RDF(S)	RDFox
OWL/DL	Pellet, RACER, FaCT++, HermiT
First-order Logic	Vampire, E, leanCoP
First-order Modal Logic	MleanCoP, nanoCoP-M
Higher-order Logic	LEO, Satallax

Table 4 - Automated Reasoning Tools

During the last decades there the field of Automated Theorem Proving has made significant process. There exist now powerful theorem provers for classical logic, such as Vampire (Riazanov and Voronkov, 2002) and E (Schulz et al., 2019, and for first-order modal logics, such as MleanCoP (Otten, 2014, Otten and Bibel, 2017) and nanoCoP-M (Otten, 2017b; Otten, 2021). MleanCoP is based on the very compact leanCoP prover (Otten and Bibel, 2003; Otten, 2008; Otten, 2010), nanoCoP-M is based on the nanoCoP prover (Otten, 2016; Otten, 2017a), which is a very compact implementation of the non-clausal connection calculus (Otten, 2011).

3.3 Axiomatizations of TLOs

Most of the TLOs presented in Chapter 2 have been axiomatized in a formal language. This section gives an overview of these efforts.

3.3.1 BFO

BFO has been axiomatized in OWL. Version 2.0 represents a major update to BFO and is not strictly backwards compatible with BFO 1.1. The previous OWL version of BFO, version 1.1.1 will remain available at http://ifomis.org/bfo/1.1 and will no longer be updated. The BFO 2.0 OWL is a classes-only specification.

There is also an axiomatization of BFO in Common Logic (CL) as specified in ISO/IEC 24707. It has been proven consistent using standard automated theorem provers. Furthermore, is was proven that BFO-OWL is derivable from BFO-CL.

For the new ISO/IEC 21838-2 standard, BFO has been axiomatized in FOL (https://basic-formal-ontology.org/fol.html) which is available in compiled form (https://buffalo.app.box.com/v/BFO-2020-FOL). A version of these axioms in Common Logic syntax, together with consistency proofs and other material, is available on the ISO Standards Maintenance Portal. All files are available under a Creative Commons "Attribution 4.0 International" license. An earlier FOL axiomatization of BFO, using the Isabelle language, is still available at http://www.acsu.buffalo.edu/~bittner3/Theories/BFO/,

More details on the FOL formalization of BFO is given in the following paper:

- Barry Smith, Farhad Ameri, Hyunmin Cheong, Dimitris Kiritsis, Dusan Sormaz, Chris Will, J. Neil Otte. A First-Order Logic Formalization of the Industrial Ontologies Foundry Signature Using Basic Formal Ontology. In 10th International Workshop on Formal Ontologies meet Industry (FOMI), Vol. 2518, CEUR Workshop Proceedings, http://ceur-ws.org/Vol-2518/, 2019.

3.3.2 EMMO

EMMO has been axiomatized in OWL-DL. Work is currently going on to also axiomatize it in FOL. The OWL2-DL sources are available in turtle and RDF/XML format (https://emmo-repo.github.io/). It draws on Mereotopology (MT), which is a FOL theory. FOL MT can be used as a tool at the EMMO "interpreter" level, to enable understanding what EMMO OWL entities stand for in the real world.

3.3.3 DOLCE

DOLCE has been axiomatized in FOL, more precisely in first-order quantified modal logic (FOML). It has 37 basic categories characterized using 7 primitive relations. The theory comprises 82 axioms and 103 definitions.

There also exist axiomatizations in other languages, e.g., in

- CLIF (Common Logic Interchange Format), part of Common Logic (ISO/IEC 24707),
- OWL 2.0 and sublanguages (http://www.w3.org/TR/owl2-overview/), and
- HETS (The heterogeneous tool set), the parsing, analysis and prover integration tool for CASL (Common Algebraic Specification Language).

For the axiomatizations, see http://www.loa.istc.cnr.it/index.php/dolce/ and references within it.

3.3.4 ISO 15926 Part 2 & 4

The ISO 15926 Parts 2 & 4 ontology has been axiomatized in OWL in part 8 of the ISO standardization. It is a specification for data exchange and life-cycle information integration using OWL and the Resource Description Framework (RDF). It provides rules for implementing the upper ontology specified by ISO 15926-2 and the template methodology specified by ISO 15926-7 into the RDF and OWL languages, including models for reference data as specified by ISO/TS 15926-3 and ISO/TS 15926-4, and for metadata. The axiomatization of ISO 15926-2 in OWL 2 is in development as part 12 of the ISO standardization.

3.3.5 ISO 15926 Part 14

ISO 15926-14 is implemented in OWL 2. Serialisations in Turtle, RDF/XML, JSON-LD, N-triples, and Manchester Syntax are available at http://rds.posccaesar.org/ontology/lis14/ont/core.

3.3.6 SUMO

SUMO has been written in the SUO-KIF language, which is a higher-order logic (HOL with a minimal syntax. There are automated translators for OWL-DL, TPTP (first-order logic with equality) (Trac et al, 2008, (Pease&Schulz, 2014), TF0 (typed first order logic with arithmetic) (Pease, 2019) and THF (typed higher-order logic) (Benzmüller&Pease, 2010).

Appendix A: List of TLOs (UK Survey)

Table 4 includes the ontologies listed in "A survey of Top-Level Ontologies" (UKRI), 2020.

Acronym	Preferred Name	Full Name	Initial Release	Links
BFO	Basic Formal Ontology	Basic Formal Ontology	2002	http://basic-formal-ontology.org/, https://en.wikipedia.org/wiki/Basic_Formal_Ontology, https://en.wikipedia.org/wiki/Upper_ontology#Basic_Formal_Ontology_(BFO)
BORO	BORO	Business Objects Reference Ontology	late 1980s	https://www.borosolutions.net/, https://en.wikipedia.org/wiki/BORO, https://en.wikipedia.org/wiki/Upper_ontology#BORO
CIDOC (ISO 21127:2014)	CIDOC Conceptual Reference Model	CIDOC object-oriented Conceptual Reference Model	1999	http://www.cidoc-crm.org/, https://en.wikipedia.org/wiki/CIDOC_Conceptual_Reference_Model, https://en.wikipedia.org/wiki/Upper_ontology#CIDOC_Conceptual_Reference_Model
CIM	Common Information Model	Common Information Model	1999	https://www.dmtf.org/standards/cim, https://en.wikipedia.org/wiki/Common_Information_Model_(computing)
ConML+ CHARM	ConML	Conceptual Modelling Language (ConML)	2011	http://www.conml.org/, http://www.conml.org/Resources/TechSpec.Aspx, http://www.charminfo.org/
COSMO	COSMO	COmmon Semantic MOdel	not known - pre-2006	http://www.micra.com/, https://en.wikipedia.org/wiki/Upper_ontology#COSMO
Cyc	Cyc	Cyc	1984	https://www.cyc.com/the-cyc-platform,

				https://en.wikipedia.org/wiki/Cyc, https://en.wikipedia.org/wiki/Upper_ontology#Cyc
DC	The Dublin Core (DC) ontology	The Dublin Core ontology	1995	http://dublincore.org/, https://en.wikipedia.org/wiki/Dublin_Core
DOLCE	DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering	2019	http://www.loa.istc.cnr.it/dolce/overview.html, https://en.wikipedia.org/wiki/Upper_ontology#DOLCE
EMMO	EMMO	Elemental Multiperspec-tive Material Ontology (EMMO)	2019	https://github.com/emmo-repo/EMMO, https://materialsmodelling.com/2019/06/14/european-materials-modelling-ontology- emmo-release/
FIBO	Financial Industry Business Ontology	Financial Industry Business Ontology	2010	https://spec.edmcouncil.org/fibo/
FrameNet	FrameNet	FrameNet	2000	https://framenet.icsi.berkeley.edu/fndrupal/, https://en.wikipedia.org/wiki/FrameNet
GFO	General Formal Ontology	General Formal Ontology	2006	https://www.onto-med.de/ontologies/gfo, https://en.wikipedia.org/wiki/General_formal_ontology, https://en.wikipedia.org/wiki/Upper_ontology#General_Formal_Ontology_(GFO)
gist	gist	gist	2007	https://www.semanticarts.com/gist/, https://en.wikipedia.org/wiki/Upper_ontology#gist
HQDM	HQDM	High Quality Data Models	2011	http://www.informationjunction.co.uk/hqdm_framework/
IDEAS	IDEAS	International Defence Enterprise	2006	https://en.wikipedia.org/wiki/IDEAS_Group,

		Architecture Specification		https://en.wikipedia.org/wiki/Upper_ontology#IDEAS
IEC 62541	IEC 62541 - OPC Unified Architecture	IEC 62541 - OPC Unified Architecture	2006	https://opcfoundation.org/developer-tools/specifications-unified-architecture, https://en.wikipedia.org/wiki/OPC_Unified_Architecture
IEC 63088	IEC PAS 63088:2017	Smart manufacturing - Reference architecture model industry 4.0 (RAMI4.0)	2017	https://webstore.iec.ch/publication/30082
ISO 12006-3	ISO 12006-36:27:00	ISO 12006-3:2007 - Building construction —Organization of information about construction works — Part 3: Framework for object-oriented information	2007	https://www.iso.org/standard/38706.html, https://en.wikipedia.org/wiki/ISO_12006
ISO 15926-2	ISO 15926	Industrial automation systems and integration—Integration of life-cycle data for process plants including oil and gas production facilities	2003	https://www.iso.org/standard/29557.html, https://en.wikipedia.org/wiki/ISO_15926, https://en.wikipedia.org/wiki/Upper_ontology#ISO_15926
KKO	KKO	KBpedia Knowledge Ontology (KKO)	not known	https://kbpedia.org/docs/kko-upper-structure/

KR Ontology	KR Ontology	KR Ontology	1999	http://www.jfsowa.com/ontology/toplevel.htm
MarineTLO	MarineTLO	Marine Top Level Ontology	2013	https://projects.ics.forth.gr/isl/MarineTLO/, https://en.wikipedia.org/wiki/Upper_ontology#MarineTLO
MIMOSA CCOM	MIMOSA CCOM	MIMOSA CCOM (Machinery Information Management Open Systems Alliance - Common Conceptual Object Model)	not known	https://www.mimosa.org/mimosa-ccom/ , https://en.wikipedia.org/wiki/OpenO%26M
OWL	Web Ontology Language	OWL	2004	https://www.w3.org/OWL/, https://en.wikipedia.org/wiki/Web_Ontology_Language
PROTON	PROTON	PROTo ONtology	2005	https://ontotext.com/documents/proton/Proton-Ver3.0B.pdf, https://en.wikipedia.org/wiki/Upper_ontology#PROTON
Schema.org	Schema.org	Schema.org	2011	https://schema.org/, https://en.wikipedia.org/wiki/Schema.org
SENSUS	The SENSUS ontology	The SENSUS ontology	2001	https://www.isi.edu/natural-language/projects/ONTOLOGIES.html
SKOS	SKOS	Simple Knowledge Organization System	2009	https://www.w3.org/2004/02/skos/, https://en.wikipedia.org/wiki/Simple_Knowledge_Organization_System
SUMO	SUMO	Suggested Upper Merged Ontology	2000	http://www.adampease.org/OP/, https://en.wikipedia.org/wiki/Suggested_Upper_Merged_Ontology, https://en.wikipedia.org/wiki/Upper_ontology#SUMO_(Suggested_Upper_Merged_Ontology)

TMRM	The Topic Maps Reference Model	The Topic Maps Reference Model	late 1990s	https://www.isotopicmaps.org/tmrm/, https://en.wikipedia.org/wiki/Topic_map
UFO	UFO	Unified Foundational Ontology	2005	https://nemo.inf.ufes.br/en/projetos/ufo/, https://en.wikipedia.org/wiki/OntoUML, https://en.wikipedia.org/wiki/Upper_ontology#UFO_(Unified_Foundational_Ontology)
UMBEL	UMBEL	Upper Mapping and Binding Exchange Layer	2008	https://en.wikipedia.org/wiki/UMBEL, https://en.wikipedia.org/wiki/Upper_ontology#UMBEL
UML	UML	Unified Modeling Language (UML)	1994	http://uml.org/, https://en.wikipedia.org/wiki/Unified_Modeling_Language
UMLS	Unified Medical Language System	UMLS	1986	https://www.nlm.nih.gov/research/umls/index.html, https://en.wikipedia.org/wiki/Unified_Medical_Language_System
WordNet	WordNet	WordNet	1985	https://wordnet.princeton.edu/, https://en.wikipedia.org/wiki/WordNet, https://en.wikipedia.org/wiki/Upper_ontology#WordNet
YAMATO	YAMATO	Yet Another More Advanced Top Ontology	1999	https://en.wikipedia.org/wiki/Upper_ontology#YAMATO_(Yet_Another_More_Advanced_Top_Ontology)

Table 5 - List of Top-Level Ontologies (UKRI Survey)

References

This list of references also contains additional resources not mentioned in the report.

"ISO 15926-2:2003 Industrial Automation Systems and Integration — Integration of Life-Cycle Data for Process Plants Including Oil and Gas Production Facilities — Part 2: Data Model." 2003. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/02/95/29557.html.

"ISO 15926-1:2004 Industrial Automation Systems and Integration — Integration of Life-Cycle Data for Process Plants Including Oil and Gas Production Facilities — Part 1: Overview and Fundamental Principles." 2004. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/02/95/29556.html.

"ISO 12006-3:2007 Building Construction — Organization of Information about Construction Works — Part 3: Framework for Object-Oriented Information." 2007. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/03/87/38706.html.

"ISO/TS 15926-7:2011 Industrial Automation Systems and Integration — Integration of Life-Cycle Data for Process Plants Including Oil and Gas Production Facilities — Part 7: Implementation Methods for the Integration of Distributed Systems: Template Methodology." 2011. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/24/52455.html.

"ISO/TS 15926-8:2011 Industrial Automation Systems and Integration — Integration of Life-Cycle Data for Process Plants Including Oil and Gas Production Facilities — Part 8: Implementation Methods for the Integration of Distributed Systems: Web Ontology Language (OWL) Implementation." 2011. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/24/52456.html.

"ISO/PAS 19450:2015 Automation Systems and Integration — Object-Process Methodology." 2015. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/22/62274.html.

"ISO/TS 15926-12:2018 Industrial Automation Systems and Integration — Integration of Life-Cycle Data for Process Plants Including Oil and Gas Production Facilities — Part 12: Life-Cycle Integration Ontology Represented in Web Ontology Language (OWL)." 2018. ISO. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/07/06/70695.html.

"ISO/TS 15926-11:2015 Industrial Automation Systems and Integration — Integration of Life-Cycle Data for Process Plants Including Oil and Gas Production Facilities — Part 11: Methodology for Simplified Industrial Usage of Reference Data." n.d. ISO. Accessed November 5, 2021. https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/05/78/57859.html.

"15926browser." n.d. Accessed November 5, 2021. http://data.15926.org/rdl.

"15926.Org - Welcome." n.d. Accessed November 5, 2021. https://15926.org/home/.

"15926tools." n.d. Accessed November 5, 2021. https://15926.tools/#toolbox.

"A4BLUE |." n.d. Accessed November 5, 2021. https://a4blue.eu/.

"Applied Ontology - Volume Pre-Press, Issue Pre-Press - Journals." n.d. *Applied Ontology* Preprint (Preprint). Accessed November 5, 2021. https://content.iospress.com/journals/applied-ontology/Pre-press/Pre-press.

Arena, D., F. Ameri, and D. Kiritsis. 2018. "Skill Modelling for Digital Factories." n.d. In *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0*, edited by Ilkyeong Moon, Gyu M. Lee, Jinwoo Park, Dimitris Kiritsis, and Gregor von Cieminski, 318–26. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-99707-0_40.

Arena, D., M. Oliva, I. Eguia, C. Del Valle, and D. Kiritsis. 2019. "Semantic Model-Driven PLM Data Interoperability: An Application for Aircraft Ground Functional Testing with Eco-Design Criteria." In *Advances in Production Management Systems. Production Management for the Factory of the Future*, edited by Farhad Ameri, Kathryn E. Stecke, Gregor von Cieminski, and Dimitris Kiritsis, 566:299–306. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-30000-5_38.

Arena, D., K. Ziazios, I.N. Metaxa, S. Parcharidis, S. Zikos, A. Tsolakis, S. Krinidis, D. Ioannidis, D. Tzovaras, and D. Kiritsis. 2017. "Towards a Semantically-Enriched Framework for Human Resource Management." In *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing*, edited by Hermann Lödding, Ralph Riedel, Klaus-Dieter Thoben, Gregor von Cieminski, and Dimitris Kiritsis, 306–13. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-66923-6_36.

Arena, Damiano, and Dimitris Kiritsis. 2017. "A Methodological Framework for Ontology-Driven Instantiation of Petri Net Manufacturing Process Models." In *Product Lifecycle Management and the Industry of the Future*, edited by José Ríos, Alain Bernard, Abdelaziz Bouras, and Sebti Foufou, 557–67. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-72905-3_49.

Arena, Damiano, Dimitris Kiritsis, Chrysovalantou Ziogou, and Spyros Voutetakis. 2017. "Semantics-Driven Knowledge Representation for Decision Support and Status Awareness at Process Plant Floors." In *2017 International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, 902–8. https://doi.org/10.1109/ICE.2017.8279979.

Arena, Damiano Nunzio, and Dimitris Kiritsis. 2016. "A Method Towards Modelling and Analysis of Semantically-Enriched Reconfigurable Manufacturing Systems." In *Advances in Production Management Systems. Initiatives for a Sustainable World*, edited by Irenilza Nääs, Oduvaldo Vendrametto, João Mendes Reis, Rodrigo Franco Gonçalves, Márcia Terra Silva, Gregor von Cieminski, and Dimitris Kiritsis, 45–52. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-51133-7_6.

Arena, Damiano, Stefano Perini, Marco Taisch, and Dimitris Kiritsis. 2018. "The Training Data Evaluation Tool: Towards a Unified Ontology-Based Solution for Industrial Training Evaluation." *Procedia Manufacturing*, "Advanced Engineering Education & Training for Manufacturing Innovation"8th CIRP Sponsored Conference on Learning Factories (CLF 2018), 23 (January): 219–24. https://doi.org/10.1016/j.promfg.2018.04.020.

Arena, Damiano, Apostolos Charalampos Tsolakis, Stylianos Zikos, Stelios Krinidis, Chrysovalantou Ziogou, Dimosthenis Ioannidis, Spyros Voutetakis, Dimitrios Tzovaras, and Dimitris Kiritsis. 2018. "Human Resource Optimisation through Semantically Enriched Data." *International Journal of Production Research* 56 (8): 2855–77. https://doi.org/10.1080/00207543.2017.1415468.

Arp, Robert, Barry Smith, and Andrew D. Spear. 2015. *Building Ontologies with Basic Formal Ontology*. Cambridge, Massachusetts: Massachusetts Institute of Technology.

"Basic Formal Ontology." 2020. BFO Basic Formal Ontology. https://basic-formal-ontology.org.

"Basic Formal Ontology (BFO) | First-Order Logic Based Implementation." n.d. Accessed November 5, 2021. https://basic-formal-ontology.org/fol.html.

"Basic Formal Ontology (BFO) | Home." n.d. Accessed November 5, 2021. http://basic-formal-ontology.org/.

Batres, Rafael, Matthew West, David Leal, David Price, Katsube Masaki, Yukiyasu Shimada, Tetsuo Fuchino, and Yuji Naka. 2007. "An Upper Ontology Based on ISO 15926." *Computers & Chemical Engineering*, ESCAPE-15, 31 (5): 519–34. https://doi.org/10.1016/j.compchemeng.2006.07.004.

Battery INterFace Ontology (BattINFO). 2021. Python. BIG-MAP. https://github.com/BIG-MAP/BattINFO.

"Bclearer - the Approach | BORO." n.d. Accessed November 5, 2021. http://www.borosolutions.net/bclearer-approach.

"BFO 2020 Continuant Mereology Axioms." n.d. Accessed November 5, 2021. https://buffalo.app.box.com/v/BFO-2020-FOL.

Bologne, Emanuele Ghedini, University of, Gerhard Goldbeck Consulting Goldbeck, Jesper Friis SINTEF, Adham Hashibon IWM Fraunhofer, and Georg Schmitz ACCESS. 2021. "European Materials & Modelling Ontology." November 3, 2021. https://emmo-repo.github.io/.

"Boost 4.0 | Big Data for Factories." n.d. Accessed November 5, 2021. https://boost40.eu/.

"BORO." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=BORO&oldid=1000353761.

Burton, Jim, Lopamudra Choudhury, and Mihir Chakraborty. 2018. "A Survey and Evaluation of Diagrams for Navya-Nyāya." In *Diagrammatic Representation and Inference*, edited by Peter Chapman, Gem Stapleton, Amirouche Moktefi, Sarah Perez-Kriz, and Francesco Bellucci, 10871:280–95. Lecture Notes in Computer Science. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-91376-6_27.

"CASL - CoFI." n.d. Accessed November 5, 2021. http://www.informatik.uni-bremen.de/cofi/index.php/CASL.

CCO working group. n.d. "Common Core Ontologies Repository." Accessed October 30, 2021. https://github.com/CommonCoreOntology/CommonCoreOntologies.

Cesare, Sergio de, and Chris Partridge. 2016. "BORO as a Foundation to Enterprise Ontology." *Journal of Information Systems* 30 (2): 83–112. https://doi.org/10.2308/isys-51428.

"CFIHOS Standards - Capital Facilities Information HandOver Specification." n.d. *JIP36: CFIHOS* (blog). Accessed November 5, 2021. https://www.jip36-cfihos.org/cfihos-standards/.

Cho, Sangje, Marlène Hildebrand-Ehrhardt, Gokan May, and Dimitris Kiritsis. 2020. "Ontology for Strategies and Predictive Maintenance Models." *IFAC-PapersOnLine*, 4th IFAC Workshop on Advanced Maintenance Engineering, Services and Technologies - AMEST 2020, 53 (3): 257–64. https://doi.org/10.1016/j.ifacol.2020.11.042.

Cho, Sangje, Gökan May, and Dimitris Kiritsis. 2019. "A Semantic-Driven Approach for Industry 4.0." In *2019 15th International Conference on Distributed Computing in Sensor Systems (DCOSS)*, 347–54. https://doi.org/10.1109/DCOSS.2019.00076.

Cho, Sangje, Gökan May, Ioannis Tourkogiorgis, Roberto Perez, Oscar Lazaro, Borja de la Maza, and Dimitris Kiritsis. 2018. "A Hybrid Machine Learning Approach for Predictive Maintenance in Smart Factories of the Future." In *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0*, edited by Ilkyeong Moon, Gyu M. Lee, Jinwoo Park, Dimitris Kiritsis, and Gregor von Cieminski, 311–17. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-99707-0_39.

"CIDOC Conceptual Reference Model." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=CIDOC_Conceptual_Reference_Model&oldid=1016486118.

"CIF Dictionaries." n.d. CIF - Crystallographic Information Framework. Accessed November 5, 2021. https://www.iucr.org/resources/cif/dictionaries.

Codescu, Mihai, Fulya Horozal, Michael Kohlhase, Till Mossakowski, and Florian Rabe. 2011. "Project Abstract: Logic Atlas and Integrator (LATIN)." In *Intelligent Computer Mathematics*, edited by James H. Davenport, William M. Farmer, Josef Urban, and Florian Rabe, 6824:289–91. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-22673-1_24.

"Common Information Model." 2021. In *Wikipedia*. https://de.wikipedia.org/w/index.php?title=Common_Information_Model&oldid=211446784.

"Common Logic." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Common_Logic&oldid=1027022892.

"ConML Technical Specifications." n.d. Accessed November 5, 2021. http://www.conml.org/Resources/TechSpec.Aspx.

Correia, Ana, Dragan Stokic, Rebecca Siafaka, and Sebastian Scholze. 2017a. "Ontology For Colaborative Development Of Product Service Systems Based On Basic Formal Ontology," June. https://doi.org/10.5281/ZENODO.836667.

Correia, Ana teresa, Dragan Stokic, Rebecca Siafaka, and Sebastian Scholze. 2017b. "Ontology for Colaborative Development of Product Service Systems Based on Basic Formal Ontology." In . Funchal, Madeira Island, Portugal: Zenodo. https://doi.org/10.5281/zenodo.836667.

Crystallography Domain Ontology. 2021. Elemental Multiperspective Material Ontology (EMMO). https://github.com/emmo-repo/domain-crystallography.

"Cyc." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Cyc&oldid=1050993693.

Datamodel Ontology. 2021. Elementary Multiperspective Material Ontology (EMMO). https://github.com/emmo-repo/datamodel-ontology.

Demoly, Frédéric, Aristeidis Matsokis, and Dimitris Kiritsis. 2012. "A Mereotopological Product Relationship Description Approach for Assembly Oriented Design." *Robotics and Computer-Integrated Manufacturing* 28 (6): 681–93. https://doi.org/10.1016/j.rcim.2012.03.003.

Demoly, Frédéric, Aristeidis Matsokis, Dimitris Kiritsis, and Samuel Gomes. 2012. "Mereotopological Description of Product-Process Information and Knowledge for PLM." In *Product Lifecycle Management. Towards Knowledge-Rich Enterprises*, edited by Louis Rivest, Abdelaziz Bouras, and Borhen Louhichi, 70–84. IFIP Advances in Information and Communication Technology. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-35758-9_7.

"Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE) – Laboratory for Applied Ontology (LOA)." n.d. Accessed November 5, 2021. http://www.loa.istc.cnr.it/index.php/dolce/.

"DEXPI – Data Exchange in the Process Industry." n.d. Accessed November 5, 2021. https://dexpi.org/.

"Digital Open Marketplace Ecosystem 4.0 | DOME 4.0 Project | Fact Sheet | H2020 | CORDIS | European Commission." n.d. Accessed November 5, 2021. https://cordis.europa.eu/project/id/953163.

Domain: Mechanical-Testing. 2021. Elementary Multiperspective Material Ontology (EMMO). https://github.com/emmo-repo/domain-mechanical-testing.

Domain Ontology for Atomistic and Electronic Modelling. 2021. Python. Elementary Multiperspective Material Ontology (EMMO). https://github.com/emmo-repo/domain-atomistic.

Dome4.0 Consortium. n.d. "Home | DOME 4.0 - EU Project." Accessed November 5, 2021. https://dome40.eu/.

Dori, Dov. 1995. "Object-Process Analysis: Maintaining the Balance Between System Structure and Behaviour." *Journal of Logic and Computation* 5 (2): 227–49. https://doi.org/10.1093/logcom/5.2.227.

Dori, Dov. 2016. *Model-Based Systems Engineering with OPM and SysML*. New York, NY: Springer New York. https://doi.org/10.1007/978-1-4939-3295-5.

"Dublin Core." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Dublin_Core&oldid=1049732882.

El Kadiri, Soumaya, and Dimitris Kiritsis. 2015. "Ontologies in the Context of Product Lifecycle Management: State of the Art Literature Review." *International Journal of Production Research* 53 (18): 5657–68. https://doi.org/10.1080/00207543.2015.1052155.

El Kadiri, Soumaya, Ana Milicic, and Dimitris Kiritsis. 2013. "Linked Data Exploration in Product Life-Cycle Management." In *Advances in Production Management Systems. Sustainable Production and Service Supply Chains*, edited by Vittal Prabhu, Marco Taisch, and Dimitris Kiritsis, 460–67. IFIP Advances in Information and Communication Technology. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-41263-9_57.

El Kadiri, Soumaya, Walter Terkaj, Esmond Neil Urwin, Claire Palmer, Dimitris Kiritsis, and Robert Young. 2015. "Ontology in Engineering Applications." In *Formal Ontologies Meet Industry*, edited by Roberta Cuel and Robert Young, 126–37. Lecture Notes in Business Information Processing. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-21545-7_11.

"EMMO." 2019. *The European Materials Modelling Council* (blog). May 2, 2019. https://emmc.eu/news/emmo-new-name-and-logo/.

"EMMO Github Repository." n.d. GitHub. Accessed November 5, 2021. https://github.com/emmo-repo/EMMO.

EMMOntoPy. 2021. Python. Elementary Multiperspective Material Ontology (EMMO). https://github.com/emmo-repo/EMMO-python.

"FIBO - The Financial Industry Business Ontology." n.d. Accessed November 5, 2021. https://spec.edmcouncil.org/fibo/.

"Final Report Summary - EUJOINT (European Japanese Ontology Interaction) | FP7 | CORDIS | European Commission." n.d. Accessed November 5, 2021. https://cordis.europa.eu/project/id/247503/reporting/de.

"FrameNet." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=FrameNet&oldid=1027189059.

"GECKO - Generic Evolutionary Control Knowledge-Based Module | Istituto Di Scienze e Tecnologie Della Cognizione." n.d. Accessed November 5, 2021. https://www.istc.cnr.it/en/project/gecko-generic-evolutionary-control-knowledge-based-module.

"General Formal Ontology." 2020. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=General_formal_ontology&oldid=937344733.

"Gist - The Semantic Arts Minimalist Upper Ontology." n.d. *Semantic Arts* (blog). Accessed November 5, 2021. https://www.semanticarts.com/gist/.

Grenon, Pierre, and Barry Smith. 2011. "Foundations of an Ontology of Philosophy." *Synthese* 182 (2): 185–204. https://doi.org/10.1007/s11229-009-9658-x.

Hastings, Janna, Nina Jeliazkova, Gareth Owen, Georgia Tsiliki, Cristian R. Munteanu, Christoph Steinbeck, and Egon Willighagen. 2015. "ENanoMapper: Harnessing Ontologies to Enable Data Integration for Nanomaterial Risk Assessment." *Journal of Biomedical Semantics* 6 (1): 10. https://doi.org/10.1186/s13326-015-0005-5.

"Highly Customizable Robotic Solutions for Effective and Safe Human Robot Collaboration in Manufacturing Applications | FourByThree Project | Fact Sheet | H2020 | CORDIS | European Commission." n.d. Accessed November 5, 2021. https://cordis.europa.eu/project/id/637095.

Hildebrand, Marlène. n.d. "EEC MATERIALS AND MANUFACTURING ONTOLOGY WORKSHOP," 10.

Hildebrand, Marlène, Ioannis Tourkogiorgis, Foivos Psarommatis, Damiano Arena, and Dimitris Kiritsis. 2019. "A Method for Converting Current Data to RDF in the Era of Industry 4.0." In *Advances in Production Management Systems. Production Management for the Factory of the Future*, edited by Farhad Ameri, Kathryn E. Stecke, Gregor von Cieminski, and Dimitris Kiritsis, 566:307–14. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-30000-5_39.

"History | MxD." n.d. *Https://Www.Mxdusa.Org/* (blog). Accessed November 5, 2021. https://www.mxdusa.org/about/history/.

Hodkiewicz, Melinda, Johan W. Klüwer, Caitlin Woods, Thomas Smoker, and Emily Low. 2021. "An Ontology for Reasoning over Engineering Textual Data Stored in FMEA Spreadsheet Tables." *Computers in Industry* 131 (October): 103496. https://doi.org/10.1016/j.compind.2021.103496.

"Home | CIDOC CRM." n.d. CIDOC Conceptual Reference Model. Accessed November 5, 2021. http://www.cidoc-crm.org/.

"Home - BIG-MAP." n.d. Https://Www.Big-Map.Eu. Accessed November 5, 2021. https://www.big-map.eu/.

"Home - BORO." n.d. BORO Solutions. Accessed November 5, 2021. https://www.borosolutions.net/.

"Home - CIM | DMTF." n.d. DMTF's Common Information Model (CIM). Accessed November 5, 2021. https://www.dmtf.org/standards/cim.

"Home - Dublin Core Metadata Initiative." n.d. Accessed November 5, 2021. https://www.dublincore.org/.

"Home - INCITS." n.d. Accessed November 5, 2021. https://www.incits.org/.

"Home: CHARM." n.d. CHARM: Cultural Heritage Abstract Reference Model. Accessed November 5, 2021. http://www.charminfo.org/.

"Home: ConML." n.d. ConML: Conceptual Modelling. Accessed November 5, 2021. http://www.conml.org/.

Horsch, Martin Thomas, Silvia Chiacchiera, Michael A. Seaton, Ilian T. Todorov, Karel Šindelka, Martin Lísal, Barbara Andreon, et al. 2020. "Ontologies for the Virtual Materials Marketplace." *KI - Künstliche Intelligenz* 34 (3): 423–28. https://doi.org/10.1007/s13218-020-00648-9.

"HQDM_FRAMEWORK Data Model." n.d. Accessed November 5, 2021. http://www.informationjunction.co.uk/hqdm_framework/.

Hutter, Dieter, Bruno Langenstein, Claus Sengler, Jörg H. Siekmann, Werner Stephan, and AndreasWolpers Wolpers. 1996. "Deduction in the Verification Support Environment (VSE)." In *FME'96: Industrial Benefit and Advances in Formal Methods*, edited by Marie-Claude Gaudel and James Woodcock, 1051:268–86. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/3-540-60973-3_92.

"IDEAS Group." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=IDEAS_Group&oldid=1011254195.

"IEC PAS 63088:2017 | IEC Webstore." n.d. Accessed November 5, 2021. https://webstore.iec.ch/publication/30082.

"IEEE SA P1872.2 Autonomous Robotics (AuR) Ontology Working Group." n.d. IEEE SA P1872.2 Autonomous Robotics (AuR) Ontology Working Group. Accessed November 5, 2021. https://sagroups.ieee.org/1872-2/.

"Index of Isabelle/FOL/BFO (Isabelle2007: November 2007)." n.d. Accessed November 5, 2021. http://www.acsu.buffalo.edu/~bittner3/Theories/BFO/.

"Industrial Ontologies Foundry - Confluence." 2021. https://oagiscore.atlassian.net/wiki/spaces/IOF/overview.

"Integrated Open Access Materials Modelling Innovation Platform for Europe | OpenModel Project | Fact Sheet | H2020 | CORDIS | European Commission." n.d. Accessed November 5, 2021. https://cordis.europa.eu/project/id/953167.

Intersect Consortium. 2018. "Home -INTERSECT PROJECT." July 2, 2018. https://intersect-project.eu/.

IOF Consortium. 2019. "Industrial Ontologies Foundry." Industrial Ontologies Foundry. 2019. https://www.industrialontologies.org.

"ISO/IEC 24707:2018(En), Information Technology — Common Logic (CL) — A Framework for a Family of Logic-Based Languages." n.d. Accessed November 5, 2021. https://www.iso.org/obp/ui/#iso:std:iso-iec:24707:ed-2:v1:en.

Jinzhi, Lu, Ma Junda, Xiaochen Zheng, Guoxin Wang, and Dimitris Kiritsis. 2020. "Design Ontology Supporting Model-Based Systems-Engineering Formalisms." *ArXiv:2010.07627 [Cs, Eess]*, October. http://arxiv.org/abs/2010.07627.

Karray, Hedi. 2021. *Reference Ontology Of Maintenance*. https://github.com/HediKarray/ReferenceOntologyOfMaintenance.

Karray, Hedi, Farhad Ameri, Melinda Hodkiewicz, and Thierry Louge. 2019. "ROMAIN: Towards a BFO Compliant Reference Ontology for Industrial Maintenance." *Applied Ontology* 14 (April): 1–24. https://doi.org/10.3233/AO-190208.

Kim, Byung Chul, Bongcheol Kim, Sangjin Park, Hans Teijgeler, and Duhwan Mun. 2020. "ISO 15926–Based Integration of Process Plant Life-Cycle Information Including Maintenance Activity." *Concurrent Engineering* 28 (1): 58–71. https://doi.org/10.1177/1063293X19894041.

Kiritsis, Dimitris. 2013. "Semantic Technologies for Engineering Asset Life Cycle Management." *International Journal of Production Research* 51 (23–24): 7345–71. https://doi.org/10.1080/00207543.2012.761364.

Kiritsis, Dimitris, Soumaya El Kadiri, Apostolos Perdikakis, Ana Milicic, Dimitris Alexandrou, and Kostas Pardalis. 2013. "Design of Fundamental Ontology for Manufacturing Product Lifecycle Applications." In *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services*, edited by Christos Emmanouilidis, Marco Taisch, and Dimitris Kiritsis, 376–82. IFIP Advances in Information and Communication Technology. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-40352-1_47.

Koukias, Andreas, Dražen Nadoveza, and Dimitris Kiritsis. 2013. "Semantic Data Model for Operation and Maintenance of the Engineering Asset." In *Advances in Production Management Systems. Competitive Manufacturing for Innovative Products and Services*, edited by Christos Emmanouilidis, Marco Taisch, and Dimitris Kiritsis, 49–55. IFIP Advances in Information and Communication Technology. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-40361-3_7.

———. 2015a. "Towards Ontology-Based Modeling of Technical Documentation and Operation Data of the Engineering Asset." In *Engineering Asset Management - Systems, Professional Practices and Certification*, edited by Peter W. Tse, Joseph Mathew, King Wong, Rocky Lam, and C.N. Ko, 983–94. Lecture Notes in Mechanical Engineering. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-09507-3_84.

———. 2015b. "An Ontology–Based Approach for Modelling Technical Documentation towards Ensuring Asset Optimisation." *International Journal of Product Lifecycle Management* 8 (1): 24–45. https://doi.org/10.1504/IJPLM.2015.068012.

Kulvatunyou, Boonserm (Serm), Evan Wallace, Dimitris Kiritsis, Barry Smith, and Chris Will. 2018. "The Industrial Ontologies Foundry Proof-of-Concept Project." In *Advances in Production Management Systems. Smart Manufacturing for Industry 4.0*, edited by Ilkyeong Moon, Gyu M. Lee, Jinwoo Park, Dimitris Kiritsis, and Gregor von Cieminski, 402–9. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-99707-0_50.

"Laboratory for Applied Ontology - DOLCE." n.d. Accessed November 5, 2021. http://www.loa.istc.cnr.it/dolce/overview.html.

"Laboratory for Applied Ontology (LOA)." n.d. Accessed November 5, 2021. http://www.loa.istc.cnr.it/.

Leal, D. 2005. "ISO 15926 'Life Cycle Data for Process Plant': An Overview." *Oil & Gas Science and Technology* 60 (4): 629–37. https://doi.org/10.2516/ogst:2005045.

Mappings Ontology. 2021. Elementary Multiperspective Material Ontology (EMMO). https://github.com/emmo-repo/domain-mappings.

Mark Schildhauer, Matthew B. Jones. 2016. *OBOE: The Extensible Observation Ontology, Version 1.1*. KNB Data Repository. https://doi.org/10.5063/F11C1TTM.

Martín-Recuerda, Francisco, Dirk Walther, Siegfried Eisinger, Graham Moore, Petter Andersen, Per-Olav Opdahl, and Lillian Hella. 2020. "Revisiting Ontologies of Units of Measure for Harmonising Quantity Values – A Use Case." In *The Semantic Web – ISWC 2020*, edited by Jeff Z. Pan, Valentina Tamma, Claudia d'Amato, Krzysztof Janowicz, Bo Fu, Axel Polleres, Oshani Seneviratne, and Lalana Kagal, 551–67. Lecture Notes in Computer Science. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-62466-8_34.

Masolo, Claudio, Stefano Borgo, Aldo Gangemi, Nicola Guarino, and Alessandro Oltramari. n.d. "WonderWeb Deliverable D18." D18.

"Materials Modelling Marketplace for Increased Industrial Innovation | MarketPlace Project | Fact Sheet | H2020 | CORDIS | European Commission." n.d. Accessed November 5, 2021. https://cordis.europa.eu/project/id/760173.

Matsokis, Aristeidis, Hedi M. Karray, Brigitte Chebel-Morello, and Dimitris Kiritsis. 2010. "An Ontology-Based Model for Providing Semantic Maintenance." *IFAC Proceedings Volumes*, 1st IFAC Workshop on Advanced Maintenance Engineering, Services and Technology, 43 (3): 12–17. https://doi.org/10.3182/20100701-2-PT-4012.00004.

Matsokis, Aristeidis, and Dimitris Kiritsis. 2010. "An Ontology-Based Approach for Product Lifecycle Management." *Computers in Industry*, Semantic Web Computing in Industry, 61 (8): 787–97. https://doi.org/10.1016/j.compind.2010.05.007.

———. 2011. "Ontology Applications in PLM." *International Journal of Product Lifecycle Management* 5 (1): 84–97. https://doi.org/10.1504/IJPLM.2011.038104.

"MICRA Home Page." n.d. Accessed November 5, 2021. http://www.micra.com/.

Milicic, A, A. Perdikakis, S. El. Kadiri, and D Kiritsis. 2013. "PLM Ontology Exploitation through Inference and Statistical Analysis A Case Study for LCC." *IFAC Proceedings Volumes*, 7th IFAC Conference on Manufacturing Modelling, Management, and Control, 46 (9): 1004–8. https://doi.org/10.3182/20130619-3-RU-3018.00043.

Milicic, Ana, Soumaya El Kadiri, Joerg Clobes, and Dimitris Kiritsis. 2017. "An Autonomous System for PLM Domain Data Exploitation." *International Journal of Computer Integrated Manufacturing* 30 (1): 109–20. https://doi.org/10.1080/0951192X.2015.1067913.

Milicic, Ana, Dimitris Kiritsis, and Nesat Efendioglu. 2016. "From English to RDF - A Meta-Modelling Approach for Predictive Maintenance Knowledge Base Design." In *Advances in Production Management Systems. Initiatives for a Sustainable World*, edited by Irenilza Nääs, Oduvaldo Vendrametto, João Mendes Reis, Rodrigo Franco Gonçalves, Márcia Terra Silva, Gregor von Cieminski, and Dimitris Kiritsis, 214–24. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-51133-7_26.

Milicic, Ana, Apostolos Perdikakis, Soumaya El Kadiri, Dimitris Kiritsis, and Petko Ivanov. 2012. "Towards the Definition of Domain Concepts and Knowledge through the Application of the User Story Mapping Method." In *Product Lifecycle Management. Towards Knowledge-Rich Enterprises*, edited by Louis Rivest, Abdelaziz Bouras, and Borhen Louhichi, 58–69. IFIP Advances in Information and Communication Technology. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-35758-9_6.

Milicic, Ana, Apostolos Perdikakis, Soumaya El Kadiri, Dimitris Kiritsis, Sergio Terzi, Paolo Fiordi, and Silvia Sadocco. 2012. "Specialization of a Fundamental Ontology for Manufacturing Product Lifecycle Applications: A Case Study for Lifecycle Cost Assessment." In *On the Move to Meaningful Internet Systems: OTM 2012 Workshops*, edited by Pilar Herrero, Hervé Panetto, Robert Meersman, and Tharam Dillon, 69–72. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-33618-8_12.

"Model-Based System Engineering | OPCloud | OPM." n.d. OPCloud. Accessed November 5, 2021. https://www.opcloud.tech.

Nadoveza, Dražen, and Dimitris Kiritsis. 2014. "Ontology-Based Approach for Context Modeling in Enterprise Applications." *Computers in Industry*, Special Issue on The Role of Ontologies in Future Web-based Industrial Enterprises, 65 (9): 1218–31. https://doi.org/10.1016/j.compind.2014.07.007.

National Center for Ontological Research. n.d. "BFO-Based Engineering Ontologies." Accessed October 30, 2021. http://ncorwiki.buffalo.edu/index.php/BFO-Based_Engineering_Ontologies.

Nezami, Zeinab, Kamran Zamanifar, Damiano Arena, and Dimitris Kiritsis. 2019. "Ontology-Based Resource Allocation for Internet of Things." In *Advances in Production Management Systems. Production Management for the Factory of the Future*, edited by Farhad Ameri, Kathryn E. Stecke, Gregor von Cieminski, and Dimitris Kiritsis, 566:323–30. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-30000-5_41.

"Object Process Methodology." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Object_Process_Methodology&oldid=1010965367.

"Object Process Methodology (OPM) Is a Conceptual Modeling Lan... - Samim." n.d. Accessed November 5, 2021. https://samim.io/p/2020-01-07-object-process-methodology-opm-is-a-conceptual-model/.

"Ontobee." n.d. Accessed November 5, 2021. http://www.ontobee.org/ontobeep.

"Ontology Driven Open Translation Environment | OntoTRANS Project | Fact Sheet | H2020." n.d. CORDIS | European Commission. Accessed November 5, 2021. https://cordis.europa.eu/project/id/862136.

OntoTrans Consortium. n.d. "Start | OntoTrans." Accessed November 5, 2021. https://ontotrans.eu/.

"OPC Unified Architecture." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=OPC_Unified_Architecture&oldid=1051885358.

"OPC Unified Architecture Specification." n.d. *OPC Foundation* (blog). Accessed November 5, 2021. https://opcfoundation.org/members/.

"OpenModel Project." n.d. OpenModel. Accessed November 5, 2021. https://open-model.eu/.

O'Reilly, Liam, Markus Roggenbach, and Yoshinao Isobe. 2009. "CSP-CASL-Prover: A Generic Tool for Process and Data Refinement." *Electronic Notes in Theoretical Computer Science* 250 (2): 69–84. https://doi.org/10.1016/j.entcs.2009.08.018.

Otte, J. Neil, Dimitris Kiritsi, Munira Mohd Ali, Ruoyu Yang, Binbin Zhang, Ron Rudnicki, Rahul Rai, and Barry Smith. 2019. "An Ontological Approach to Representing the Product Life Cycle." Edited by Bob Young, Yoshinobu Kitamura, and Emilio M. Sanfilippo. *Applied Ontology* 14 (2): 179–97. https://doi.org/10.3233/AO-190210.

Otten, Jens. 2005. "Clausal connection-based theorem proving in intuitionistic first-order logic." In: Beckert, B. (ed.) TABLEAUX 2005. LNAI, vol. 3702, pp. 245–261. Springer, Heidelberg.

Otten, Jens. 2008. "leanCoP 2.0 and ileanCoP 1.2: High performance lean theorem proving in classical and intuitionistic logic." In: Armando, A., Baumgartner, P., Dowek, G. (eds.) IJCAR 2008. LNAI, vol. 5195, pp. 283–291. Springer, Heidelberg.

Otten, Jens. 2010. "Restricting backtracking in connection calculi." AI Commun. 23(2–3), 159–182.

Otten, Jens. 2011. "A non-clausal connection calculus." In: Brunnler, K., Metcalfe, G. (eds.) TABLEAUX 2011. LNAI, vol. 6793, pp. 226–241. Springer, Heidelberg.

Otten, Jens. 2014. "MleanCoP: A connection prover for first-order modal logic." In: Demri, S., Kapur, D., Weidenbach, C. (eds.) IJCAR 2014. LNAI, vol. 8562, pp. 269–276. Springer, Heidelberg.

Otten, Jens. 2016. "nanoCoP: A non-clausal connection prover." In: Olivetti, N., Tiwari, A. (eds.) IJCAR 2016. LNAI, vol. 9706, pp. 302–312. Springer, Heidelberg.

Otten, Jens. 2017. "nanoCoP: Natural non-clausal theorem proving." In: Sierra, C. (ed.) Proceedings of the Twenty-Sixth International Joint Conference on Artificial Intelligence, IJCAI-17, Sister Conference Best Paper Track. pp. 4924–4928. IJCAI.

Otten, Jens. 2017. "Non-clausal connection calculi for non-classical logics." In: Schmidt, R., Nalon, C. (eds.) TABLEAUX 2017. LNAI, vol. 10501, pp. 209–227. Springer, Cham.

Otten, Jens. 2021. "The nanoCoP 2.0 Connection Provers for Classical, Intuitionistic and Modal Logics." In: Das, A., Negri, S. (eds) TABLEAUX 2021. LNAI, vol 12842, pp. 236–249. Springer, Cham.

Otten, Jens, Wolfgang Bibel. 2003. "leanCoP: lean connection-based theorem proving." Journal of Symbolic Computation 36(1–2), 139–161.

Otten, Jens, Wolfgang Bibel. 2017. "Advances in connection-based automated theorem proving." In: Hinchey, M., Bowen, J.P., Olderog, E.R. (eds.) Provably Correct Systems. pp. 211–241. NASA Monographs in Systems and Software Engineering, Springer, Cham.

"OWL 2 Web Ontology Language Document Overview (Second Edition)." n.d. Accessed November 5, 2021. https://www.w3.org/TR/owl2-overview/.

"PCA 'Part 14' Upper Ontology." n.d. Accessed November 5, 2021. https://rds.posccaesar.org/ontology/lis14/ont/core/1.0/.

Pelzer, Björn, and Christoph Wernhard. 2007. "System Description: E- KRHyper." In *Automated Deduction – CADE-21*, edited by Frank Pfenning, 4603:508–13. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-73595-3_37.

Perdikakis, A., A. Shukla, and D. Kiritsis. 2015. "Optimize Energy Efficiency in the Supply Chain of FMCGs with the Use of Semantic Web Technologies." *Procedia Engineering*, MESIC Manufacturing Engineering Society International Conference 2015., 132 (January): 1112–19. https://doi.org/10.1016/j.proeng.2015.12.603.

Perdikakis, Apostolos, and Dimitris Kiritsis. 2015. "Ontology-Based Automated Reporting for PLM Applications." *International Journal of Product Lifecycle Management* 8 (4): 283–310. https://doi.org/10.1504/IJPLM.2015.075927.

Perini, Stefano, Damiano Arena, Dimitris Kiritsis, and Marco Taisch. 2017. "An Ontology-Based Model for Training Evaluation and Skill Classification in an Industry 4.0 Environment." In *Advances in Production Management Systems. The Path to Intelligent, Collaborative and Sustainable Manufacturing*, edited by Hermann Lödding, Ralph Riedel, Klaus-Dieter Thoben, Gregor von Cieminski, and Dimitris Kiritsis, 314–21. IFIP Advances in Information and Communication Technology. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-66923-6_37.

"Product Service System WG – IOF Website." n.d. Accessed November 5, 2021. https://www.industrialontologies.org/product-service-system-wg/.

"PROV-O: The PROV Ontology." n.d. Accessed November 5, 2021. https://www.w3.org/TR/prov-o/.

Qu4lity Consortium. n.d. "Home: Qu4lity." Qu4lity. Accessed November 5, 2021. https://qu4lity-project.eu/.

"ReaxPro EU-Project for multiscale Modelling." n.d. ReaxPro EU-Project for multiscale Modelling. Accessed November 5, 2021. https://www.reaxpro.eu/.

"Reference Data Service." n.d. Accessed November 5, 2021. http://data.posccaesar.org/rdl/.

Reina, Alice, Sang-Je Cho, Gökan May, Eva Coscia, Jacopo Cassina, and Dimitris Kiritsis. 2018. "Maintenance Planning Support Tool Based on Condition Monitoring with Semantic Modeling of Systems." In *Enterprise Interoperability*, 271–76. John Wiley & Sons, Ltd. https://doi.org/10.1002/9781119564034.ch33.

Riazanov, Alexandre, Andrei Voronkov. 2002. "The design and implementation of Vampire." AI Communications 15(2-3): 91–110.

Schulz, Stefan, et al. 2019. "Faster, higher, stronger: E 2.3." In: Fontaine, P. (ed.) CADE 27. LNCS, vol. 11716, pp. 495–507. Springer, Cham (2019).

"SFI PhysMet - Centre for Sustainable and Competitive Metallurgical and Manufacturing Industry - NTNU." n.d. Accessed November 5, 2021. https://www.ntnu.edu/physmet/physmet.

SimDOME Consortium. n.d. "SimDOME – A Horizon 2020 Project." Accessed November 5, 2021. https://simdome.eu/.

Skjæveland, Martin G, Morten R Strand, Arild Waaler, and Per Øyvind Øverli. n.d. "Semantic Material Master Data Management at Aibel" 2.

Smith, Barry. 2006. "Against Idiosyncrasy in Ontology Development," 12.

Smith, Barry, Farhad Ameri, Hyunmin Cheong, Dimitris Kiritsis, Dusan Sormaz, Chris Will, and J. Neil Otte. 2019. "A First-Order Logic Formalization of the Industrial Ontology Foundry Signature Using Basic Formal Ontology." In *Proceedings of the Joint Ontology Workshops (JOWO), Graz*.

Smith, Barry, Farhad Ameri, Hyunmin Cheong, Dimitris Kiritsis, Dusan Sormaz, Chris Will, and J Neil Otte. n.d. "A First-Order Logic Formalization of the Industrial Ontologies Foundry Signature Using Basic Formal Ontology," 12.

———. n.d. "A First-Order Logic Formalization of the Industrial Ontologies Foundry Signature Using Basic Formal Ontology," 12.

Suárez-Figueroa, Mari Carmen, Asunción Gómez-Pérez, and Mariano Fernández-López. 2012. "The NeOn Methodology for Ontology Engineering." In *Ontology Engineering in a Networked World*, edited by Mari Carmen Suárez-Figueroa, Asunción Gómez-Pérez, Enrico Motta, and Aldo Gangemi, 9–34. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-24794-1_2.

The ENanoMapper Ontology. 2021. Java. eNanoMapper. https://github.com/enanomapper/ontologies.

Trokanas, Nikolaos, Madeleine Bussemaker, Eirini Velliou, Hella Tokos, and Franjo Cecelja. 2015. "BiOnto: An Ontology for Biomass and Biorefining Technologies." In *Computer Aided Chemical Engineering*, edited by Krist V. Gernaey, Jakob K. Huusom, and Rafiqul Gani, 37:959–64. 12 International Symposium on Process Systems Engineering and 25 European Symposium on Computer Aided Process Engineering. Elsevier. https://doi.org/10.1016/B978-0-444-63577-8.50005-X.

"Upper Ontology." 2021. In *Wikipedia*. https://en.wikipedia.org/w/index.php?title=Upper_ontology&oldid=1052004360.

Varakhedi, Shrinivasa. n.d. "Introduction to Knowledge Representation and Navya Nyaya Dr. Shrinivasa Varakhedi - [PPT Powerpoint]." Vdocuments.Mx. Accessed November 5, 2021. https://vdocuments.mx/introduction-to-knowledge-representation-and-navya-nyaya-dr-shrinivasa-varakhedi.html.

VIMMP Consortium. n.d. "Virtual Materials Marketplace, VIMMP." Virtual Materials Marketplace. Accessed November 5, 2021. https://www.vimmp.eu/.

"VIPCOAT Homepage." n.d. Accessed November 5, 2021. https://ms.hereon.de/vipcoat/.

"Virtual Open Innovation Platform for Active Protective Coatings Guided by Modelling and Optimization | VIPCOAT Project | Fact Sheet | H2020 | CORDIS | European Commission." n.d. Accessed November 5, 2021. https://cordis.europa.eu/project/id/952903.

"W3C Semantic Web Best Practices and Deployment Working Group." n.d. Accessed November 5, 2021. https://www.w3.org/2001/sw/BestPractices/.

"Welcome to FrameNet! | Fndrupal." n.d. Accessed November 5, 2021. https://framenet.icsi.berkeley.edu/fndrupal/.

West, Matthew. 2011. *Developing High Quality Data Models*. Burlington, MA: Morgan Kaufmann.

"WonderWeb: Ontology Infrastructure for the Semantic Web | WONDERWEB Project | Fact Sheet | FP5." n.d. CORDIS | European Commission. Accessed November 5, 2021. https://cordis.europa.eu/project/id/IST-2001-33052.

Yoo, Min-Jung, Clément Grozel, and Dimitris Kiritsis. 2016. "Closed-Loop Lifecycle Management of Service and Product in the Internet of Things: Semantic Framework for Knowledge Integration." *Sensors* 16 (7): 1053. https://doi.org/10.3390/s16071053.

Yoo, Min-Jung, Prodromos Kolyvakis, Dimitris Kiritsis, Dirk Werthmann, and Robert Hellbach. 2016. "Semantic Model for IoT-Enabled Electric Vehicle Services: Puzzling with Ontologies." In *2016 IEEE 4th International Conference on Future Internet of Things and Cloud (FiCloud)*, 387–92. https://doi.org/10.1109/FiCloud.2016.61.

"Z-Fact0r – Zero-Defect Manufacturing Strategies towards on-Line Production Management for European Factories." n.d. Accessed November 5, 2021. https://www.z-fact0r.eu/.

"Developing High Quality Data Models." n.d. Accessed November 5, 2021. https://www.elsevier.com/books/developing-high-quality-data-models/west/978-0-12-375106-5.