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Report D3.7 "Report on harmonized and developed ontologies"

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Report D3.7 "Report on harmonized and developed ontologies"

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Task	T3.4 | Investigating Intra- and Cross-domain Interoperability
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Glossary of terms

Item	Description
DLO	Domain level ontology
NMBP	Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing
LOT	Linked Open Terms
LOT4OCES	Linked Open Terms methodology for OntoCommons Ecosystem
OCES	ontology commons ecosystem
FAIR	Findable, Accessible, Interoperable and Reusable
KARMA	Kombination of ARchitecture Model specificAtion
FCN	transmitting function module
IPO	Input-Process-Output
SLCP	system life cycle processes
RSWO	resistance spot welding ontology
CQ	competency question
RDF	Resource Description Framework
IOF	Industry Ontology Foundry
OOPS!	Ontology Pitfall Scanner
TribOnt	Tribological Characterisation Ontology

Keywords

Alignment; Data; Harmonization; Ontology; Standardization

Disclaimer

Executive Summary

To achieve interoperability between different domain-level ontologies (DLOs), OntoCommons aims to harmonize these ontologies while facilitating agreement in their development. In Work Package 3, OntoCommons aims to provide alignments among existing DLOs from the stakeholders' community as well as develop new DLOs to fill the gaps. This task (T3.4) involves several activities, including but not limited to: identifying existing DLOs and corresponding disciplines that need to be covered by the alignment effort; defining the level of alignment that needs to be achieved by the DLOs to ensure interoperability; identifying gaps in the disciplines that can be filled with new DLOs; and developing some new DLOs to cover the gaps. The first report (D3.6) on harmonized and developed ontologies was published in the 27th month. This report (D3.7) was a significant milestone for OntoCommons, as it marked the first step towards greater interoperability between different DLOs. The report focused on domain coverage analysis, gap identification, and harmonization among existing DLOs through bridge concept engineering. By identifying gaps and harmonizing existing DLOs, OntoCommons hoped to pave the way for new DLO development. Now, in this second report, OntoCommons will focus on new DLO development and any updates on the alignment of existing DLOs. The goal is to further improve interoperability and facilitate agreement in the development of DLOs. By providing alignments among existing DLOs and developing new DLOs, OntoCommons hopes to create a more comprehensive and cohesive ontology landscape. OntoCommons recognizes the importance of ontology harmonization in enabling the sharing and reuse of data across different domains and applications. Through these efforts, OntoCommons aims to promote greater collaboration and innovation within the ontology community, and facilitate the development of more effective and efficient systems.

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1.Introduction

1.1 Overview of T3.4 and its first report

T3.4 is a crucial step in the development and harmonization of DLOs regarding NMBP (Nanotechnologies, Advanced Materials, Biotechnology, and Advanced Manufacturing and Processing). The main objective of T3.4 is to harmonize and develop DLOs that cover the whole domain of NMBP. To achieve this goal, the T3.4 team performed several sub-tasks, including the identification of domains where DLOs already exist, and domains where new development is needed.

To effectively carry out the work, the team followed the focus areas and focus groups from T3.3, which allowed them to divide the domain into more specific subareas. The focus groups for the initial investigation included Systems Engineering, Product and Service, Material Science, Manufacturing, and Maintenance. Each focus group had its own particularities, and to accommodate these specific needs, the team tailored the general workflow according to the circumstances of each focus area.

For the first report [1], the T3.4 team adopted a robust methodology to ensure that all the focus groups could work smoothly in parallel. First, they defined and followed a general workflow that contained three distinctive phases as a high-level guideline, as shown in Table 1. Second, they tailored the general workflow to accommodate the particularities of each focus group, according to their special needs and circumstances. Lastly, they used a common harmonization approach called bridge concept, which had been predefined by work package 2. This approach involved selecting candidate-bridge-concept terms. The team showed the candidate-bridge-concept terms selection through a test case in Product and Service focus group as an example and other developed bridge concepts for each focus area in the result section.

Table 1 General workflow of DLO harmonization and development

	Phase I Domain coverage analysis	Phase II Harmonization of existing DLOs	Phase III Development of new DLOs
Purpose	To determine the domains for which existing DLOs may be reused but need harmonization and the topics for which new DLO need to be developed.	To harmonize 10 identified ontologies for each area both horizontally and vertically.	To develop 3 new domain ontologies for gap areas covered by the project demonstrators.

Activity	Identify area-specific existing ontologies, Extract similar terms based on glossary for the area, Create a list of ontologies to be harmonized with a ranking, Flag ontologies as selected, Flag domains for harmonizing existing ontologies, Flag areas for new ontology development.	Identify bridge concepts, Elucidate concepts of bridge concepts, Map bridge concepts to DLOs, Map bridge concepts to MLOs.	Select the gap areas covered by the project demonstrators, Develop new domain ontologies following LOT methodology.
Output	A list of domain(s) for which at least one existing ontology exists, A list of domains for which no ontology exist, A list of ontologies which are covered by domain(s).	Documents of bridge concepts in the concept elucidation template [1], Mappings between bridge concepts and DLOs, Mappings between bridge concepts and MLOs.	3 new domain ontologies, 3 new domain ontologies aligned with MLOs.

It is worth noting that the first report did not include the identification of domains for new DLO development, also known as Phase III in the general workflow. The reason for this is that it requires more information on standardized domain vocabulary and DLO-related requirements to be collected and published in the second version of domain requirements (D3.5) as well as an automated method to measure coverage. However, the T3.4 team committed to providing regular updates in the subsequent versions as they continued their work on the development and harmonization of DLOs.

1.2 Structure of the second report

As a continuation of the first report, this report presents the results from the third phase of the general workflow in more detail. Additionally, the harmonization of existing DLOs has continued since the publication of the first report. The results of this harmonization are also presented in this report, along with any updates made to the alignments as a result. Overall, this report provides a supplementary overview of the progress made in the project since the publication of the first report, including updates on the DLOs and the results of the third phase of the general workflow. The report serves as a valuable resource for anyone interested in the project, and provides a foundation for future work in this area.

In this report, we first provide a detailed analysis of the development of new DLOs. The development methodology we employed is Linked Open Terms (LOT) methodology, which is a comprehensive approach to ontology development. In Section 2, we provide an overview of the LOT methodology, explaining its key components and how they were utilized during the development process. Furthermore, we focused on documenting the ontologies in accordance with the methodological guidelines provided by LOT methodology. This documentation is critical for ensuring that the new ontologies are properly developed and aligned with the project's objectives. In Section 3.1, we present all the proposals of new ontology candidates that were identified and defined during the requirement identification phase. We provide detailed explanations of each candidate, highlighting their key features and whether they are selected to contribute to the development of new DLOs. Finally, in Sections 3.2 to 3.4, we present the documentations of four new DLOs. These documentations provide a comprehensive analysis of each DLO, focusing on their development, implementation, and integration with the overall project.

Regarding the updates on ontology harmonization, Section 4 reports the further alignment work done by each focus group. Specifically, the report covers the progress made in reconciling discrepancies between different ontologies, as well as the efforts made towards standardizing terminology and improving the interoperability of ontology across different domains. Additionally, Section 4 also includes a summary of the key findings and recommendations from each focus group, providing valuable insights into the ongoing efforts to harmonize ontologies in the field.

2.Linked Open Terms for OntoCommons

2.1 Overview of the methodology

The Linked Open Terms methodology for OntoCommons Ecosystem (LOT4OCES) is a lightweight methodology for developing ontologies and vocabularies that served as the methodological guidelines for the ontology commons ecosystem (OCES) toolkit [3]. This methodology provides a comprehensive and practical guide to ontology development that aims to be compatible with the OntoCommons ecosystem in which sprints and iterations represent the main workflow organization. This approach ensures that the ontology development process is aligned with software development agile practices, resulting in a more efficient and effective process.

To achieve this, the LOT4OCES methodology focuses on two key aspects. Firstly, it emphasizes the reuse of terms, including ontology classes, properties, and attributes, that already exist in published vocabularies and ontologies, such as the resources on Industry Portal[1]. This not only reduces duplication of effort, but also ensures consistency across different projects and promotes interoperability. Secondly, the methodology places great importance on the publication of the built ontology according to Linked Data principles, which promotes open data and data sharing.

[1] http://industryportal.enit.fr/

It is also worth noting that the LOT methodology builds on top of the ontological engineering activities defined in the NeOn methodology [4] when available. This further enhances the methodology's scope and provides a more robust foundation for OCES. Overall, the LOT methodology is a valuable component of the OCES toolkit, providing a practical approach that emphasizes reuse, interoperability, and open data principles. Figure 1 shows the OntoCommons ecosystem and the positioning of LOT4OCES.

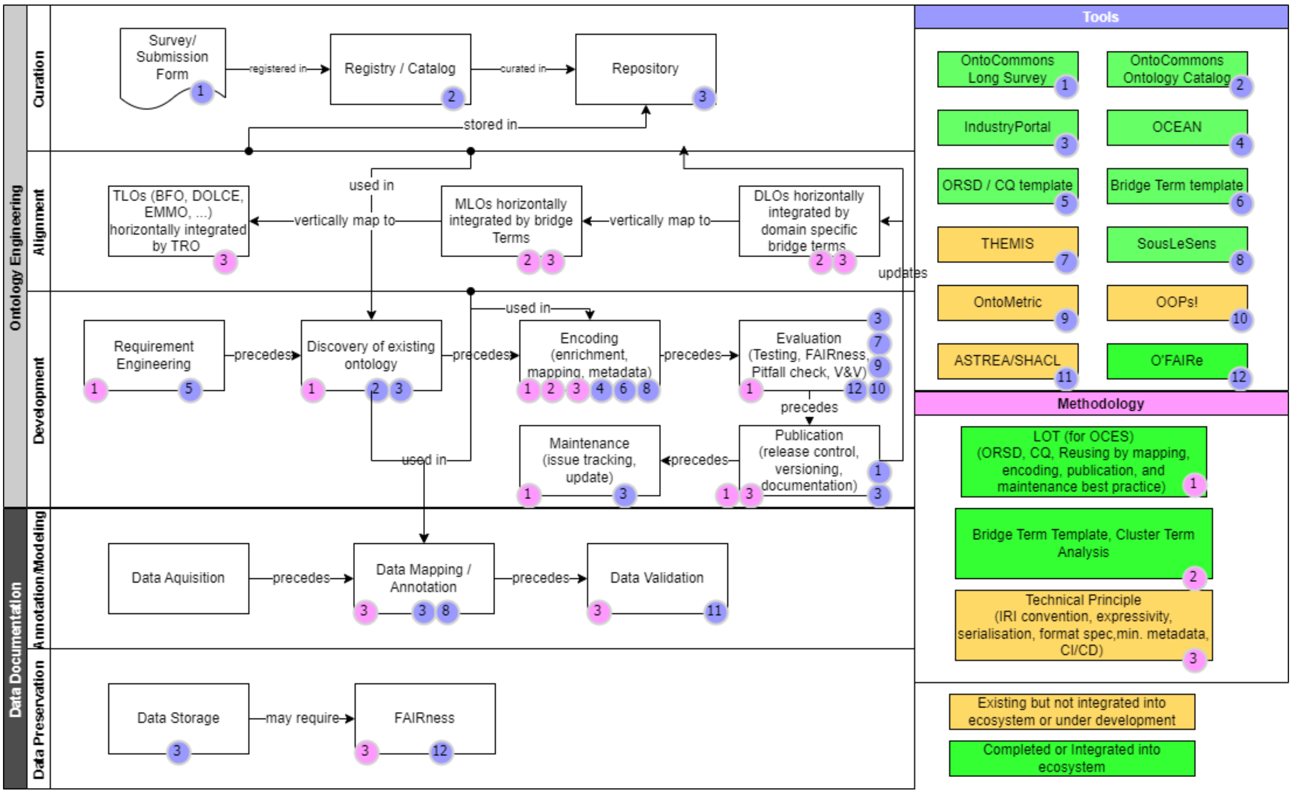

Figure 1 LOT4OCES in the ontology commons ecosystem [5]

The LOT methodology is a comprehensive approach to ontology development that involves several iterations over a basic workflow. This workflow is made up of four main activities: (1) Ontological requirements specification; (2) Ontology implementation; (3) Ontology publication; and (4) Ontology maintenance. Each of these activities has its own set of roles and main expected outputs, all of which are depicted in Figure 2.

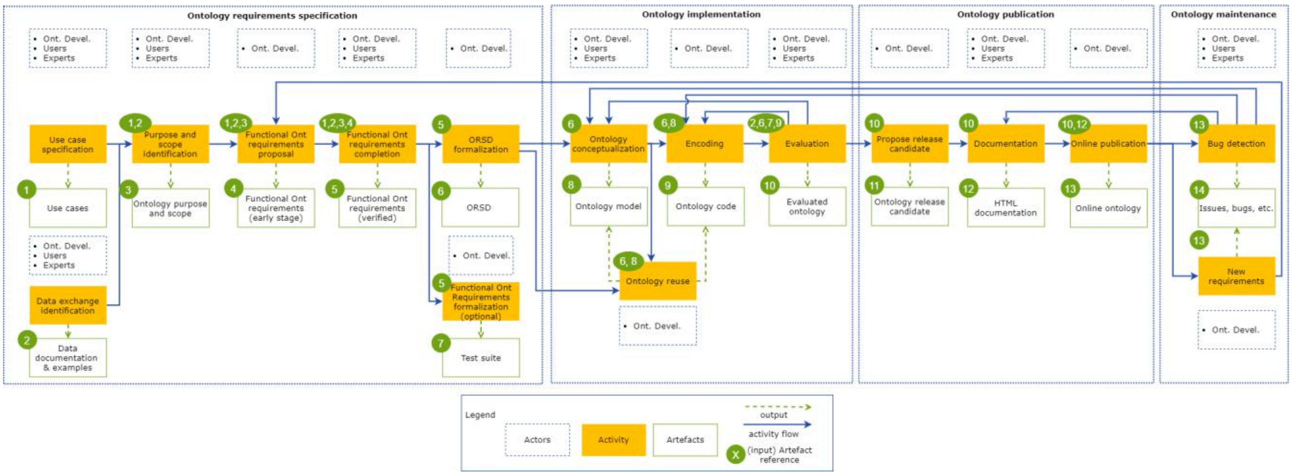

Figure 2 LOT methodology workflow [2]

The main workflow of LOT is inspired by core workflows of existing methodologies where the sequence "Requirements Elicitation-Implementation-Evaluation" appears. However, the LOT methodology has been enriched with Semantic Web oriented best practices and goals, such as ontology publication, which was not taken into account in previous methodologies. The LOT methodology also offers several different ways of describing ontology requirements, including Competency Questions (Natural language statements, and tabular information based on METHONTOLOGY) [6]. It also provides a template for ontology functional requirements description, which includes information to ease traceability.

The LOT methodology groups the various roles involved in ontology development projects into the following categories:

- Ontology developer: a highly knowledgeable member of the ontology development team who specializes in knowledge representation and development.
- Domain expert: an expert in the subject area covered by the ontology, but does not need to know about ontology development.
- Ontology user: a potential end user of the ontology, including software developers who use it in their applications. We refer to users who would use the ontology directly instead of embedded in broader systems.

2.2 Ontology documentation

If the ontology has been selected as release, or there are other reasons to document it, then the ontology development team, in collaboration with the domain experts, generates the ontology documentation. This documentation takes as input the ontology code and potentially other artefacts, such as requirements, tests, and examples. According to the best practices for publishing FAIR (Findable, Accessible, Interoperable and Reusable) vocabularies and ontologies [7], this documentation should include:

- A detailed and comprehensive human-readable description of the ontology, commonly as an HTML document, that describes the classes, properties, data properties, and individuals of the ontology. The domain experts must collaborate with the ontology development team to provide rich descriptions of the classes and the properties. If they are not available, then the ontology developers should look for sound descriptions of the terms included in the model. This information is normally included in the form of annotations in the OWL code of the ontology.

- Additionally, the HTML description of an ontology should contain metadata, such as the license URI, the title being used, the creator, the publisher, the date of creation, the last modification, and the version number. This information associated with the ontology is important to provide an overview and identify an ontology, understand its usage conditions, and its provenance. This information is normally included in the form of annotations in the OWL code of the ontology.
- The HTML documentation should also contain information oriented to human consumption about the intended use of the ontology, its purpose, and scope. To help users better understand the ontology, it is encouraged to add abstract and detailed descriptions of the model.
- Diagrams that store the graphical representation of the ontology, including taxonomy and class diagrams. For doing so, following the Chowlk [7] notation is suggested in the methodology. These diagrams provide a visual representation of the ontology that can help users better understand its structure.
- Examples of use that illustrate how to use ontologies in practice. These examples can help users understand how to use the ontology in real-world scenarios. This examples could be provided as diagrams and as RDF code.

Additionally, the documentation of the ontology can also include the following artefacts generated during the development process:

- The list of requirements identified during the requirement specification activity that should be satisfied by the ontology. This list provides a comprehensive overview of the requirements that the ontology should meet.
- The list of test cases used during the ontology evaluation activity to verify the ontology. This list provides a comprehensive overview of the tests that were performed to ensure that the ontology meets the requirements.

3.Developed ontologies.

3.1 Identification of new DLOs

In Figure 3, we can observe the initial steps to use LOT4OCES. The process starts by asking a fundamental question: do you have the appropriate ontologies to document the data? If the answer is affirmative, then you can proceed with either reusing harmonized ontologies from OCES or ontology mapping. However, if the answer is negative, then it is necessary to examine the existing ontologies from OCES to determine if there are available ontologies, such as those from Industry Portal that could be used. If there are no suitable ontologies available, then there is a requirement to develop a new ontology that fits the specific requirements of the data.

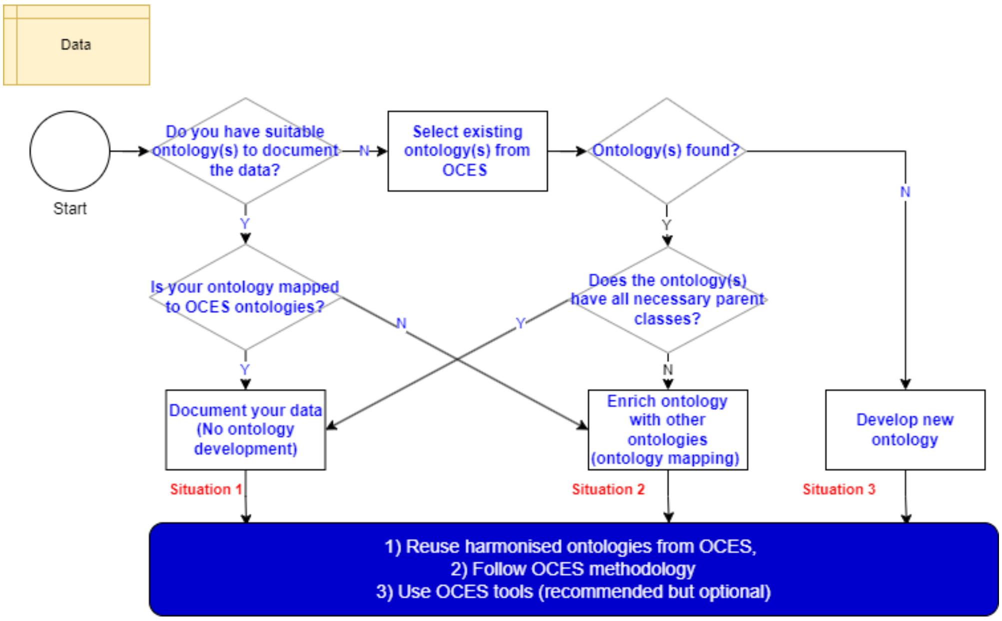

Figure 3 Context of using LOT4OCES [6]

The T3.4 team proposed seven candidates for new ontology development, each with its own unique set of strengths and challenges. After careful consideration, these ideas were evaluated based on several important criteria, such as relevance to the project's goals, the specific requirements for the ontology, and the feasibility of each proposal. Table 2 summarizes the seven proposals and the decisions on how to proceed, highlighting the strengths and drawbacks of each proposal and how the team reached their final decision.

Table 2 New DLO candidates

Potential title of the ontology	Relevant focus area	Feasibility	Domain expert	Ontology developer	Ontology user	Comments	Decision
Model-based Systems Engineering	Systems Engineering	Ã	Ã	Ã	Ã	The existing ontology needs to be aligned with another DLO	Proceed

Modelling Tool Ontology							
System Life Cycle Process Ontology	Systems Engineering	Ã	Ã	Ã	Ã	The existing ontology needs to be aligned with a TLO/MLO	Proceed
Measurement of Meteorological Variables Ontology	Manufacturing	×	Ã	Ã	Ã	Manufacturing, as micro-climate changes (< 1 km) can have an impact on manufacturing and materials for industries that are sensitive to temperature changes. So taking data measurements from industry site weather stations can be quite important if properly linked into factory data.	
An Ontology for Functions and Components of Laser Cutting Machines	Maintenance	×	Ã	×	×	A working and well-thought-out OWL ontology is plausibly possible to develop, if strictly restricted to the domain of the use case, though it will require time to consolidate. A state-of-the-art, more general ontology for maintenance would require significantly more effort.	
Product Service System Ontology	Manufacturing - Product and Service	Ã	Ã	×	Ã	The existing ontology needs to be extended to fulfill new requirements The existing ontology needs to be aligned with another DLO	

ADE - Alignment of DOME 4.0 and EMMO	Materials Science	×	Ã	×	Ã	The ADE contains both domain level and mid-level aspects. It has been developed within the DOME 4.0 project in collaboration with EMMO developers, relates to the EVMPO (part of VIMMP and OntoCommons demonstrator #05), and was first released Nov'22[2]. There are plans to improve ADE, as part of DOME 4.0 and OntoCommons collaborations and general DOME 4.0 ontology maintenance activities. However, this refinement activity is currently postponed.	
Welding Ontology	Manufacturing	Ã	Ã	Ã	Ã	The existing ontology needs to be aligned with a TLO/MLO	Proceed
TribOnt	Material Science	Ã	Ã	Ã	Ã	The new ontology will provide a common representation of tribological experiments, enable enriching existing data with additional background knowledge, and easing data retrieval and navigation through related resources to shorten the time, number and size of experiments required to identify the	Proceed

[2] See DOME 4.0 Deliverable D3.2 "Ecosystem information model ontology", https://dome40.eu/deliverables

						behaviour under specific operation conditions.	

3.2 Model-based systems engineering modeling tool ontology

3.2.1 Background

Model-based systems engineering integrates multi-disciplinary content to design and simulate complex systems, which can be challenging. Designers need information from multiple fields, such as mechanics, electricity, and control, and integrate them for a complete solution. These complex systems involve multiple domains, components, and processes, and are highly non-linear, dynamic, and uncertain. Different subject knowledge is applied to different modelling and simulation tools, resulting in semantic heterogeneity. Researchers often rely on their own experience and customary judgements, which leads to language ambiguity and affects communication efficiency and accuracy. Semantic heterogeneity is usually manifested in different aspects, such as the definition, quantity, unit, and expression of model variables.

3.2.1.1 **KARMA and GOPPRR-E methodology**

KARMA language, also known as Kombination of ARchitecture Model specificAtion, is a modelling language for system models. The KARMA language is a higher-level, text-based modelling language with object-oriented methods as the core. It supports descriptions of various system architecture perspectives, architecture model conversion, hybrid state-based machines, and static verification solutions based on meticulous model theory. The name KARMA represents the integration of architecture model specifications. Although the KARMA can be used to build different graphical architectural models such as SysML, UPDM, and BPMN, it supports different system engineering perspectives.

The core of the KARMA language is the GOPPRR-E ontology[3]. This is a modelling framework based on the meta-metamodel. The meta-metamodel refers to the constructed model combination and its basic elements that connect to each other, including graphs, objects, properties, points, relationships, roles, and related extensions.

3.2.1.2 **AMEsim, Simulink, and Openmodelica**

AMEsim[4] is a simulation software that utilizes physical phenomenon-based models. It uses a component-based modelling principle to describe and analyse multi-physical field coupling systems by constructing physical models. Each physical model represents a system component, such as an

[3] http://industryportal.enit.fr/ontologies/GOPPRRE_ONTOLOGY

[4] https://plm.sw.siemens.com/en-US/simcenter/systems-simulation/amesim/

engine, transmission system, suspension system, etc. These models can be combined freely to form a complex system model.

Simulink[5] is a simulation tool based on mathematical models and graphical modelling. It can simulate and analyse various complex dynamic systems and apply modular modelling principles to design. Simulink's simulation model consists of different blocks with which to build the entire system model. Users can establish system models by dragging and connecting different modules, with each module representing a component of the system. These modules can be basic mathematical operations, logical operations, signal processing, controllers, etc., or other elements such as custom subsystems. Simulink is typically used to control the modelling and simulation of the system.

Openmodelica[6] is an open-source simulation software that can be used for system-level modelling and simulation in various fields, supporting modelling in multiple fields and multi-physical phenomena. It theoretically integrates the advantages of AMEsim and Simulink, with the model being reusable and the modelling method being simple, requiring no symbolic processing. Users can use standard components in the model library to build system models, or they can customize components and functions to expand the model library. Openmodelica supports a variety of modelling languages. The compilation process of Openmodelica converts the model code written by the user into an executable code to run in the tool.

3.2.1.3 MetaGraph

MetaGraph is developed based on KARMA. It includes field modelling, architecture driver, code generation, indicator analysis verification, and demand management. It supports the automation generation of architecture models to other code, as well as automation transmission between architecture models. Additionally, MetaGraph provides network-end interoperability APIs, supporting the interoperability of KARMA data and visualization of the network model structure.

The core concept of MetaGraph is based on a text-readable formal language to model the needs, functions, logic, architecture, and other system engineering viewpoints of complex equipment. Simulation analysis and testing are used to verify the satisfaction and demand verification of the indicators. With KARMA, key information, such as early-stage system development, can be formed. It can also check whether the system design meets the demand specifications during the concept design phase before the system plan preliminary confirmation, thereby reducing the cost and risk of product development.

3.2.1.4 Rationale for ontology alignment and development

Applying tools such as AMEsim, Simulink, and Openmodelica for integrated simulation is a special situation of model establishment and simulation in multiple fields. These tools are widely used in the fields of mechanical, control, and power, but due to their differences in semantic differences, synergy

5 https://uk.mathworks.com/products/simulink.html
6 https://openmodelica.org/

simulation is difficult. Therefore, it is necessary to apply ontologies to achieve cross-domain model integration and simulation and to achieve semantic integration.

3.2.2 Ontology requirements specification

Using the hydraulic system as an example, which is a common complex system in the scientific field, the design of the hydraulic system may require simulation using AMEsim, while the design of the control system needs to be modelled using Simulink. For mechanical design, tools such as Openmodelica are required. However, the phenomenon of semantic heterogeneity among different tools can lead to difficulties in collaborative modelling.

For instance, consider the expression of pipeline components. In the AMEsim tool, pipeline components are composed of parameters such as length and cross-sectional area, and a set of differential equations is used to describe their dynamic behavior. In contrast, the Simulink tool abstracts the pipeline as a delay block. Finally, for the Openmodelica tool, the pipeline element is determined as an object by programming, and the code is written through the Modelica language to determine the location, function, attribute, and other related information of the object.

The differences among these tools lead to certain difficulties in collaborative modelling, resulting in low efficiency and difficult quality assurance.

Based on the background above, ontologies and semantic integration have become a necessary technical means to ensure that multidisciplinary tools can smoothly run in complex system design. Semantic integration includes the sharing, integration, exchange, and processing of information between two or more systems in a distributed heterogeneous environment, under a common understanding of the meaning of information. In the design of complex systems using multidisciplinary tools, professionals in different disciplines often use their own scientific terms and code languages, which can lead to difficulties in communication. Ontologies provide a standardized means of communication, enabling a common understanding and exchange of key concepts in system design between different disciplines. This standardized communication method can help the development team make full use of existing professional knowledge, reduce work duplication and waste to a considerable extent, share and use tools such as data, models, and algorithms, and help discover potential conflicts and defects, making system design more efficient and greatly improving its quality and reliability.

3.2.3 Ontology implementation

3.2.3.1 **Ontology implementation regarding Openmodelica**

i. Ontology conceptualization

Openmodelica uses its own Modelica language during development that cannot be directly understood and transformed by other tools. In order to be applied in MetaGraph, an alignment corresponding to GOPPRR-E needs to be constructed. This involves analysing the abstract semantics of the Modelica language, understanding the correspondence of the Modelica code model, finding out the grammatical expression structure, further abstracting the meta model of the Modelica language, and then aligning it to the GOPPRR-E ontology. The semantic instance is used to express the Modelica metaphysical model. A component in Openmodelica can be abstracted into a meta model in MetaGraph. Table 3 summarizes the alignment between the Modelica language and the GOPPRR-E ontology.

Table 3 Alignment between Modelica and the GOPPRR-E ontology

GOPPRR-E ontology	Modelica
Graph	Model
Object	Component/Block
Point	Connector
Relationship	Connection
Role	Variable
Property	Name, Type, Parameter
Extension	

After defining the above-mentioned alignment, the DoublePendulum model was used to further verify the accuracy of the alignment. Figure 4 shows the model diagram of the model in the Openmodelica tool, and Figure 5 shows the corresponding model in MetaGraph. The comparison of the two figures suggests that the alignment has achieved good results.

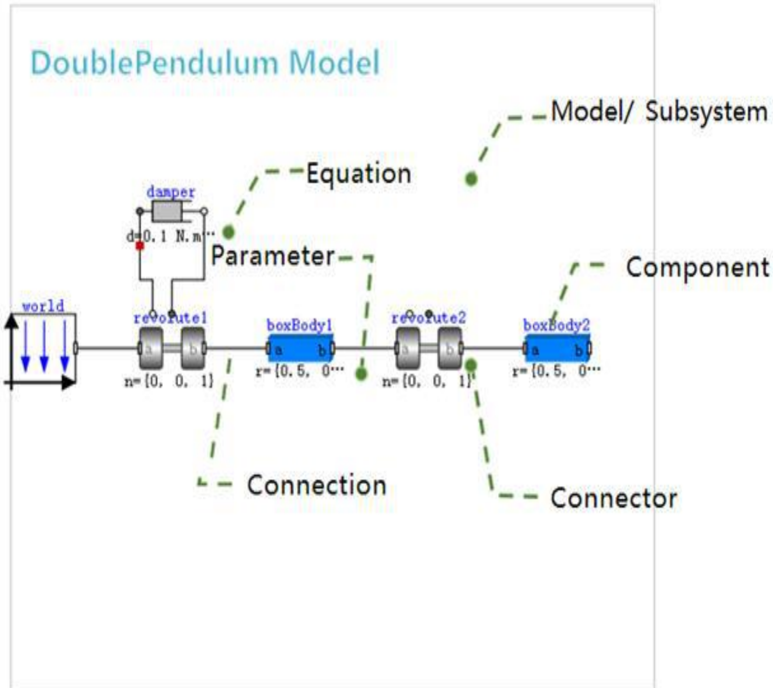

Figure 4 DoublePendulum model in Openmodelica

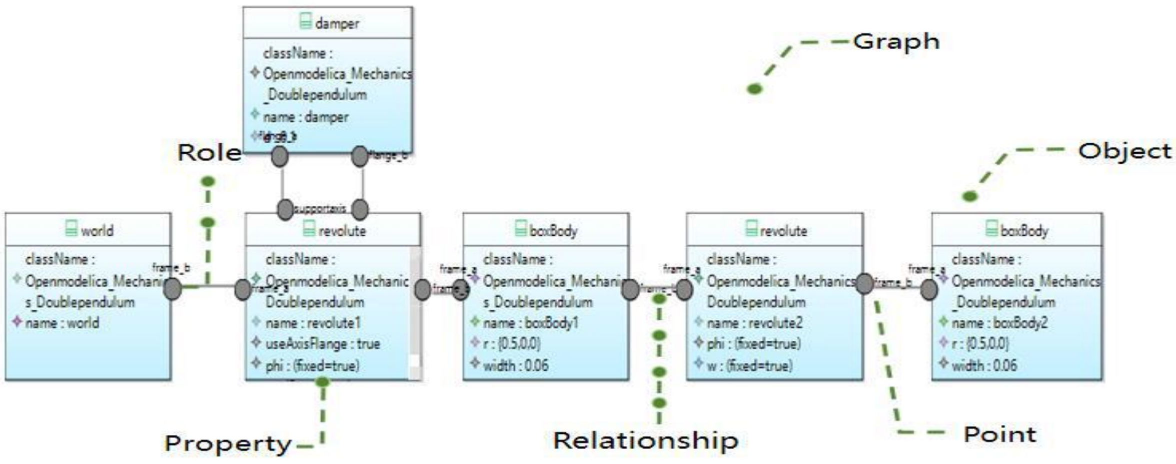

Figure 5 DoublePendulum model established in MetaGraph

ii. *Ontology encoding and reuse of GOPPRR-E*

The class hierarchy of Openmodelica constructed and aligned to GOPPRR-E ontology is shown in Figure 6.

Figure 6 Openmodelica class hierarchy

Reusing and aligning with GOPPRR-E, the Graph class corresponds to the Model class in the Openmodelica tool. That is, subsystem models, component models, and connections. This alignment is shown in Figure 7.

Figure 7 Class alignment of Graph in GOPPRR-E and Model in Openmodelica

Reusing and aligning with GOPPRR-E, the Object class corresponds to the Component/Block class in the Openmodelica tool. This alignment is shown in Figure 8.

Figure 8 Class alignment of Object in GOPPRR-E and Component/Block in Openmodelica

Reusing and aligning with GOPPRR-E, the Point class corresponds to the Connector class in the Openmodelica tool, which is an interface on the subsystem or component model. Figure 9 shows this alignment.

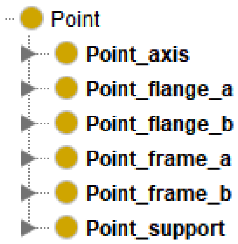

Figure 9 Class alignment of Point in GOPPRR-E and Connector in Openmodelica

Reusing and aligning with GOPPRR-E, the Property class corresponds to the name information of the Name, Type, Parameter, and Modification class in the Openmodelica tool. These can be types, equations, and modification statements that can be regarded as models. As shown in Figure 10, the Property model is obtained by extracting the DoublePendulum model.

Figure 10 Class alignment of Property in GOPPRR-E and relevant classes in Openmodelica

Reusing and aligning with GOPPRR-E, the Relationship class corresponds to the content of the Connection in the Openmodelica tool, which is the coupling relationship based on the connector. Figure 11 shows this alignment.

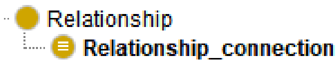

Figure 11 Class alignment of Relationship in GOPPRR-E and Connection in Openmodelica

Reusing and aligning with GOPPRR-E, the Role class corresponds to the variable content in the Openmodelica tool. Variables refer to the physical quantity or information flow of the connector. The two subclasses are owlRoleSubClassSource, named Role_In, and the owlRoleSubClassTarget, named Role_Out. Figure 12 and Figure 13 show the two classes and their instances.

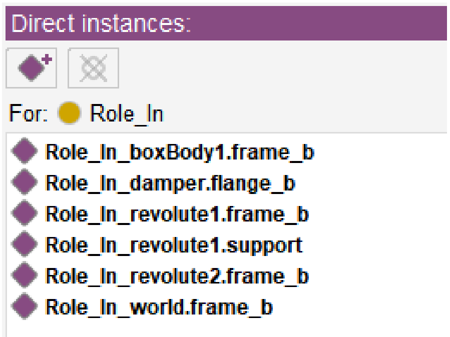

Figure 12 Class alignment of Role in GOPPRR-E and Role_In in Openmodelica

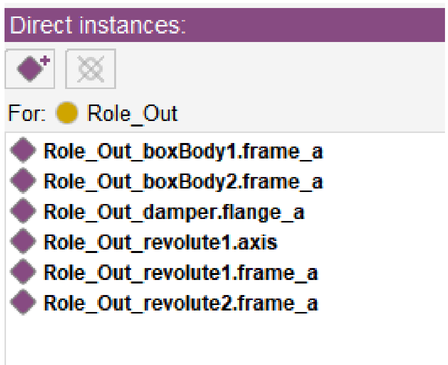

Figure 13 Class alignment of Role in GOPPRR-E and Role_Out in Openmodelica

The Connector class defines the connection relationship of the entire model, indicating that each class in the model does not exist as a separate individual, but has a specific connection relationship. Figure 14 shows the Connector class and their instances.

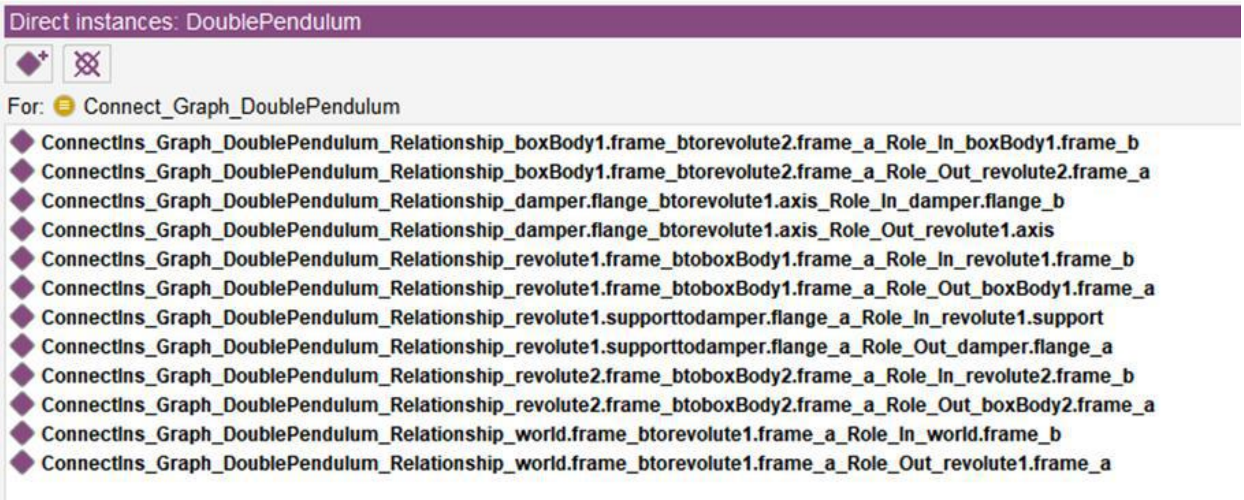

Figure 14 Definition of class Connector for Openmodelica

At present, these classes still exist independently and do not generate various relationships between them. The class expressions need to be established respectively.

The class expressions for Openmodelica regarding Graph, Object, Relationship, Language, and Connector are shown from Figure 15 to Figure 19.

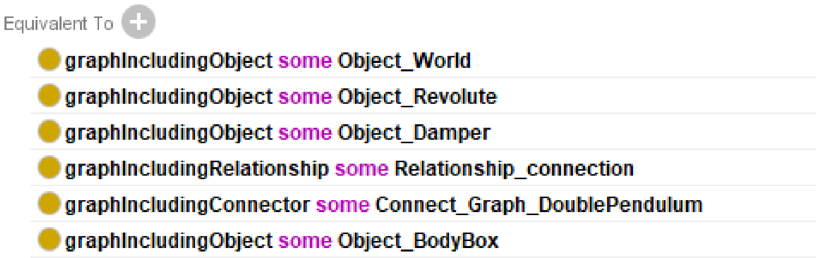

Figure 15 Class expressions regarding Graph for Openmodelica

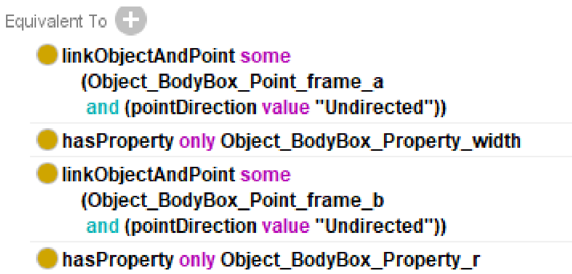

Figure 16 Class expressions regarding Object for Openmodelica

Equivalent To

- linkRelationshipAndRole some Role_Out
- linkRelationshipAndRole some Role_In

Figure 17 Class expressions regarding Relationship for Openmodelica

Equivalent To

- languageIncludingProperty some Property_width
- languageIncludingProperty some Property_d
- languageIncludingRole some Role_In
- languageIncludingPoint some Point_axis
- languageIncludingObject some Object_World
- languageIncludingProperty some Property_r
- languageIncludingRole some Role_Out
- languageIncludingPoint some Point_support
- languageIncludingProperty some Property_w
- languageIncludingGraph some Graph_DoublePendulum
- languageIncludingObject some Object_BodyBox
- languageIncludingPoint some Point_flange_b

Figure 18 Class expressions regarding Language for Openmodelica

```
Equivalent To
(linkFromRelationship some Relationship_connection)
  and (linkObjectAndPoint some Object_BodyBox_Point_frame_b)
  and (linkRelationshipAndRole some Role_Out)
  and (linkToObject some Object_BodyBox)
  and (roleBindingPoint some Object_BodyBox_Point_frame_b)
(linkFromRelationship some Relationship_connection)
  and (linkRelationshipAndRole some Role_In)
  and (linkToObject some Object_BodyBox)
  and (roleBindingObject some Object_BodyBox)
(linkFromRelationship some Relationship_connection)
  and (linkObjectAndPoint some Object_Damper_Point_flange_b)
  and (linkRelationshipAndRole some Role_Out)
  and (linkToObject some Object_Damper)
  and (roleBindingPoint some Object_Damper_Point_flange_b)
(linkFromRelationship some Relationship_connection)
  and (linkRelationshipAndRole some Role_In)
  and (linkToObject some Object_Damper)
  and (roleBindingObject some Object_Damper)
(linkFromRelationship some Relationship_connection)
  and (linkObjectAndPoint some Object_Damper_Point_flange_b)
  and (linkRelationshipAndRole some Role_In)
  and (linkToObject some Object_Damper)
  and (roleBindingPoint some Object_Damper_Point_flange_b)
(linkFromRelationship some Relationship_connection)
  and (linkObjectAndPoint some Object_Revolute_Point_frame_a)
  and (linkRelationshipAndRole some Role_In)
  and (linkToObject some Object_Revolute)
  and (roleBindingPoint some Object_Revolute_Point_frame_a)
(linkFromRelationship some Relationship_connection)
  and (linkObjectAndPoint some Object_Revolute_Point_support)
  and (linkRelationshipAndRole some Role_In)
  and (linkToObject some Object_Revolute)
  and (roleBindingPoint some Object_Revolute_Point_support)
(linkFromRelationship some Relationship_connection)
  and (linkRelationshipAndRole some Role_In)
  and (linkToObject some Object_Revolute)
  and (roleBindingObject some Object_Revolute)
```

Figure 19 Class expressions regarding Connector for Openmodelica

Take DoublePendulum model for an instance. The object property assertions regarding Graph, Object, Relationship and Connector are shown from Figure 20 to Figure 23.

Object property assertions

- graphIncludingRelationship Relationship_revolute2.frame_btoboxBody2.frame_a
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_revolute1.supporttodamper.flange_a_Role_Out_damper.flange_a
- graphIncludingObject Object_boxBody2
- graphIncludingRole Role_Out_revolute2.frame_a
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_world.frame_btorevolute1.frame_a_Role_In_world.frame_b
- graphIncludingRole Role_Out_boxBody1.frame_a
- graphIncludingRelationship Relationship_world.frame_btorevolute1.frame_a
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_revolute2.frame_btoboxBody2.frame_a_Role_Out_boxBody2.frame_a
- graphIncludingRelationship Relationship_revolute1.supporttodamper.flange_a
- graphIncludingObject Object_world
- graphIncludingRelationship Relationship_damper.flange_btorevolute1.axis
- graphIncludingRole Role_Out_boxBody2.frame_a
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_revolute1.supporttodamper.flange_a_Role_In_revolute1.support
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_revolute1.frame_btoboxBody1.frame_a_Role_Out_boxBody1.frame_a
- graphIncludingObject Object_revolute2
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_world.frame_btorevolute1.frame_a_Role_Out_revolute1.frame_a
- graphIncludingRole Role_In_revolute2.frame_b
- graphIncludingObject Object_damper
- graphIncludingObject Object_boxBody1
- graphIncludingRole Role_In_world.frame_b
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_damper.flange_btorevolute1.axis_Role_In_damper.flange_b
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_revolute2.frame_btoboxBody2.frame_a_Role_In_revolute2.frame_b
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_boxBody1.frame_btorevolute2.frame_a_Role_Out_revolute2.frame_a
- graphIncludingRole Role_Out_revolute1.axis
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_damper.flange_btorevolute1.axis_Role_Out_revolute1.axis
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_boxBody1.frame_btorevolute2.frame_a_Role_In_boxBody1.frame_b
- graphIncludingConnector ConnectIns_Graph_DoublePendulum_Relationship_revolute1.frame_btoboxBody1.frame_a_Role_In_revolute1.frame_b
- graphIncludingRole Role_In_revolute1.frame_b
- graphIncludingRole Role_Out_revolute1.frame_a
- graphIncludingRelationship Relationship_boxBody1.frame_btorevolute2.frame_a
- graphIncludingRole Role_Out_damper.flange_a
- graphIncludingObject Object_revolute1

Figure 20 Object property assertions regarding Graph for DoublePendulum model in Openmodelica

Object property assertions

- linkObjectAndPoint Point_damper.flange_b
- linkObjectAndPoint Point_damper.flange_a
- hasProperty Object_damper_Property_d

Figure 21 Object property assertions regarding Object for DoublePendulum model in Openmodelica

Object property assertions

- linkRelationshipAndRole Role_In_boxBody1.frame_b
- linkRelationshipAndRole Role_Out_revolute2.frame_a

Figure 22 Object property assertions regarding Relationship for DoublePendulum model in Openmodelica

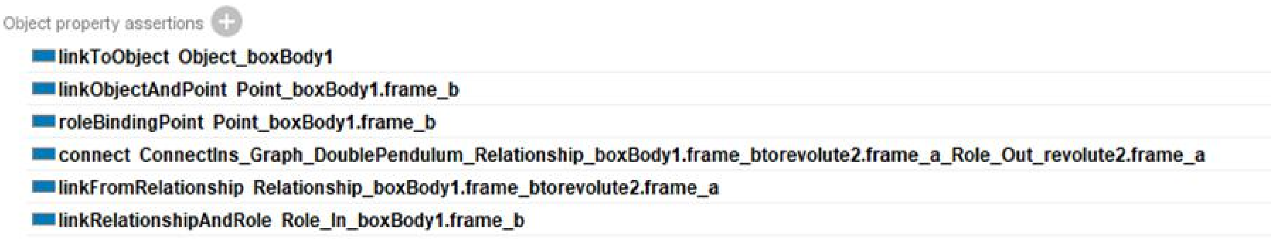

Figure 23 Object property assertions regarding Connector for DoublePendulum model in Openmodelica

At this point, we have been able to generate the ontology completely and strictly aligned with GOPPRR-E.

3.2.3.2 Ontology implementation regarding Simulink

i. Ontology conceptualization

When using the Simulink tool for modelling, each component exists in the form of a module. This module includes the model component and its parameter settings, but it does not display the code language of the complete model. Sometimes, due to a lack of information, the model file is derived in text format. In order to obtain the original information of the Simulink model, it must be mapped to the GOPPRR-E and opened in compressed form. The compressed model can then be stored in the blockdiagram document in XML format. By reading the content of the document, one can understand the implementation principle and grammar expression structure of Simulink, and establish an alignment as shown in Table 4.

Table 4 Alignment between Simulink and the GOPPRR-E ontology

GOPPRR-E ontology	Simulink
Graph	Model/System
Object	Object/Block
Point	
Relationship	Line
Role	Src#out/Dst#in
Property	P name
Extension	

The models in the Simulink Model Library are relatively complex and not suitable for simple examples. Therefore, it's best to learn how to build a simple control model in the Simulink tool. Figure 24 shows the simple control model established in Simulink. The actual physical significance of the model is that the output signal is controlled by the proportional unit P. The dynamic performance of the controlled object is described through the Transfer FCN (transmitting function module) and delayed the object, and the waveform display is performed on the oscilloscope. Figure 25 shows the simple control model created in MetaGraph.

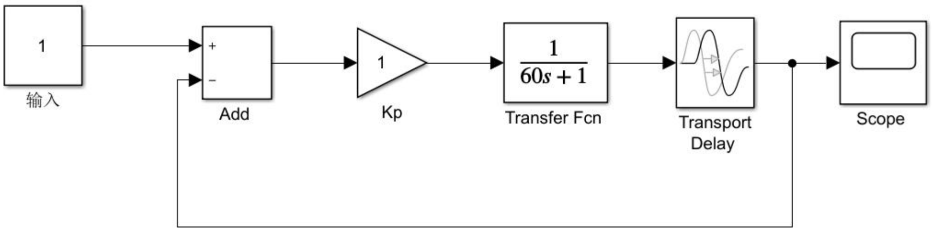

Figure 24 A simple control model in Simulink

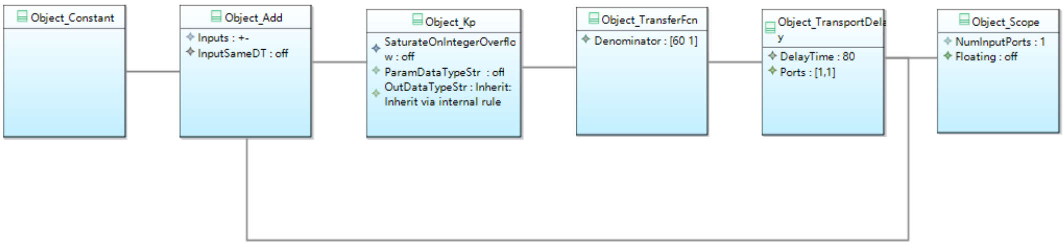

Figure 25 A simple control model established in MetaGraph

It should be noted that the concept of the Point model is severely weakened in the Simulink tool.

ii. Ontology encoding and reuse of GOPPRR-E

Reusing and aligning with GOPPRR-E, the Graph class corresponds to the Model/System class in the Simulink tool. This represents the model or system, covering all the objects and connections in the model. Figure 26 shows the alignment with the Graph class.

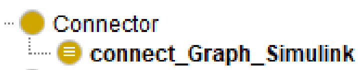

Figure 26 Class alignment of Graph in GOPPRR-E and Model/System in Simulink

Reusing and aligning with GOPPRR-E, the Object/Block class corresponds to the Object class, which signs a module independent of its own information and functions in the model. Figure 27 shows the alignment with the Object class.

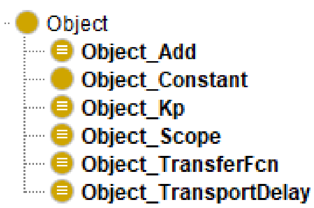

Figure 27 Class alignment of Object in GOPPRR-E and Object/Block in Simulink

Model Reusing and aligning with GOPPRR-E, the Property class corresponds to the P Name in the Simulink tool, characterizing the attribute information that the name, parameter, and modification statements can be regarded as objects. Figure 28 shows the alignment with the Object class.

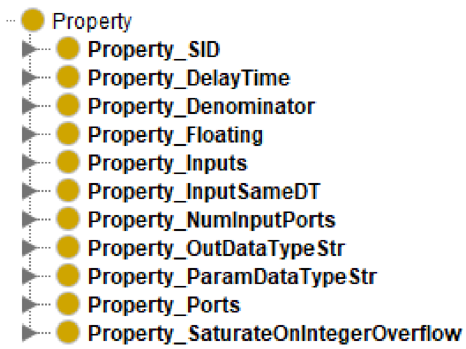

Figure 28 Class alignment of Property in GOPPRR-E and P Name in Simulink

Reusing and aligning with GOPPRR-E, the Relationship model corresponds to the Line class in the Simulink tool, which signs a coupling relationship based on different modules. Figure 29 shows the alignment with the Relationship model.

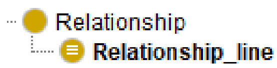

Figure 29 Class alignment of Relationship in GOPPRR-E and Line in Simulink

Model Reusing and aligning with GOPPRR-E, the Role model corresponds to the input or output of the energy/current corresponding to the connection relationship in the SRC#OUT/DST#in content in the Simulink tool. Figure 30 shows the alignment with the Role class.

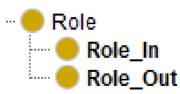

Figure 30 Class alignment of Role in GOPPRR-E and relevant classes in Simulink

Similar to Openmodelica, the Connector class is additionally added. The Connector class defines the connection relationship of the entire model, indicating that each class in the model does not exist in a separate individual but a specific connection relationship. Figure 31 shows the Connector class.

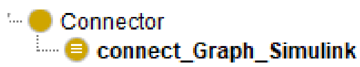

Figure 31 Definition of class Connector for Simulink

At present, these meta models still exist independently and do not generate various relationships between different classes. The class expressions need to be established respectively. Except for the relevant content of the Point model, other processes and content are the same as the Openmodelica tools. The class expressions are not repeated or explained. Figure 32 to Figure 39 show the class expressions for Simulink regarding Graph, Object, Relationship, and Connector.

Equivalent To

- graphIncludingObject some Object_Add
- graphIncludingObject some Object_Kp
- graphIncludingConnector some connect_Graph_Simulink
- graphIncludingObject some Object_Constant
- graphIncludingObject some Object_Scope
- graphIncludingObject some Object_TransportDelay
- graphIncludingObject some Object_TransferFcn
- graphIncludingRelationship some Relationship_line

Figure 32 Class expressions regarding Graph for Simulink

Equivalent To

- hasProperty only Object_Add_Property_InputSameDT
- hasProperty only Object_Add_Property_Inputs

Figure 33 Class expressions regarding Object for Simulink

Equivalent To

- linkRelationshipAndRole some Role_Out
- linkRelationshipAndRole some Role_In

Figure 34 Class expressions regarding Relationship for Simulink

```
Equivalent To
(linkFromRelationship some Relationship_line)
 and (linkRelationshipAndRole some Role_Out)
 and (linkToObject some Object_Scope)
 and (roleBindingObject some Object_Scope)
(linkFromRelationship some Relationship_line)
 and (linkRelationshipAndRole some Role_In)
 and (linkToObject some Object_TransportDelay)
 and (roleBindingObject some Object_TransportDelay)
(linkFromRelationship some Relationship_line)
 and (linkRelationshipAndRole some Role_In)
 and (linkToObject some Object_Kp)
 and (roleBindingObject some Object_Kp)
(linkFromRelationship some Relationship_line)
 and (linkRelationshipAndRole some Role_Out)
 and (linkToObject some Object_Kp)
 and (roleBindingObject some Object_Kp)
(linkFromRelationship some Relationship_line)
 and (linkRelationshipAndRole some Role_In)
 and (linkToObject some Object_Scope)
 and (roleBindingObject some Object_Scope)
(linkFromRelationship some Relationship_line)
 and (linkRelationshipAndRole some Role_Out)
 and (linkToObject some Object_TransportDelay)
 and (roleBindingObject some Object_TransportDelay)
(linkFromRelationship some Relationship_line)
 and (linkRelationshipAndRole some Role_In)
 and (linkToObject some Object_Add)
 and (roleBindingObject some Object_Add)
```

Figure 35 Class expressions regarding Connector for Simulink

Take the simple control model for an instance. The object property assertions regarding Graph, Object, Relationship and Connector are shown from Figure 36 to Figure 39.

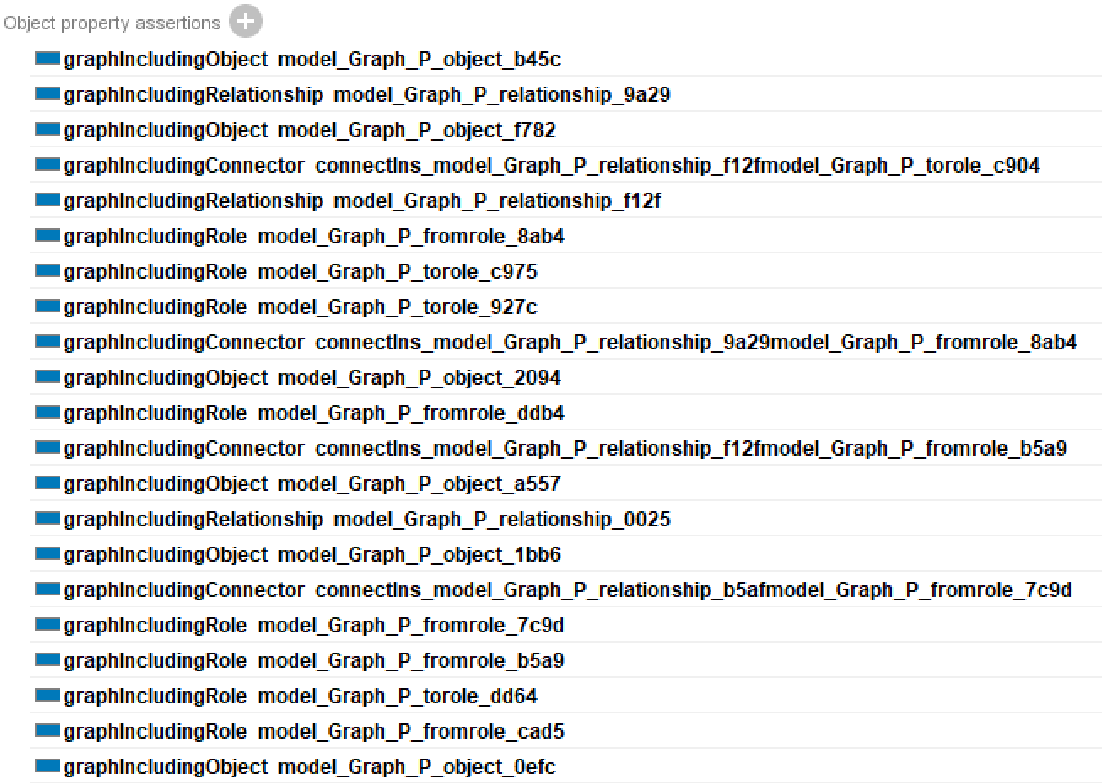

Figure 36 Object property assertions regarding Graph for a simple control model in Simulink

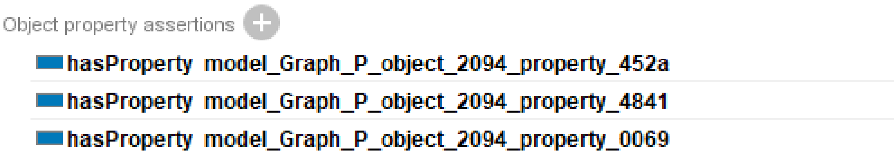

Figure 37 Object property assertions regarding Property for a simple control model in Simulink

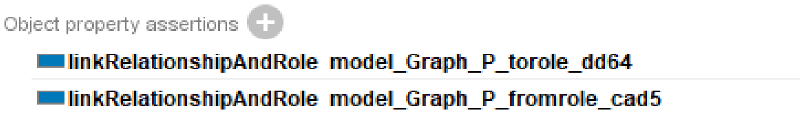

Figure 38 Object property assertions regarding Relationship for a simple control model in Simulink

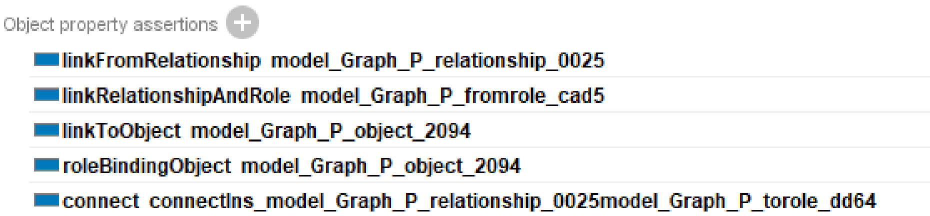

Figure 39 Object property assertions regarding Connector for a simple control model in Simulink

At this point, all classes and instances has been completed, and we have been able to generate the ontology completely and strictly aligned with GOPPRR-E.

3.2.3.3 Ontology implementation regarding AMEsim

i. Ontology conceptualization

When using AMEsim for modeling, the tool emphasizes the setting of model parameters. The text information associated with the AMEsim model can be quite complex, consisting of storage components, connection relationships, and other parameter-related data that is stored separately. It is necessary to establish an alignment between the AMEsim tool and the GOPPRR-E ontology (shown in Table 5).

Table 5 Alignment between AMEsim and the GOPPRR-E ontology

GOPPRR-E ontology	AMEsim
Graph	System
Object	Component
Point	
Relationship	Connect
Role	Variable
Property	Parameter
Extension	Simulation

The model in the model library of the AMEsim is complicated, and there is no relevant annotation information. Only simulation operation and parameter settings make it difficult to understand. Therefore, in order to verify the accuracy of the above definition rules, a simple mechanical dynamic model (Mechanics) is created in the AMEsim tool, as shown in Figure 40. The understanding of this model is to connect the quality block on the spring, and the spring movement is driven by the left input signal source to generate elasticity to drive the quality block motion.

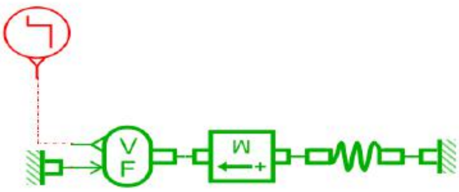

Figure 40 Mechanics model in AMEsim

Based on the completed alignment in Table 5, conceptual modeling is carried out using the MetaGraph tool, as illustrated in Figure 41, where a model diagram is generated that does not take into account the specific value of the coordinate. It is evident that the alignment is more reasonable, and the definition rules effectively capture the AMEsim component relationship.

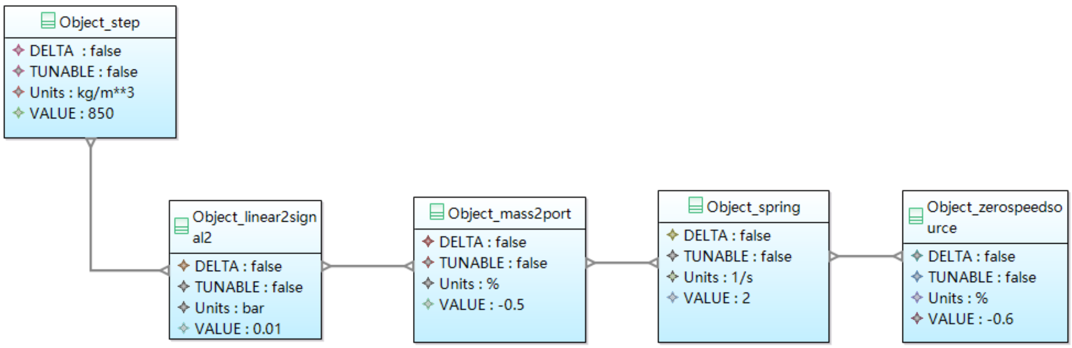

Figure 41 Mechanics model established in MetaGraph

It should be noted that the concept of the Point model is also severely weakened in the AMEsim tool, similar to Simulink.

ii. Ontology encoding and reuse of GOPPRR-E

Reusing and aligning with GOPPRR-E, the Graph class corresponds to the System class in the AMEsim tool, which integrates all information from the entire model. Figure 42 shows the alignment with the Graph class, obtained by extracting the Mechanics model.

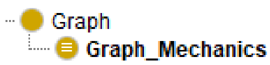

Figure 42 Class alignment of Graph in GOPPRR-E and System in AMEsim

AMEsim places a strong emphasis on simulation processes and data processing, setting it apart from other tools. To create the Graph model, it is necessary to extract certain information from the original model, including the simulation time, whether the simulation status is on or off, and the simulation interval details. This extracted information is referred to as the Property model. This will be explained later.

Reusing and aligning with GOPPRR-E, the Object class corresponds to the Component class in the AMEsim tool. It characterizes a module that contains various parameters and properties. In addition to the concept of a component, AMEsim also has the concept of a subsystem, which needs to be clearly distinguished. The subsystem concept also includes annotation information for related parameters. However, similar to Simulink, the subsystem concept only indicates which larger system the component belongs to. Figure 43 shows the alignment with the Object class.

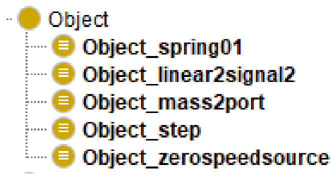

Figure 43 Class alignment of Object in GOPPRR-E and Component in AMEsim

Reusing and aligning with GOPPRR-E, the Property class corresponds to Parameter information in the AMEsim tool. This information includes measuring outlines, values, and judgment statements. Furthermore, AMEsim emphasizes the simulation process. Figure 44 shows the alignment with the Property model.

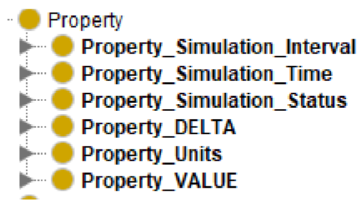

Figure 44 Class alignment of Property in GOPPRR-E and Parameter in AMEsim

Reusing and aligning with GOPPRR-E, the Relationship class corresponds to the Connect class in the AMEsim tool. This class represents a coupling relationship based on different modules. Similar to Simulink, the relationship is not the result of point-to-point connections, but is directly established between the two objects. Figure 45 shows the alignment with the Relationship class.

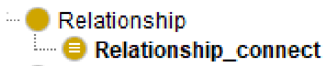

Figure 45 Class alignment of Relationship in GOPPRR-E and Connect in AMEsim

Reusing and aligning with GOPPRR-E, the Role model represents the variables in the AMEsim tool and expresses the input or output of physical quantities in the real world. Figure 46 shows the alignment with Role model.

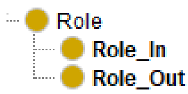

Figure 46 Class alignment of Role in GOPPRR-E and Variable in AMEsim

An additional Connector class is generated for defining the connection relationships of the entire model, indicating that each class in the model has a specific correlation. It contains the information of the entire model, which corresponds to the concept of the Figure element model in the original model. Figure 47 shows the Connector class.

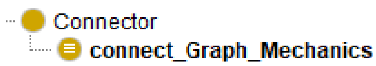

Figure 47 Definition of class Connector for AMEsim

At present, these meta models still exist independently and do not generate various relationships between different classes. The class expressions need to be established respectively. This is exactly the same as the previous two tools. Figure 48 to Figure 53 show the class expressions for AMEsim regarding Graph, Object, Relationship, Language and Connector.

Equivalent To

- hasProperty only Graph_Mechanics_Property_Simulation_Interval
- graphIncludingObject some Object_linear2signal2
- graphIncludingObject some Object_mass2port
- graphIncludingRelationship some Relationship_Connect
- graphIncludingObject some Object_step
- hasProperty only Graph_Mechanics_Property_Simulation_Time
- hasProperty only Graph_Mechanics_Property_Simulation_Status
- graphIncludingObject some Object_zerospeedsource
- graphIncludingObject some Object_spring01
- graphIncludingConnector some connect_Graph_Mechanics

Figure 48 Class expressions regarding Graph for AMEsim

Equivalent To

- hasProperty only Object_linear2signal2_Property_DELTA
- hasProperty only Object_linear2signal2_Property_UNITS
- hasProperty only Object_linear2signal2_Property_VALUE

Figure 49 Class expressions regarding Object for AMEsim

Equivalent To

- linkRelationshipAndRole some Role_Out
- linkRelationshipAndRole some Role_In

Figure 50 Class expressions regarding Relationship for AMEsim

Equivalent To

- languageIncludingObject some Object_zerospeedsource
- languageIncludingProperty some Property_VALUE
- languageIncludingProperty some Property_Simulation_Time
- languageIncludingProperty some Property_Simulation_Interval
- languageIncludingObject some Object_step
- languageIncludingObject some Object_mass2port
- languageIncludingRole some Role_In
- languageIncludingProperty some Property_UNITS
- languageIncludingObject some Object_spring01
- languageIncludingRole some Role_Out
- languageIncludingProperty some Property_DELTA
- languageIncludingProperty some Property_Simulation_Status
- languageIncludingObject some Object_linear2signal2
- languageIncludingRelationship some Relationship_Connect
- languageIncludingGraph some Graph_Mechanics

Figure 51 Class expressions regarding Language for AMEsim

Equivalent To

- (linkFromRelationship some Relationship_Connect)
 and (linkRelationshipAndRole some Role_Out)
 and (linkToObject some Object_zerospeedsource)
 and (roleBindingObject some Object_zerospeedsource)
- (linkFromRelationship some Relationship_Connect)
 and (linkRelationshipAndRole some Role_In)
 and (linkToObject some Object_zerospeedsource)
 and (roleBindingObject some Object_zerospeedsource)
- (linkFromRelationship some Relationship_Connect)
 and (linkRelationshipAndRole some Role_Out)
 and (linkToObject some Object_spring01)
 and (roleBindingObject some Object_spring01)

Figure 52 Class expressions regarding Connector for AMEsim

Take the Mechanics model for an instance. The object property assertions regarding Graph are shown in Figure 53.

Object property assertions

- hasProperty model_Graph_Mechanics_property_0d06
- hasProperty model_Graph_Mechanics_property_0b2e
- hasProperty model_Graph_Mechanics_property_c1fa

Figure 53 Object property assertions regarding Graph for Mechanics model in AMEsim

3.3 System life cycle processes ontology

In this section, we explore a scenario that demonstrates the practical use of the developed ontology for the system life cycle processes. The scenario focuses on how the ontology enables a dynamic and robust representation of the system life cycle processes. First, we provide an overview of these processes. Then, we propose a semantic network that connects them. Third, we demonstrate the ontology for the system life cycle processes. Finally, we reveal the interrelations between the system life cycle processes by utilizing the reasoning and inferring features of ontologies.

3.3.1 Ontology requirements specification

ISO/IEC/IEEE 15288:2015 is an international standard for systems and software engineering that outlines the system life cycle processes created by humans. This standard aims to help different stakeholders communicate effectively throughout a system's life cycle. It also provides guidance on how to tailor these processes to suit different systems engineering projects. As described in the INCOSE Systems Engineering Handbook and ISO/IEC/IEEE 15288, the system life cycle processes are grouped into four categories: technical processes, technical management processes, agreement processes, and organizational project-enabling processes. Although ISO/IEC/IEEE 15288 provides a high-level description of processes, the INCOSE Systems Engineering Handbook provides more detailed guidance on the practices and activities required to effectively implement these processes in accordance with the international standard. A common format is used to describe the system life cycle processes, which is illustrated in Figure 54.

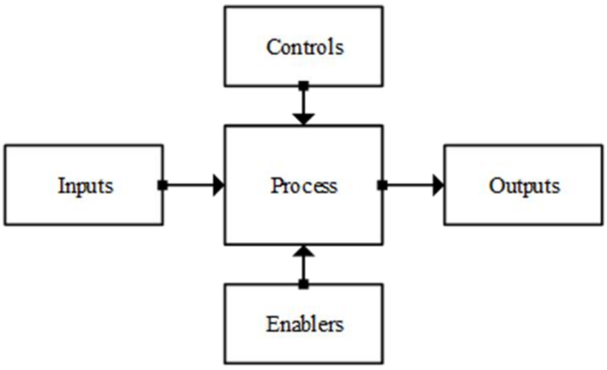

Figure 54 Sample of an IPO diagram

This diagram is called an IPO diagram, which stands for the input-process-output diagram. It displays the key inputs, resulting outputs, necessary controls, and essential enablers of a system life cycle process. Inputs, outputs, controls, and enablers are considered indispensable elements when describing a process. In other words, an input, output, control, or enabler can be seen as a specialized role played by a continuant in a system life cycle process. Sometimes, a continuant acts as both inputs and outputs for two or more processes when the continuant has sequential relationships. However, an IPO diagram can only show one life cycle process at a time and cannot represent the whole network of which all the continuant consists. This can lead to important relations being missing in the IPO diagrams and the current knowledge representation lacking the capability to describe the system life cycle processes as a semantic network. In particular, the relations between sub-processes are missing, as shown in Figure 55.

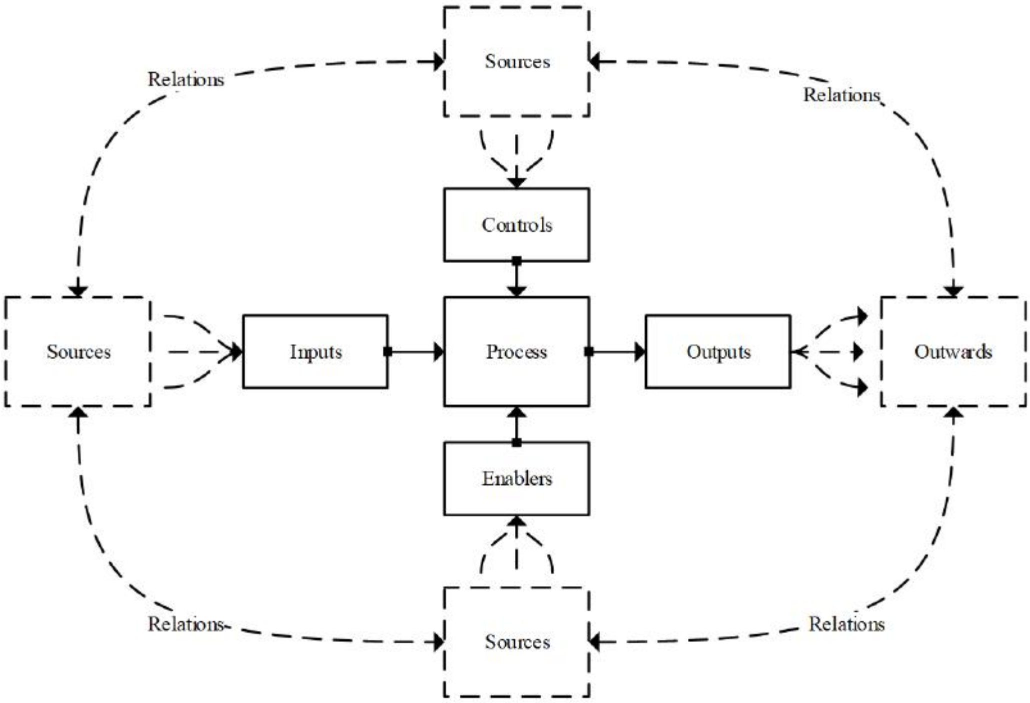

Figure 55 Extension of IPO diagram with potential relations

Within the middle lies a single IPO diagram whose boundary is limited to the continuant presented within. However, outside this boundary, all inputs, controls, and enablers must have sources that import them into the process of interest. Additionally, every output must have some destination, whether exported to another process, a few processes, or even beyond the whole system life cycle processes.

Based on this analysis, improvements and optimizations can be made to transform stand-alone IPO diagrams into a network. Doing so will reveal the relations implicitly contained within the process. To be specific, the list of requirements identified during the requirement specification activity that should be satisfied by the system life cycle processes ontology is as follows, shown in Table 6. Table 7 details the ontology requirement specification document functional use case.

Table 6 Ontology requirement specification document for system life cycle processes ontology

Ontology Requirements Specification Document	
1	Purpose (mandatory)
	According to ISO/IEC/IEEE 15288, a set of system life cycle processes are recommended for systems and software engineering. The processes are organised into four groups of subprocesses. Each subgroup has further subprocesses. All the processes follow a particular structure of definition, called Input-Process-Output diagram (IPO diagram). However, as the number of the subprocesses is large and the inputs and outputs associated to the processes are complex, it is not easy to understand the standard and clarify the internal relationships between processes. Therefore, the purpose for creating a system life cycle processes (SLCP) ontology is to help standard users to better understand the relationships within the processes.
2	Scope (mandatory)

	The scope of the SLCP ontology is what is defined in ISO/IEC/IEEE 15288 and INCOSE Systems Engineering Handbook regarding the processes, inputs, outputs, controls and enablers of system life cycle processes.
3	Implementation Language (optional)
4	Intended End-Users (optional)
5	Intended Uses
	Systems engineers, project manager, software developer
6	Ontology Requirements
	1. Non-Functional Requirements
	1. Functional Requirements: Lists or tables of requirements written as Competency Questions and sentences
7	Pre-Glossary of Terms (optional)
	1. Terms from Competency Questions
	1. Terms from Answers
	1. Objects

Table 7 Ontology requirement specification document functional use case for system life cycle processes ontology

Identifier (domain+id)	Sprint	Competency Question / Natural language sentence (fact)	Answer	Status	Superseded by	Comments	Extracted from (provenance)	Priority (High, Medium, Low)
slcp1		What is an Agreement Process?	The Agreement Processes consist of the following: a) Acquisition process - used by organizations for acquiring products or services; b) Supply process - used by organizations for supplying products or services. These processes define the activities necessary to establish an				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	High

			agreement between two organizations. If the Acquisition process is invoked, it provides the means for conducting business with a supplier. This may include products that are supplied for use as an operational system, services in support of operational activities, or elements of a system being provided by a supplier. If the Supply process is invoked, it provides the means for an agreement in which the result is a product or service that is provided to the acquirer.					
slcp2		What are the different types of Agreement Process?	Acquisition process, Supply process				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	High
slcp3		What is a Supply process?	As stated in ISO/IEC/IEEE 15288, the purpose of the Supply process is to provide an acquirer with a product or service that meets agreed requirements. The supply process is invoked to establish an agreement between two organizations under which one party supplies products or services to the other.				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	Medium
slcp4		What are the different activities of Supply process?	Prepare for the supply Respond to a tender Establish and maintain an agreement Execute the agreement Deliver and support the product or service				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	High

slcp5		What is the input(s) of Supply process?	Organization strategic plan, Request for supply, Supply payment, Validated system, Disposed system				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	High
slcp6		What type(s) of input(s) does Supply process take?	Information content entity, System			Depending on the classes in the upper level ontologies		Medium
slcp7		Where does the input(s) of Supply process come from?	Other system life cycle processes, External sources			From observation		Medium
slcp8		What is the output(s) of Supply process?	Supply strategy, Supply response, Supply agreement, Supplied system, Supply report, Supply record				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	High
slcp9		What type(s) of output(s) does Supply process take?	Information content entity, System			Depending on the classes in the upper level ontologies		Medium
slcp10		Where does the outputs(s) of Supply process go to?	Other system life cycle processes, External sources			From observation		Medium
slcp11		What is the control(s) of Supply process?	Applicable laws and regulations, Standards, Agreements, Project direction, Project control requests				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	High
slcp12		What type(s) of control(s) does Supply process take?	Information content entity			Depending on the classes in the upper level		Medium

						ontologies		
slcp13		Where does the control(s) of Supply process come from?	Other system life cycle processes, External sources			From observation		Medium
slcp14		What is the enabler(s) of Supply process?	Organization policies, procedures, and assets, Organization infrastructure, Project infrastructure, Knowledge management system				ISO/IEC/IEEE 15288, INCOSE Systems Engineering Handbook	High
slcp15		What type(s) of enabler(s) does Supply process take?	Information content entity			Depending on the classes in the upper level ontologies		Medium
slcp16		Where does the enabler(s) of Supply process come from?	Other system life cycle processes, External sources			From observation		Medium
slcp17		If Supply process is tailored, what processes will be impacted?				In need of reasoning		Medium

3.3.2 Ontology implementation

The ontology implementation phase is crucial for a successful ontology development. It is important to start with a clear and concise ontology conceptualization to ensure that all information is accurately represented. Fortunately, there are many supporting tools available that can facilitate graphical conceptualization, one of which is Chowlk. Using Chowlk, one can easily create visual representations of complex ideas, as shown in Figure 56, which demonstrates the example of conceptualizing Agreement Processes in the system life cycle processes ontology.

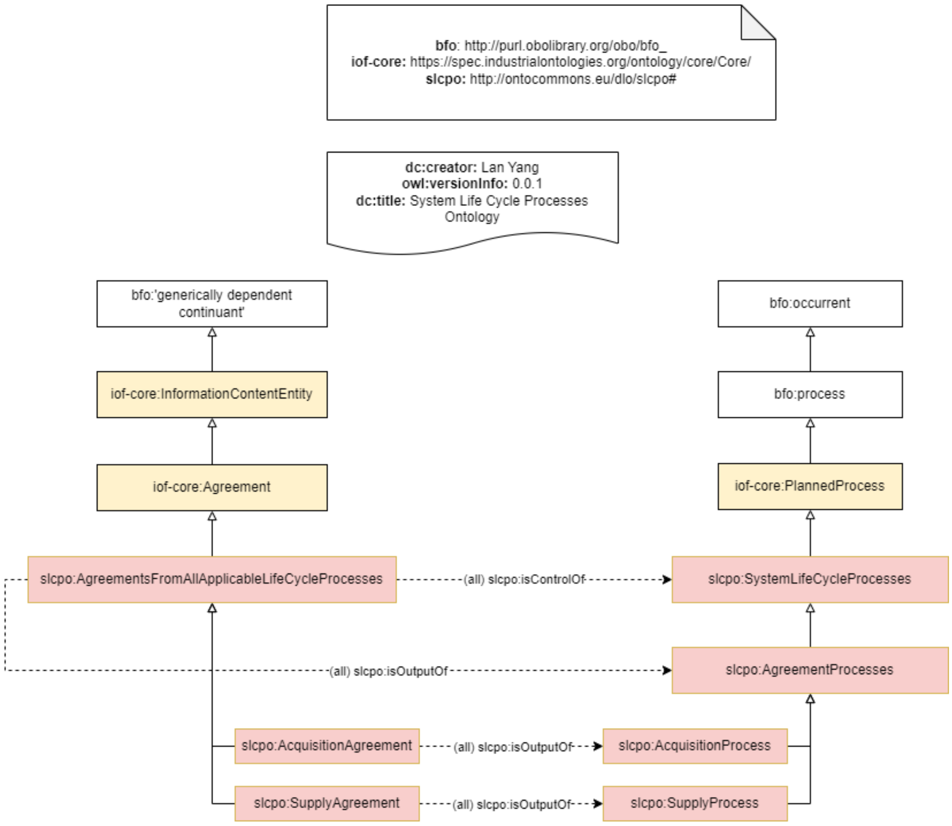

Figure 56 Ontology conceptualization using Chowlk, example of agreement processes

The system life cycle ontology consists of two main categories of classes: continuant and occurrent. Continuant entities are those that persist or endure through time while maintaining their identity. This can include things like agreements or contracts. Occurrent entities, on the other hand, are those that unfold over time or represent a temporal or spatiotemporal region. For example, a process would fall under this category.

To further elaborate on the class hierarchy of the system life cycle processes ontology, it remains at the domain level and is built upon the IOF-core ontology as a middle level. The IOF-core ontology, in turn, is based on the basic formal ontology at the top level. This hierarchical structure proposed by OCES allows for a more organized and comprehensive understanding of the ontology.

While there are a total of 268 domain-level classes within the ontology, it is not necessary to present all of them in great detail within a single report. However, it is worth noting some representative examples of classes and their direct subclasses. These can be seen in Table 8 below. By providing a brief overview of some of the classes within the ontology, we can paint a more complete picture of the system life cycle ontology as a whole.

Table 8 Human-readable description of the classes of the ontology (excerpt)

Class label	Class natural language definition
Examples of subclass of an information content entity:	

AgreementsFromAllApplicableLifeCycleProcesses	Agreements from all applicable life cycle processes, including acquisition agreements and supply agreements
AcquisitionAgreement	An understanding of the relationship and commitments between the project organization and the supplier. The agreement can vary from formal contracts to less formal interorganizational work orders. Formal agreements typically include terms and conditions
SupplyAgreement	An understanding of the relationship and commitments between the project organization and the acquirer. The agreement can vary from formal contracts to less formal interorganizational work orders. Formal agreements typically include terms and conditions
Examples of subclass of a material entity:	
AcceptedSystemOrSystemElement	System element or system is transferred from supplier to acquirer and the product or service is available to the project
AcquiredSystem	The system or system element (product or service) is delivered to the acquirer from a supplier consistent with the delivery conditions of the acquisition agreement
DisposedSystem	Disposed system that has been deactivated, disassembled, and removed from operations
InstalledSystem	Installed system ready for validation
IntegratedSystemOrSystemElement	Integrated system element or system ready for verification. The resulting aggregation of assembled system elements
KnowledgeManagementSystem	Maintained knowledge management system. Project suitability assessment results for application of existing knowledge. Lessons learned from execution of the organizational Se processes on projects. Should include mechanisms to easily identify and access the assets and to determine the level of applicability for the project considering its use. Can be used by any life cycle process
SuppliedSystem	The system or system element (product or service) is delivered from the supplier to the acquirer consistent with the delivery conditions of the supply agreement
SystemElements	System elements implemented or supplied according to the acquisition agreement
ValidatedSystem	Validated system ready for supply and operation. Also informs maintenance and disposal
VerifiedSystem	Verified system (or system element) ready for transition
Examples of subclass of a process:	
SystemLifeCycleProcesses	The System Life Cycle Processes are described in relation to a system that is composed of a set of inter-acting system elements, each of which can be implemented to fulfil its respective specified requirements

AgreementProcesses	The Agreement Processes define the activities necessary to establish an agreement between two organizations
OrganizationProjectEnablingProcesses	The Organizational Project-Enabling Processes help ensure the organization's capability to acquire and supply products or services through the initiation, support and control of projects. They provide resources and infrastructure necessary to support project
TechnicalManagementProcesses	The Technical Management Processes are used to establish and evolve plans, to execute the plans, to assess actual achievement and progress against the plans and to control execution through to fulfilment. Individual Technical Management Processes may be invoked at any time in the life cycle and at any level
TechnicalProcesses	The Technical Processes are used to define the requirements for a system, to transform the requirements into an effective product, to permit consistent reproduction of the product where necessary, to use the product to provide the required services, to sustain the provision of those services and to dispose of the product when it is retired from service

The system life cycle processes ontology does not introduce any unnecessary new object properties or data properties. Instead, it makes use of properties that already exist in the middle or top level ontologies, thus promoting reusability and interoperability.

Table 9 showcases some of the most important properties that are utilized in the system life cycle processes ontology. However, it is important to note that this table is not an exhaustive list of all the properties used in the ontology, as there are many other properties that are employed in defining the top and middle level ontologies. These definitions are inhabited by subclasses that are defined in the domain level, thereby ensuring that the ontology is robust.

Table 9 Human-readable description of the properties of the ontology (excerpt)

Property label	Property natural language definition	Subproperty of	Inverse of	Domain	Range
has input	relation from a process to someone or something physical or digital (continuant) that is a necessary precondition for the process to start	has participant at some time	is input of	process	continuant
has output	relation from a process to someone or something physical or digital (continuant) that	has participant at some time	is output of	process	continuant

	participates in the process such that it is generated or modified during the process, and that it exists at the end of the process				
has control	relation from a process to someone or something physical or digital (continuant) that is a monitor and adjustment for the process to give a desired output	has participant at some time	is control of	process	continuant
has enabler	relation from a process to someone or something physical or digital (continuant) that is a resources and assets for the process to give a desired output	has participant at some time	is enabler of	process	continuant
is input of	relates someone or something physical or digital (continuant) to a process that it is a necessary precondition for the process to start	participates in at some time	has input	continuant	process
is output of	relation from someone or something physical or digital (continuant) to a process that it participates in such that it is generated or modified during the process, and it exists at the end of the process	participates in at some time	has output	continuant	process
is control of	relates someone or something physical or digital (continuant) to a process that it is a monitor and adjustment for the process to give a desired output	participates in at some time	has control	continuant	process

is enabler of	relates someone or something physical or digital (continuant) to a process that it is a resources and assets for the process to give a desired output	participates in at some time	has enabler	continuant	process

The system life cycle processes ontology makes use of a specific set of terms, and these terms are taken from the ISO/IEC/IEEE 15288 vocabulary. In order to provide detailed descriptions of classes and properties, two main resources are utilized: the INCOSE Systems Engineering Handbook and the aforementioned vocabulary. To ensure consistency and clarity, annotations in the OWL code follow the recommended format and content. For instance, 'rdf:label' is utilized to present the name of a resource in a human-readable format, 'naturalLanguageDefinition' provides a plain text definition of the resource for better understanding, and 'abbreviation' serves as an alternative short label or synonym for the resource. Thanks to these resources, developers are able to provide rich and detailed descriptions of the system life cycle processes.

The metadata of the system life cycle processes ontology is shown in Table 10.

Table 10 Metadata of system life cycle processes ontology

Metadata item	Metadata content
License URI	http://ontocommons.eu/DLO/SLCPO#
Title	System Life Cycle Processes Ontology
Creator	Lan Yang
Publisher	Industry Portal
Date of creation	February 2023
Last modification	July 2023
Version number	V0.1

The system life cycle processes ontology plays a crucial role in streamlining and optimizing the system life cycle processes. By creating this ontology, we hope to address the lack of models available to define each process, classify the system life cycle process elements, clarify their relationships, and unify the terminology used by interdisciplinary engineers. The ontology encompasses all the key concepts outlined in ISO/IEC/IEEE 15288:2015 and the INCOSE Systems Engineering Handbook that are related to the system life cycle processes. Additionally, it infers the class hierarchy based on the properties' constraints, providing a more comprehensive and interconnected view of the processes.

Utilizing the ontology, we link the entire life cycle processes into a cohesive network by considering the flows. Each class, whether it is a continuant or an occurrent, can function as an entry point to view the system life cycle processes and can be extended with any other ontologies it may connect to. With this ontology, interdisciplinary engineers can work more efficiently and effectively, leading to better results for system life cycle processes.

From Figure 57 to Figure 62, we show some taxonomy and class diagrams of this ontology, to give a visual representation for the readers to rapidly understand the domain that this ontology describes. Additionally, it is important to note that some of these diagrams were carefully crafted to partially depict the relationships and classifications within the ontology, ensuring that readers can gain a general understanding of the subject matter but not the entire picture. Furthermore, providing these visual aids can greatly enhance the reading experience for individuals who may struggle with understanding complex written descriptions. By including these diagrams, we hope to make the ontology more accessible and user-friendly, while also emphasizing the importance of clear and concise visual communication in technical writing.

Figure 57 Taxonomy of system life cycle processes

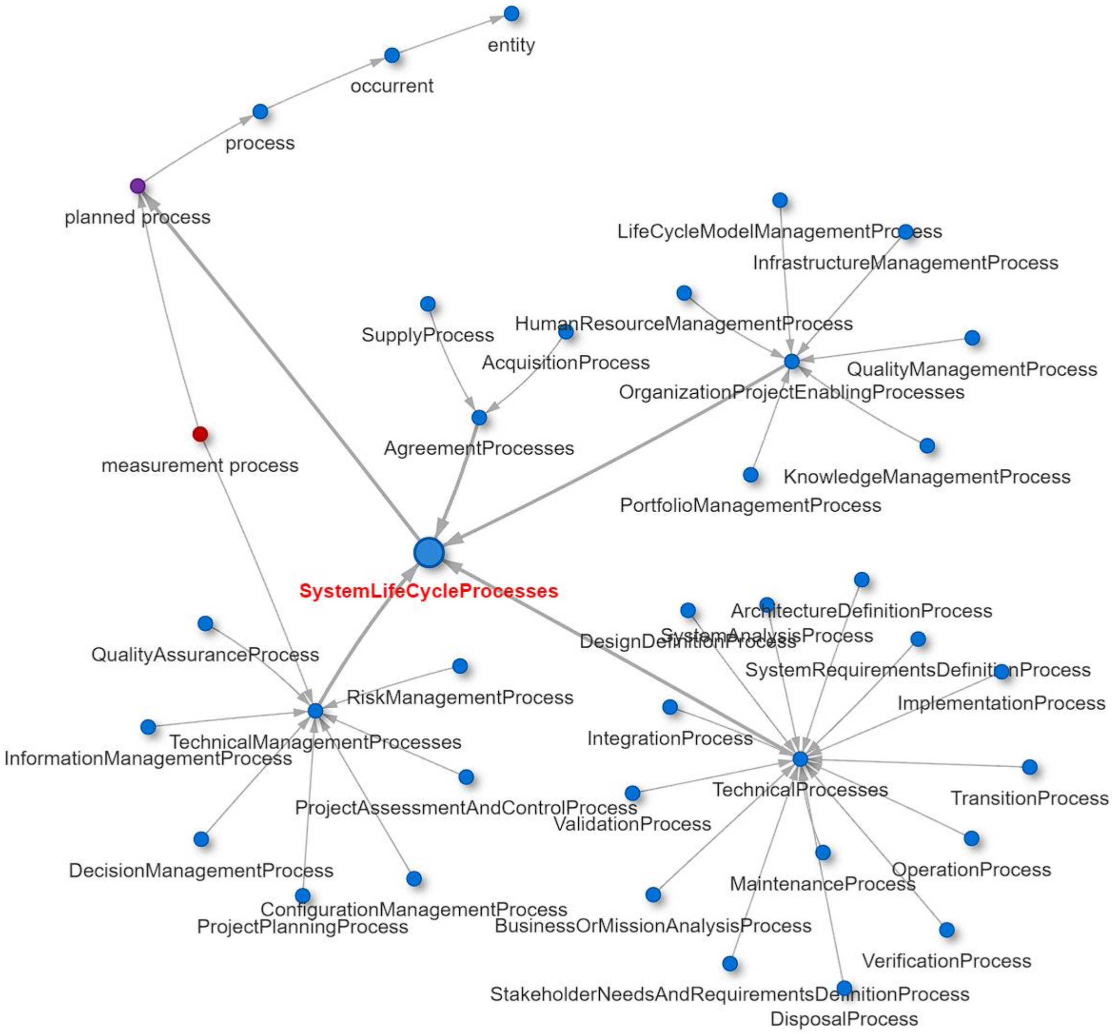

Figure 58 Class diagram of system life cycle processes

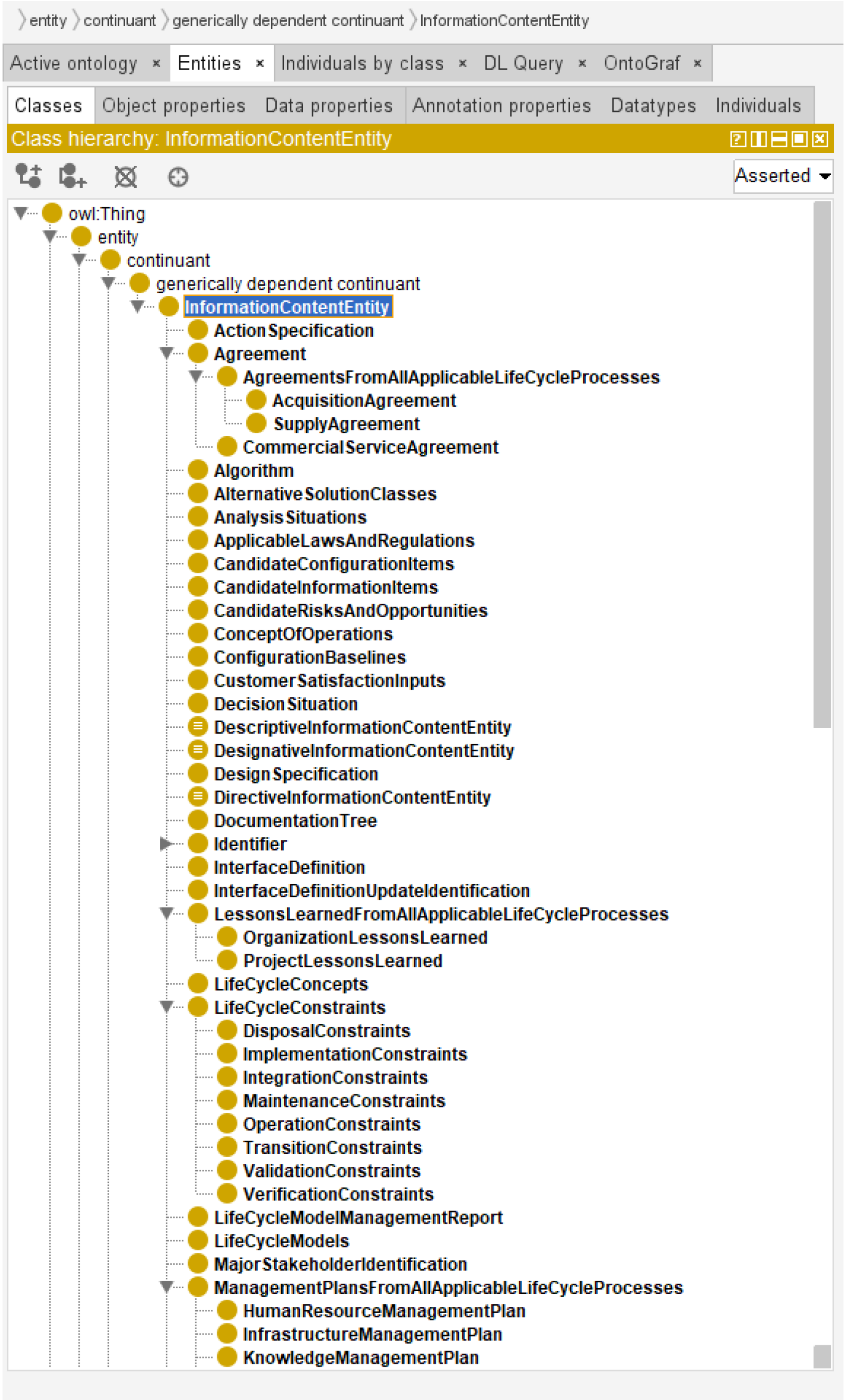

Figure 59 Taxonomy of information content entities participated in system life cycle processes (excerpt)

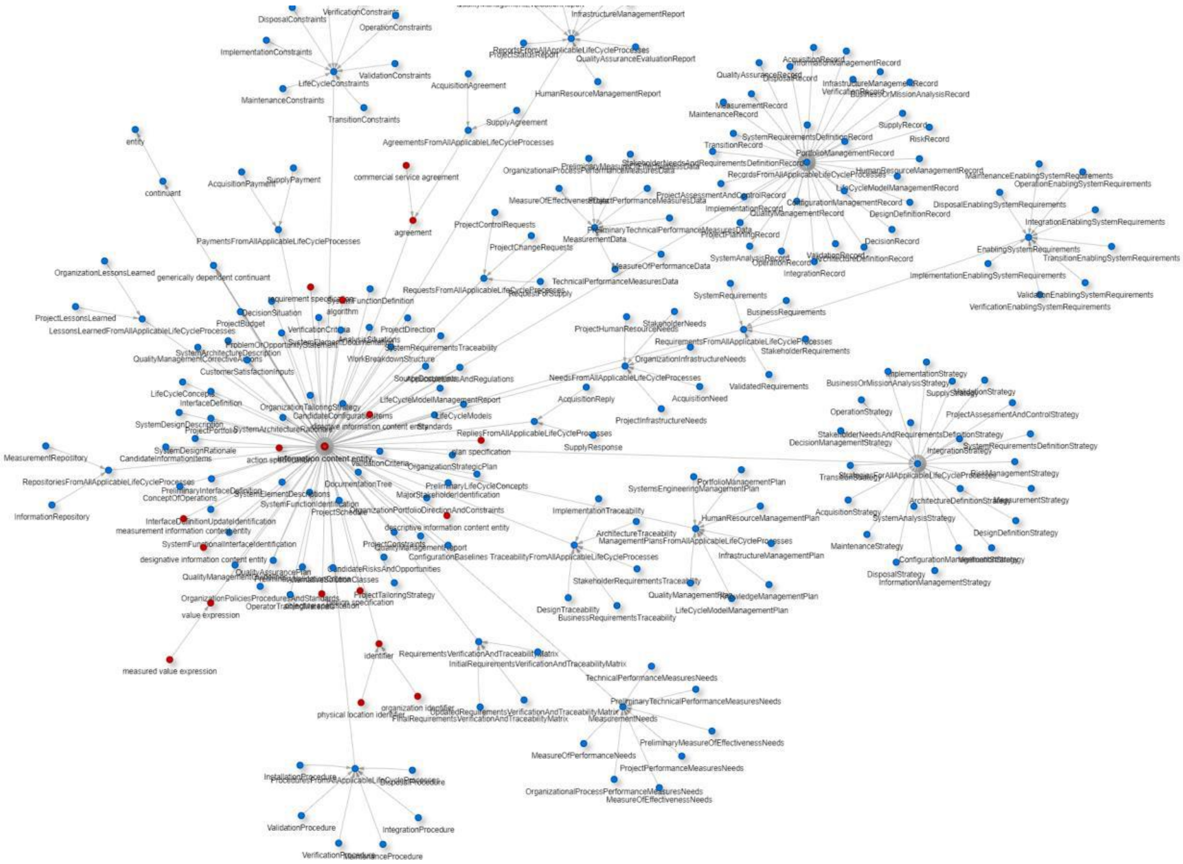

Figure 60 Class diagram of information content entities participated in system life cycle processes (excerpt)

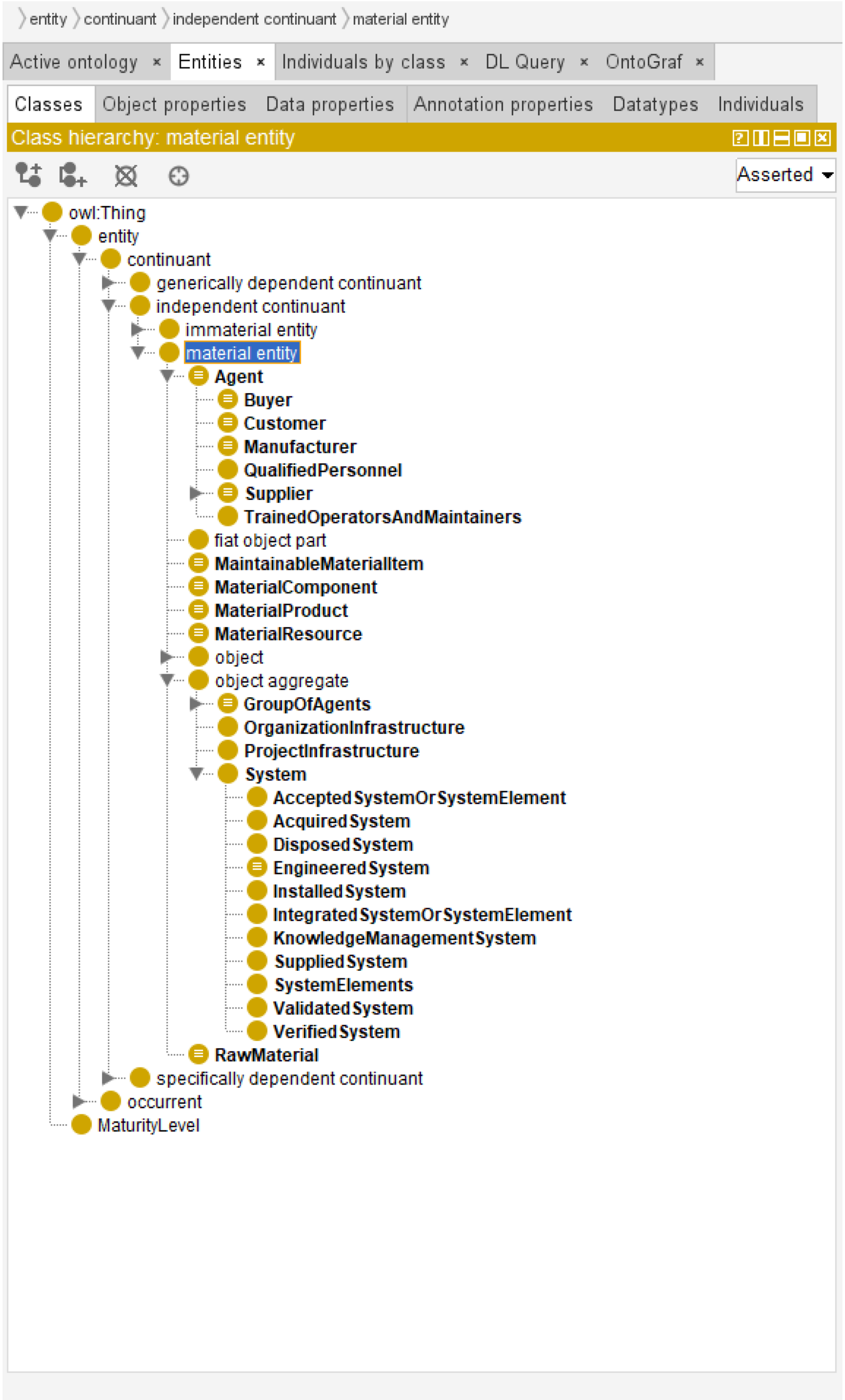

Figure 61 Taxonomy of material entities participated in system life cycle processes

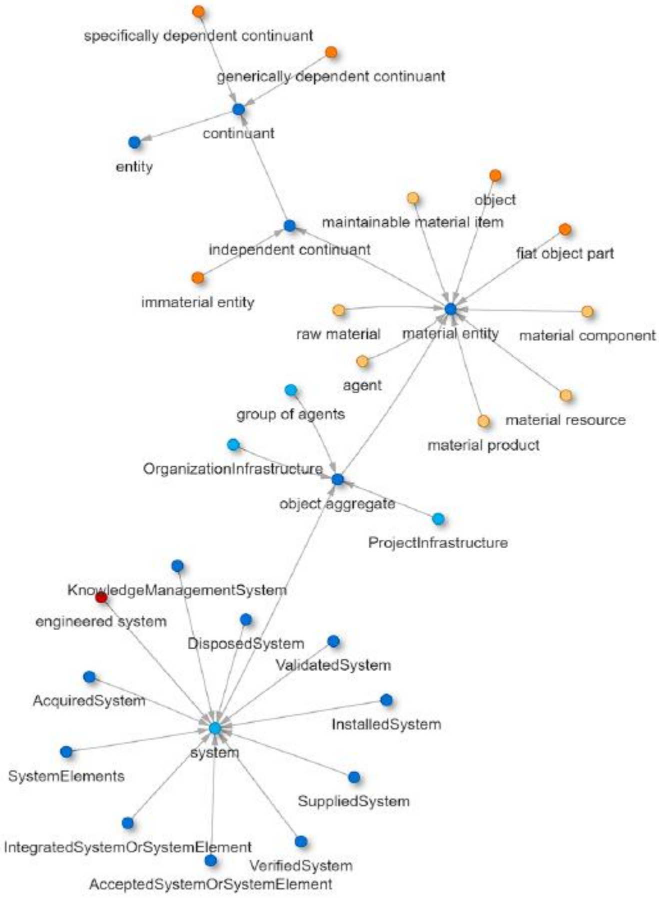

Figure 62 Class diagram of material entities participated in system life cycle processes

Regarding the first test case, it is verified that the system life cycle processes ontology can successfully restore all the relationships defined in the IPO diagrams. To demonstrate this visually, on the right shows a knowledge graph generated by the ontology to describe the acquisition process, with the original IPO diagram of the supply process on the left for comparison.

We have developed two test cases to verify the effectiveness of the ontology. The first test case aims to determine whether the ontology can successfully restore all the IPO diagrams that describe the system life cycle processes. In this case, we ensure that the ontology captures all the inputs, outputs, controls, and enablers of each process. The second test case involves evaluating the ontology using reasoning to answer some of the competency questions defined in the ontology requirement specification documentation use case (Table 7). Through this, we can verify whether the ontology has achieved its aim of transforming stand-alone IPO diagrams into a network, revealing the relations implicitly contained within the process.

To improve the ontology further, we can use ontology evaluation tools such as OOPS! and Themis. These tools can help us identify areas for improvement and enhance the overall quality of the ontology.

Regarding the first test case, we have successfully verified that the system life cycle processes ontology can restore all the relationships defined in the IPO diagrams. To visually demonstrate this, we generated a knowledge graph using the ontology to describe the acquisition process, as shown on the right side of Figure 63. We then compared it with the original IPO diagram of the supply process on the left, and it is clear that the ontology has effectively captured all the relationships between the different components of the process.

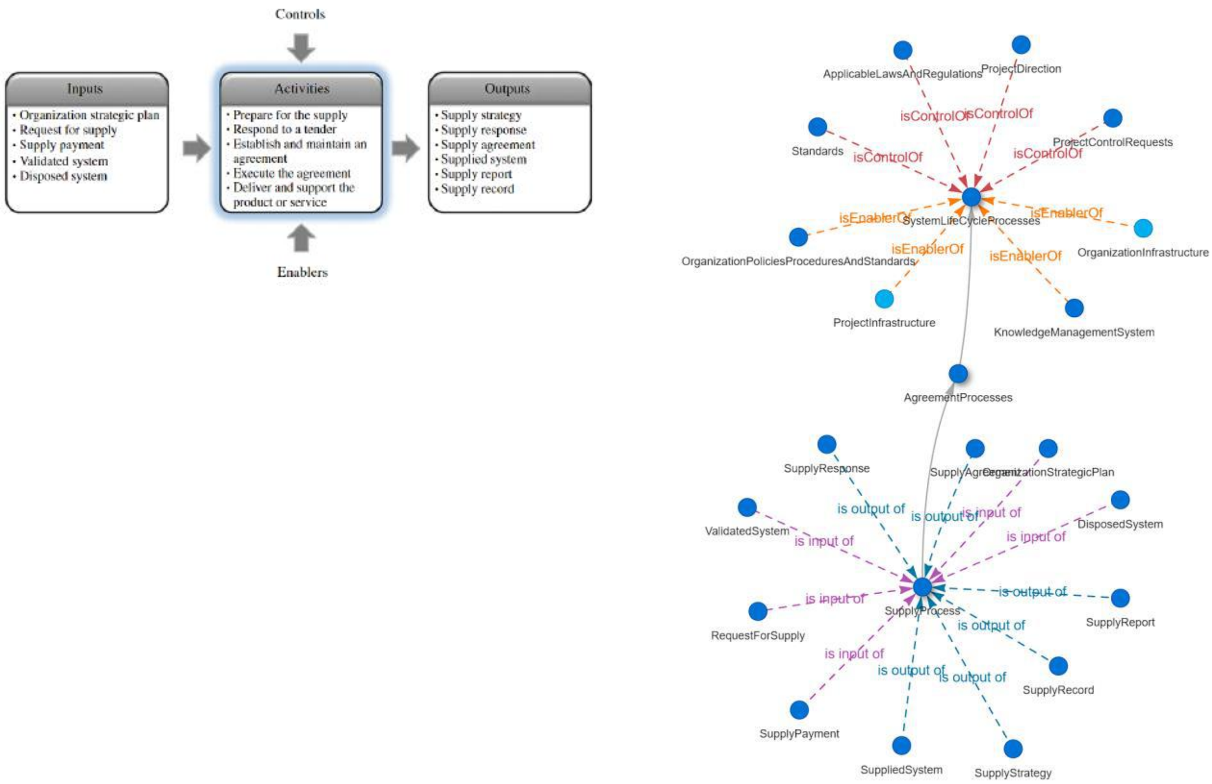

Figure 63 Test case of restoring IPO diagram, example of Supply Process

In the second test case, we can further elaborate on the knowledge presented in Figure 63 by expanding the IPO diagram. This can be achieved by adding sources and outwards, as conceptualised and illustrated by Figure 55. By doing so, we can transform stand-alone IPO diagrams into a network, which is a more comprehensive way of representing the inputs, processes, and outputs of a system life cycle. Figure 64 provides a visual representation of this network and highlights the interconnectedness of various elements within the system life cycle processes.

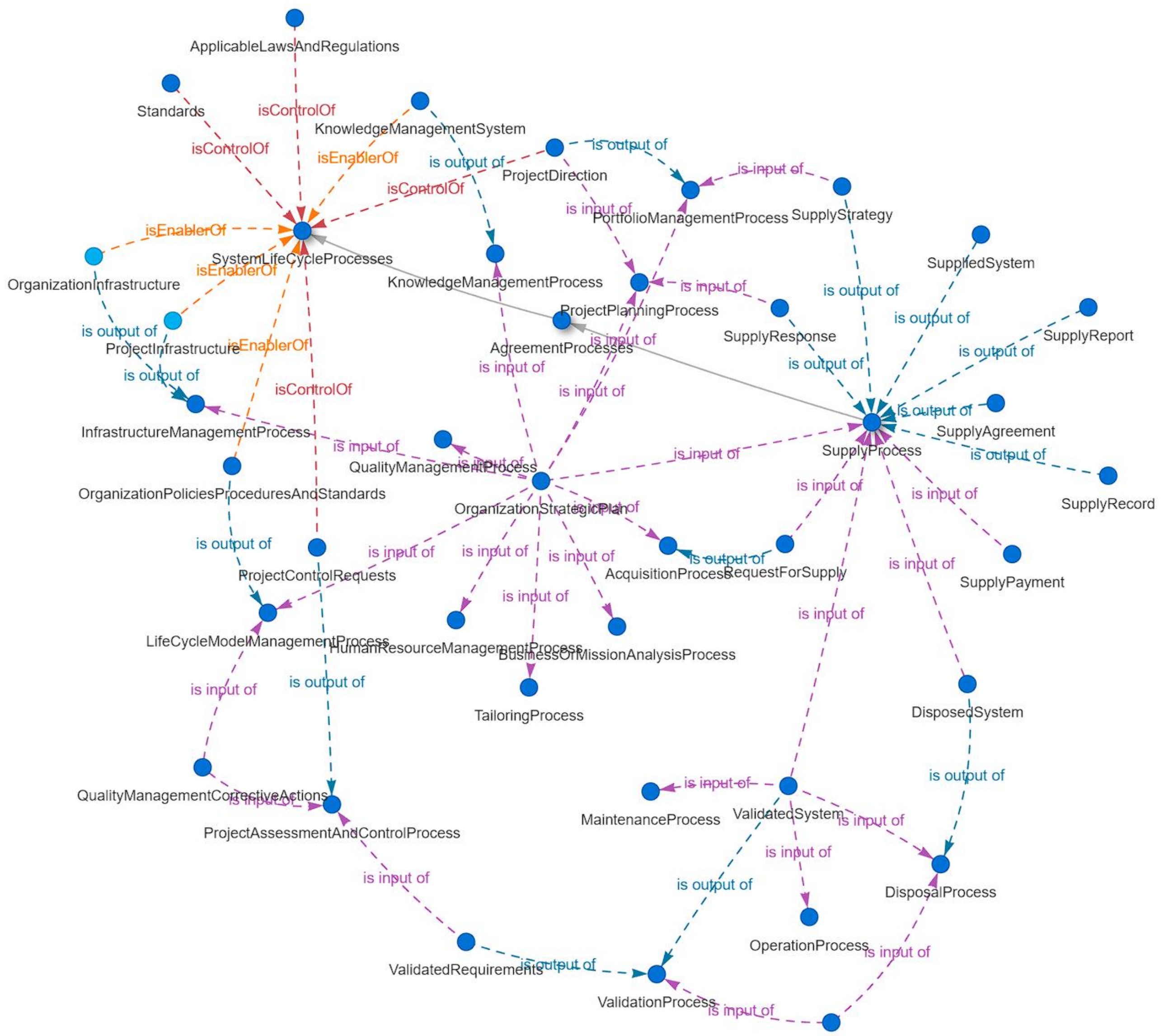

Figure 64 Test case of reasoning to obtain traceability of participants, example of Supply Process

In order to gain a more thorough understanding of the ontology's competence, we employed the use of reasoners to investigate and provide answers to a series of competency questions. These results can be presented in various formats, such as query results or visualised knowledge graphs. For the purpose of this report, we have opted to present the results through the use of knowledge graphs, which will provide a clear, visual representation of the answers to each of the competency questions. These graphs are displayed in Figure 65 through Figure 69, allowing for a comprehensive and detailed analysis of the ontology's competency and effectiveness in providing accurate and useful responses to the questions posed.

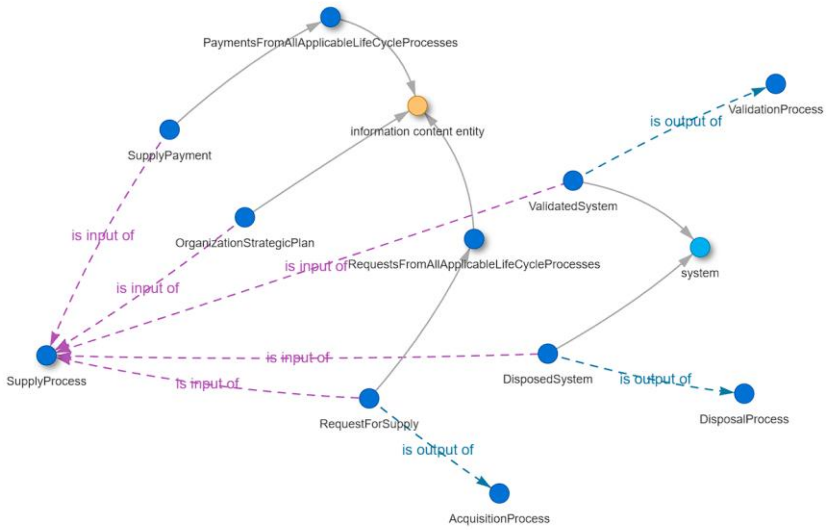

Figure 65 Validation through competency questions no. 6 and 7

Competency questions:

- slcp6. What type(s) of input(s) does Supply process take?
- slcp7. Where does the input(s) of Supply process come from?

Answers from reasoners and shown by Figure 65:

- The types of inputs that supply process takes are information content entities and systems.
- Organization strategic plan and supply payment come from external sources. Request for supply comes from acquisition process. Validated system comes from validation process. Disposed system comes from disposal process.

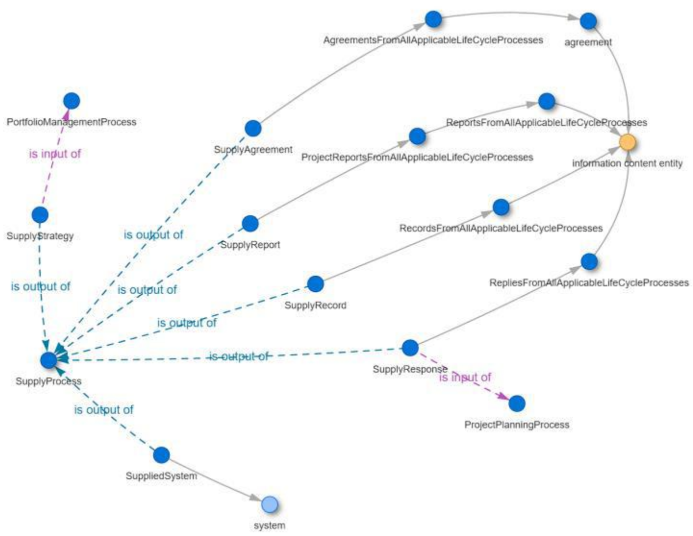

Figure 66 Validation through competency questions no. 9 and 10

Competency questions:

- slcp9. What type(s) of output(s) does Supply process take?
- slcp10. Where does the outputs(s) of Supply process go to?

Answers from reasoners and shown by Figure 66:

- The types of outputs that supply process produces are information content entities and systems.
- Supply strategy goes to portfolio management process. Supply response goes to project planning process. The other outputs go outwards of the system life cycle processes.

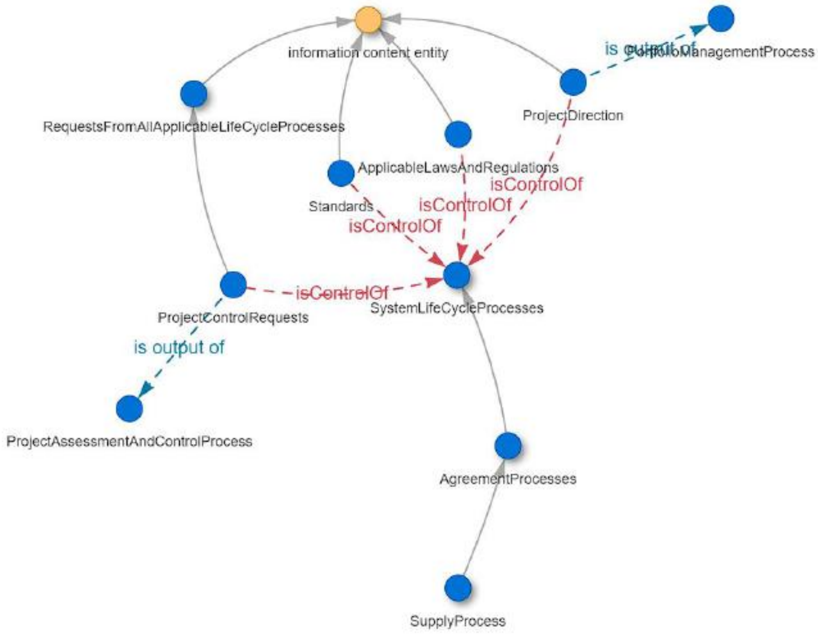

Figure 67 Validation through competency questions no. 12 and 13

Competency questions:

- slcp12. What type(s) of control(s) does Supply process take?
- slcp13. Where does the control(s) of Supply process come from?

Answers from reasoners and shown by Figure 67:

- The type of controls that supply process is under is information content entities.
- Project control request comes from project assessment and control process. Project direction comes from portfolio management process. The other controls come from external sources.

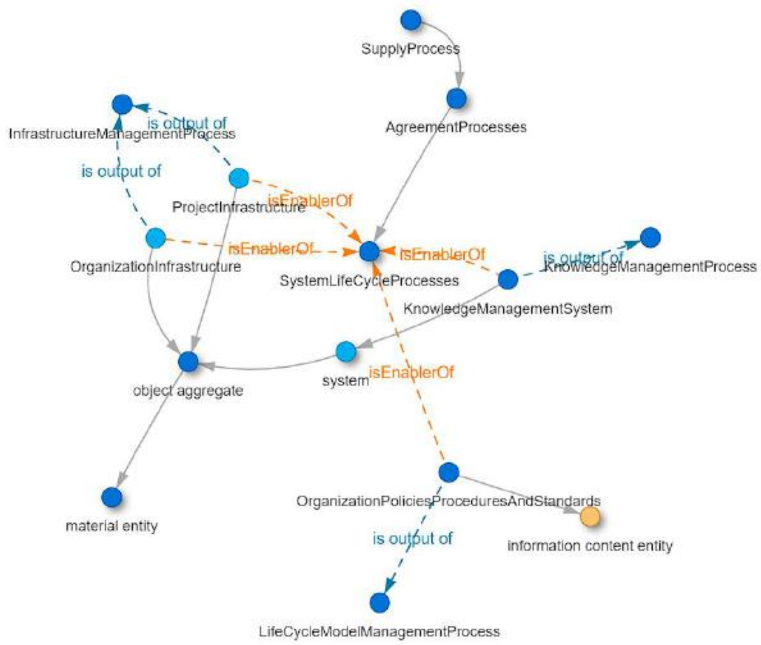

Figure 68 Validation through competency questions no. 15 and 16

Competency questions:

- slcp15. What type(s) of enabler(s) does Supply process take?
- slcp16. Where does the enabler(s) of Supply process go to?

Answers from reasoners and shown by Figure 68:

- The types of enablers that supply process needs are information content entities and material entities.
- Organization infrastructure and project infrastructure come from infrastructure management process. Knowledge management system comes from knowledge management process. Organization policies, procedures, and standards come from life cycle management process.

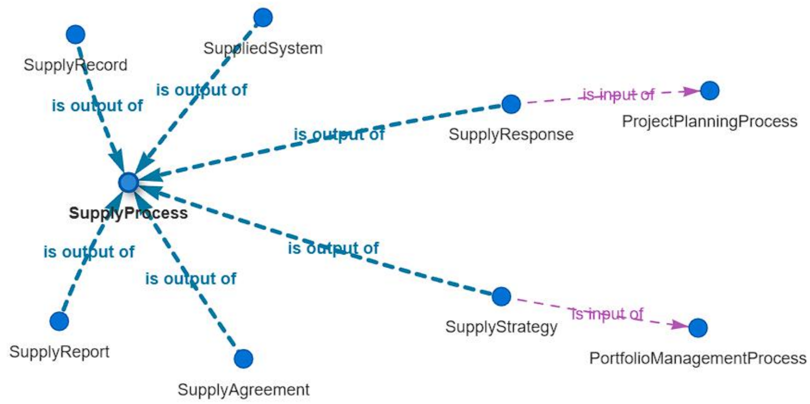

Figure 69 Validation through competency question no. 17

Competency question:

- slcp17. If Supply process is tailored, what processes will be impacted?

Answers from reasoners and shown by Figure 69:

- Project planning process and portfolio management process are impacted, as they take outputs from supply process.

3.3.3 Ontology publication

In this section, we will provide an example that shows how to practically use this ontology. By utilizing the system life cycle processes ontology, it is easier to distinguish between old and new standards when the version of ISO/IEC/IEEE 15288 and the INCOSE Systems Engineering Handbook changes. This is particularly important because changes in standards can often be subtle and difficult to identify, leading to confusion and potential errors in implementation.

For example, consider ISO/IEC/IEEE 15288, which has an old version (v3.0) that was published in 2011 and a current version (v4.0) that commenced in 2015. Both versions are in English, and there have been many changes between them, including the renaming of processes and the refining of natural language definitions. However, these changes can be more effectively managed by using the system life cycle processes ontology as the knowledge model behind the standard. This approach provides configuration support for the edition, making it easier to identify and understand the differences between versions.

In addition, since translating the English version into other languages can take some time, having terms defined by the ontology in multiple languages can ensure a smoother and quicker translation process. This, in turn, supports the transition between different versions and helps to ensure that standards are adopted more widely and effectively across different contexts and languages. Overall, the system life cycle processes ontology is an essential tool for managing and implementing standards effectively, and it can help to improve process compatibility, reduce errors, and support better communication and collaboration across different stakeholders and domains.

3.3.4 Ontology maintenance

As new requirements emerge, it is essential to engage in ontology maintenance activities to refine the ontology. In order to ensure that the ontology is up-to-date and accurate, it is also crucial to thoroughly document all changes made to it. This documentation should include the reasons for the change, the impact of the change on the ontology, and any potential implications for the ontology's users. Additionally, it may be useful to consult with domain experts when making changes to the ontology to ensure that the changes accurately reflect the domain and meet the needs of the ontology's users. All of these activities will help to ensure that the ontology remains a valuable resource for its users and continues to meet their evolving needs over time.

3.4 Resistance spot welding ontology

In this work, we aim to develop a comprehensive resistance spot welding ontology (RSWO) using the LOT methodology. This methodology has been refined to provide a more gradual refinement process throughout the ontology creation, ensuring that the ontology accurately captures both domain knowledge concepts and low-level manufacturing data. The LOT methodology involves several stages, each building upon the previous one to create a more detailed and refined ontology. In the first stage, a high-level conceptual model is created, which is then refined in the subsequent stages to gradually add more detail and specificity. This iterative process ensures that the ontology is well-structured and comprehensive, capturing all relevant information about the domain. By following this methodology, we can create a robust and detailed RSWO that accurately captures all relevant information and supports a range of manufacturing applications.

3.4.1 Ontology requirements specification

We have utilized a variety of sub-activities from the ontology requirement specification in order to ensure the development of a comprehensive and effective RSWO. With the guidance and assistance of Bosch experts, we were able to identify the specific need for an RSWO, which was then specified through the use-case of quality monitoring in resistance spot welding. In addition to this, we were provided with several documents including ISO standards, datasets description, and datasets themselves, which helped to further clarify and define the purpose and scope of the RSWO as a unified model for questioning and answering related to resistance spot welding.

To ensure that the RSW ontology meets all functional requirements, we collected natural language sentences from the Bosch experts to serve as competency questions. These sentences were then transformed into competency questions, with some examples listed in Table 11. The competency questions were provided by welding experts and grouped into two categories: Data Inspection (CQ1-CQ5) and Diagnostics (CQ6-CQ10). The former involved the inspection of RSWO-based Bosch welding process data from a variety of angles to verify and quantify welding quality, while the latter involved performing various diagnostic tasks to identify any irregularities and potential root causes.

Table 11 Competency questions provided by Bosch experts

Group	Competency question (CQ) No	CQ
Data Inspection	CQ1	How much weld force, voltage, current and power is utilized in an operation?
	CQ2	What machine parts are being used in a resistance spot welding operation?
	CQ3	How much force is utilized in the squeeze, weld and hold step of the operation?
	CQ4	How much is the resistance between the bottom Electrode and bottom sheets?
	CQ5	How many cycles of weld time is utilized in an operation?

Diagnostics	CQ6	Find all those values of Q-Value higher than a threshold along with their voltage and power in an operation.
	CQ7	Is there any spatter that occurred during a particular time?
	CQ8	Does the electrode require dressing?
	CQ9	How many weld spots have spot repetition?
	CQ10	How much force is utilized in the squeeze, weld and hold steps of the operation?

Once these functional requirements were successfully approved, we proceeded to the second phase of the ontology implementation. This comprehensive approach ensures that the RSWO is developed to meet all necessary requirements and is able to effectively address the needs of the industry.

3.4.2 Ontology implementation

We have divided the second phase of LOT methodology into two parts: formalizing concepts and validation of ontology. The successful construction of the ontology requires both of these tasks to be completed. The formalizing concepts activity includes three sub-activities: ontology conceptualization, ontology reuse, and ontology encoding.

To conceptualize the knowledge of resistance spot welding, we first search for existing ontologies that contain the necessary terminology (classes and relations). If the terminology is found, we can reuse it in the RSWO. If not, we introduce new concepts and create them. The formalization process involves creating concepts with relationships, as shown in Figure 70. The middle of the figure shows the procedure of terminology selection, and the right side shows the formalized knowledge. On the right side of the figure, the concepts in orange colour show the terms related to manufacturing resources while the concepts in yellow provide the terms process (RSWProcess) and operation (RSWOperation), and the blue colour provides the terms workpiece and weld spot, respectively.We create a concept named WeldingMachine to model a welding machine. We define a property called "hosts" to establish the relationship between WeldingMachine and the Part. We then link the WeldingMachine to the AssemblyProcess concept via the "performsA" property, and we connect it to the RSWOperation concept via the "hasOperations" relationship. The RSWOperation concept is linked to the Assembly concept through the "hasRawProduct" property. Finally, we connect the concepts WeldSpot and RSWOperation using the "isOperationProductOf" property.

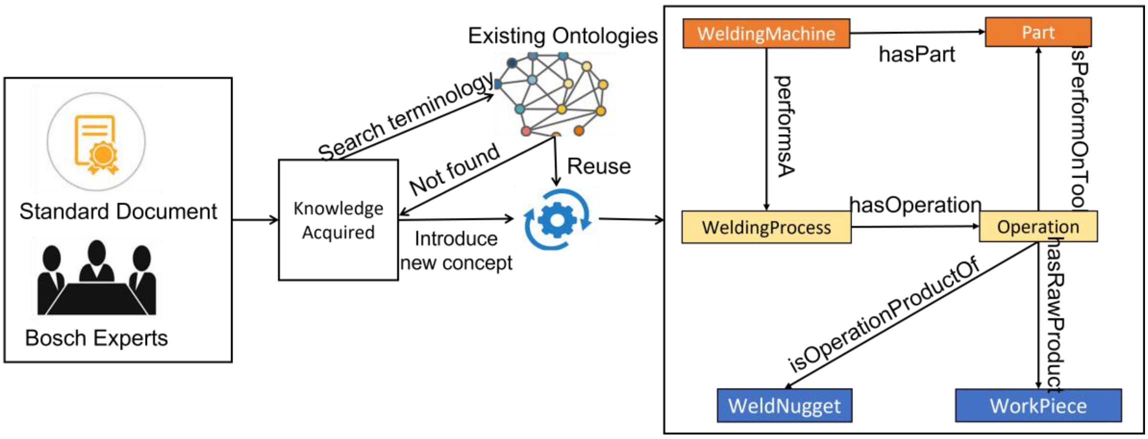

Figure 70 Semantic illustration of our process for knowledge formalization

After formalizing the concepts, we implement them using the open-source ontology editor of Protege for developing intelligent systems. We encode the RSWO into Resource Description Framework/Web Ontology Language (RDF/OWL). In addition to this, we also reuse general ontologies such as the Time ontology and Sensor ontology to provide context to the data. For example, we can add properties to the machine concept such as temperature observation during a process at a particular time (timestamp). We also reuse object properties such as "isPartOf" and "hasPart" from the Dublin core ontology to follow the best practices of Linking Open Data. These additions increase the knowledge and context of the ontology.

In this work, we reused relevant existing ontology and vocabulary. By reusing vocabulary from contemporary ontologies, we can enhance interoperability and facilitate knowledge reuse, which is crucial in the field of engineering and manufacturing.

To begin, we analysed the existing ontologies based on the context of their ontological terms of classes and relations between them. We identified relevant terms based on their semantic context with the resistance spot welding domain of the Industry Ontology Foundry (IOF) repository, which includes 52 ontologies representing the manufacturing industry. The IOF is a group that is developing a set of open reference ontologies to support the demands of the engineering and manufacturing sectors. By utilizing these ontologies, we can enhance data interoperability. Table 12 shows the prefixes and Internationalised Resource Identifiers (IRI's) used in the RSWO. Table 13 shows some of the object properties being reused from the existing ontologies. Table 14 shows the concepts and their definitions used in the RSWO, and the source from where the concepts are derived. We have observed that the concepts have been reused from the Sensor, Observation, Sample, Actuator (SOSA) ontology, which provides formal light-weight general-purpose specifications of concepts as entities in the modelling. Additionally, it shows the interaction between the entities involved in the acts of sensing, actuation, and sampling, time ontology, and ontology of units of measurement (uom).

Table 12 Prefixes and IRIs used in RSWO

Prefixes	Namespaces
rswo:	http://www.rswo.org/2022/7/rswo
sosa:	http://www.w3.org/ns/sosa/

swo:	http://www.ebi.ac.uk/swo/
time:	http://www.w3.org/2006/time
dc:	http://purl.org/dc/terms/
uom:	http://purl.obolibrary.org/obo/
owl:	http://www.w3.org/2002/07/owl
rdf:	http://www.w3.org/1999/02/22-rdf-syntax-ns
rdfs:	http://www.w3.org/2000/01/rdf-schema
xml:	http://www.w3.org/XML/1998/namespace/

Table 13 Some of the properties reused from the existing ontology

Reused property	Ontology
sosa:hosts	Sensor Ontology
sosa:hasProperty	Sensor Ontology
sosa:observes	Sensor Ontology
time:hasTime	Time Ontology
dc:hasPart	Dublin core Ontology
dc:isPartOf	Dublin core Ontology
om:hasUnit	Unit of measure ontology
rgom:performsA	rgom ontology
rgom:hasOperation	rgom ontology

Table 14 Examples of the classes, their definitions and knowledge source

Ontological term	Definition	Source
RSWOperation	A resistance spot welding operation contains a set of activities such as squeeze, weld, and hold the worksheets to a weld spot.	Domain experts
WorkPiece	A workpiece is an item that is being processed into another desirable shape. Typically, the workpiece is a chunk of reasonably stiff material like stone, wood, metal, or plastic.	Domain experts
PiecePiece interaction	The class PiecePieceInteraction is used to model interaction properties between physical entities. For example, between the two worksheets of RSW, there could exist adhesive; between any two contacting physical entities, the contact properties like thermal or electric conductivity.	Domain experts
WeldProgram	The weld program is the already planned parameter's reference value or setpoints for an operation.	Domain experts

Weld Spot	A weld spot is the output of an operation and it is a join that has been spot-welded. It is the product of the RSW operation.	Domain experts, ISO-14327, ISO-14373
Wear	Electrode wear can occur due to heavy splash, mushrooming or alloying. This can have an adverse effect on the reproducibility and validity of the results.	Domain experts, ISO-14327, ISO-14373
Software	Computer software, or generally just software, is any set of machine-readable instructions (most often in the form of a computer program) that conform to a given syntax (sometimes referred to as a language) that is interpretable by a given processor and that directs a computer's processor to perform specific operations.	The Software Ontology
Observation	An Act of carrying out an (Observation) Procedure to estimate or calculate a value of a property of a FeatureOfInterest.	SOSA Ontology
Unit	A unit of measure is a definite magnitude of a quantity, defined and adopted by convention or by law. It is used as a standard for measurement of the same quantity, where any other value of the quantity can be expressed as a simple multiple of the unit.	units of Measure Ontology
TemporalEntity	A temporal interval or instant.	Time ontology

Figure 71 shows an overview of terms being reused from relevant existing ontologies along with those from ISO-14327 and ISO-14373. We have also considered aligning the RSWO with the domain-level ontology, which is crucial in providing semantic interoperability across the domain. There exist several domain-level ontologies such as MASON, CDM-Core, and RGOM. We have selected RGOM as it is built on reusing the manufacturing ontologies with the terms being introduced that are overlooked in the previously existing vocabularies. In order to illustrate the alignment with the RGOM, consider Figure 72.

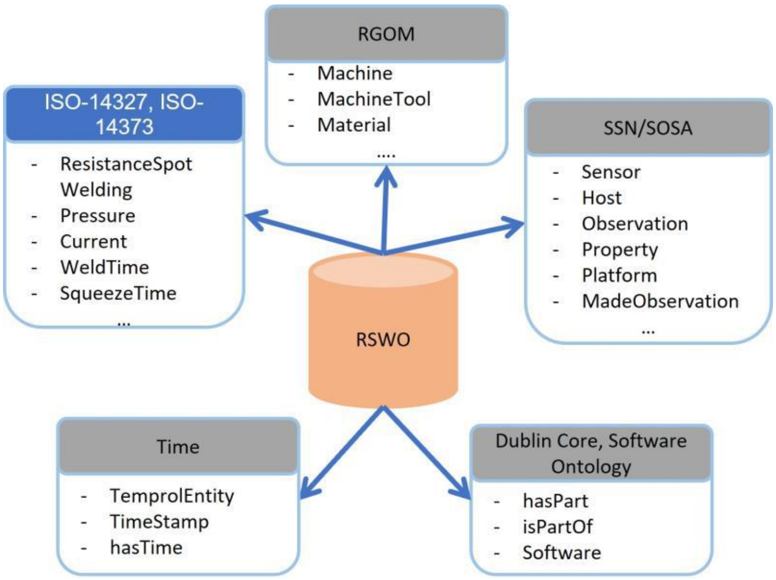

Figure 71 Ontology terms acquired from existing ontologies (highlighted in grey colour) and, ISO standards (highlighted in blue colour)

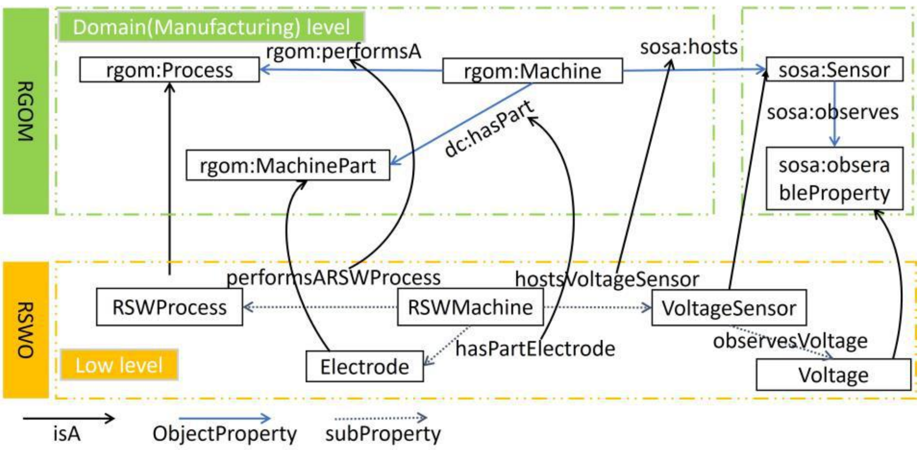

Figure 72 Alignment between RGOM and RSWO

Figure 72 shows the alignment of RSWO (orange colour) to the RGOM ontology (green colour). For example, the class RSWMachine of RSWO is created as a subClass of Machine and the Electrode class in the RSWO is created as a subClass of MachinePart of RGOM. The RSWMachine class is linked to the Electrode class through the property hasPartElectrode which is the subProperty of hasPart of the RGOM (hasPart properties is reused from the Dublin core vocabulary by RGOM). In future work, the RSWO will be aligned to the top-level ontology, which will further enhance interoperability and facilitate knowledge reuse in the engineering and manufacturing sector.

In order to ensure the quality of the RSWO, several metrics are utilized during the validation step of ontology implementation. One such metric is the use-case based CQs answering, where the CQs are provided by Bosch experts and used to determine whether the RSWO ontology has effectively captured domain knowledge. These CQs cover various aspects such as the diameter of the weld spot produced in a certain welding operation, the weld force applied to workpieces, and the resistance between electrode and workpiece. Additionally, the FAIR principles are assessed using the O'FAIRe methodology, which evaluates the ontology's Findable, Accessible, Interoperable, and Reusable characteristics. The Ontology Pitfall Scanner (OOPS!) tool is also used to evaluate the structural and functional dimensions of the ontology, identifying potential flaws and pitfalls in the design such as missing domain and range in the properties and unconnected elements. To further analyse the RSWO ontology, it is populated with data instances and uploaded to OntoMetrics, a platform for advanced analytics. This allows for a more comprehensive evaluation of the ontology's performance and effectiveness.

A detailed description of the classes, object properties, data properties, axioms, and evaluation results of RSWO can be found in the publication [8], so this report will not repeat them.

3.4.3 Ontology publication

RSWO is publicly available at [https://w3id.org/def/mo-rswo.](https://w3id.org/def/mo-rswo) We have made the RSWO available online at GitHub: https://github.com/MuhammadYahta/RSWO-UO, which can be easily accessed by anyone with an internet connection. This allows for a wider audience to view and use the ontology, which can lead to more collaboration and contributions.

The metadata of the RSWO is published on the industry portal (http://industryportal.enit.fr/ontologies/RSWO), providing important information such as the URI, license, and title used. Moreover, it also contains valuable information such as the creator, contributor, endorser, and date of creation, which can be beneficial for anyone looking to understand the ontology better.

3.4.4 Ontology maintenance

In addition to ontology publication, we have also taken steps to ensure that the ontology is maintained and updated regularly. Bugs can be reported on the GitHub page, which can then be tracked and resolved accordingly. This ensures that the RSWO remains up-to-date and accurate, providing the most benefit to its users.

3.5 Tribological Characterisation Ontology (TribOnt)

Tribology aims to study friction, wear and lubrication of interacting surfaces under specific operation conditions. Tribological characterisation is key for understanding the behaviour of a material or combination of them (e.g., metal, coating, lubricant) under specific operation conditions, driving new materials into sustainable solutions and developing new products. However, the experiments' results follow heterogeneous formats and data models due to a lack of standards TribOnt (Tribological Characterisation Ontology) aims to provide a common representation of tribological experiments, enable enriching existing data with additional background knowledge, and easing data retrieval and navigation through related resources to shorten the time, number and size of experiments required to identify the behaviour under specific operation conditions.

3.5.1 Ontology requirements specification

TribOnt follows a modular approach for increased re-usability, The ontology comprises four modules covering the key elements involved in the tribological experiments for material characterization, as well as common aspects (i.e., Core, Material, Sample, Equipment) and follows a common design pattern (i.e., isCharacterisedBy). Figure 73 includes an overview of the involved modules along with the main classes represented in each of them, and the common ontology design pattern. Different colours have been used to identify the modules and main classes included in each of them (i.e., Core: pink, Material: yellow, Sample: green, Equipment: blue, and isCharacterisedBy grey). The namespaces used in the document is shown in Table 15.

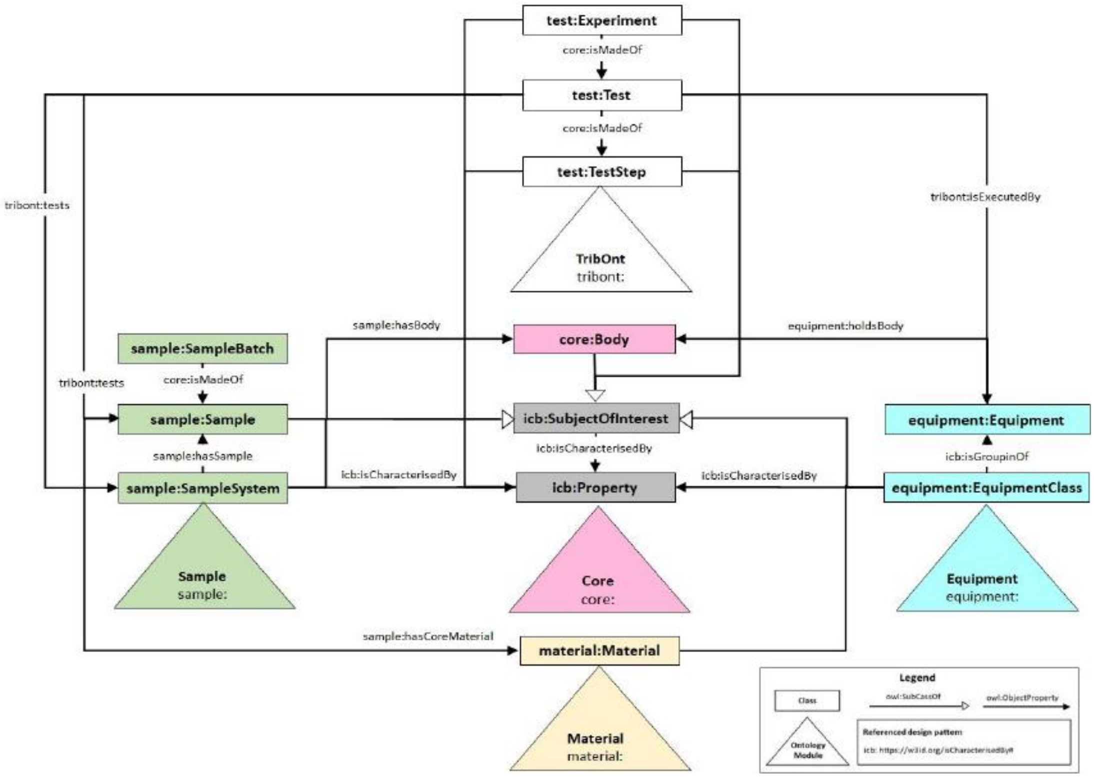

Figure 73 TribOnt Ontology modules

Table 15 Namespaces used in TribOnt

Prefix	IRI
tribont	<https://w3id.org/tribont>
ns	<http://creativecommons.org/ns>
owl	<http://www.w3.org/2002/07/owl>
isCharacterisedBy	<https://w3id.org/isCharacterisedBy>
xsd	<http://www.w3.org/2001/XMLSchema>
swrl	<http://www.w3.org/2003/11/swrl>
swrlb	<http://www.w3.org/2003/11/swrlb>

equipment	<https://w3id.org/tribont/equipment>
rdfs	<http://www.w3.org/2000/01/rdf-schema>
ns1	<http://www.w3.org/2003/06/sw-vocab-status/ns>
sample	<https://w3id.org/tribont/sample>
core	<https://w3id.org/tribont/core>
material	<https://w3id.org/tribont/material>
rdf	<http://www.w3.org/1999/02/22-rdf-syntax-ns>
terms	<http://purl.org/dc/terms>
xml	<http://www.w3.org/XML/1998/namespace>
vann	<http://purl.org/vocab/vann>

TribOnt ontology represents tribological experiments. An experiment (Experiment class) to perform the tribological characterisation of a material can be defined by a set of tests (Test class, isMadeOf object property) following a specific procedure represented by a dependency flow (hasDependency object property). In some cases, the tests involved in the experiment follow a specific sequence (hasAfterEndDependency object property, specialisation of hasDependency) but in other cases they are performed in parallel (hasNofollowDependency object property, specialisation of hasDependency). In turn, each test can be made of a set of test steps (TestStep class) following a specific procedure, as described previously. Each test is executed by an equipment (isExecutedBy object property), and can be characterised by a set of configured operation conditions (isCharcaterisedByOperationCondition object property) that can comply or not with a given standard (compliesWith object property). Furthermore, tests can be characterised by the evolution of a set of operation conditions (isCharacterisedByOperationMeasure object property) during its execution, and the measurements of the specific set of technical properties (TechnicalProperty class) resulting from it (isCharacterisedByOutputMeasure object property). Analogously each test step can be characterised by a set of configured operation conditions, the evolution of a set of operation conditions, and the specific set of technical properties measured as result of it. The values of the measured technical properties represent mean or termination values (i.e., value data property), all the intermediate values of the technical properties , along with the values of the operation conditions measured throughout the tests or tests steps, are compiled in specific output files (TestOutputDocument class). Tests can apply either to a sample or a sample system (tests object property. Tribological tests (TribologicalTest class) aim to assess one or more tribological characteristics (TribologicalProperty class) of a given sample system, while Measuring tests (MeasuringTest class) aims to measure one or more characteristics of a given sample.

The following shows the specification of the requirements for TribOnt ontology in the form of key basic Competency Questions (CQ).

- CQ.01: What type of system arrangements have been tested for a given material?
- CQ.02: What type of standard tests have tested for a given material?
- CQ.03: What type of simulated (i.e., non-standard) tests have been performed for a given material?
- CQ.04: What average coefficient of friction have been obtained with a bare steel of low roughness?

- CQ.05: Which are the lubricants with an average coefficient of friction bigger than/lower than a given value?
- CQ.06: Which are the lubricants with an average coefficient of friction bigger than/lower than a given value tested under standardised operation conditions according to a given standard?
- CQ.07: What coatings applied on a given material and tested against a bare body of a given material with a specific shape have obtained an average coefficient of friction higher/lower than a given value?
- CQ.08: What tests have involved a given coating?
- CQ.09: What lubricated tests have been performed at a given sample temperature?
- CQ.10: What tests have been performed under a given geometric arrangement and a given operation property/set of properties with values higher than/lower than a given value?
- CQ.11: What tests have been performed using a given type of lubricant?
- CQ.12: What average coefficient of friction have been obtained with a given operation condition?
- CQ.13: What output results document are linked to an experiment?
- CQ.14: What output measures are linked to an experiment?
- CQ.15: What are the tests involved in an experiment?
- CQ.16: What are the test steps involved in a test?

3.5.2 Ontology implementation

The details of classes and properties in TribOnt are documented in a permanent repository with the URI of https://w3id.org/tribont. They are not repeated in this report.

3.5.3 Ontology publication

The TribOnt ontology is published on Industry Portal:
http://industryportal.enit.fr/ontologies/TRIBONT.

3.5.4 Ontology maintenance

The TribOnt ontology is maintained on GitHub repository regarding bugs and new requirements: https://github.com/fundaciontekniker/tribont-ontology.

4.Updates on the alignment of existing DLOs

4.1 Product and service

4.1.1 Bridge concepts

4.1.1.1 ProductSpecification

In the first phase of identification of the candidate-bridge-concept terms, a standardised approach was applied (see Deliverable D3.6), and the PRONTO and PSS ontologies were studied to this end. As a result, the bridge concept ProductSpecification was created and used:

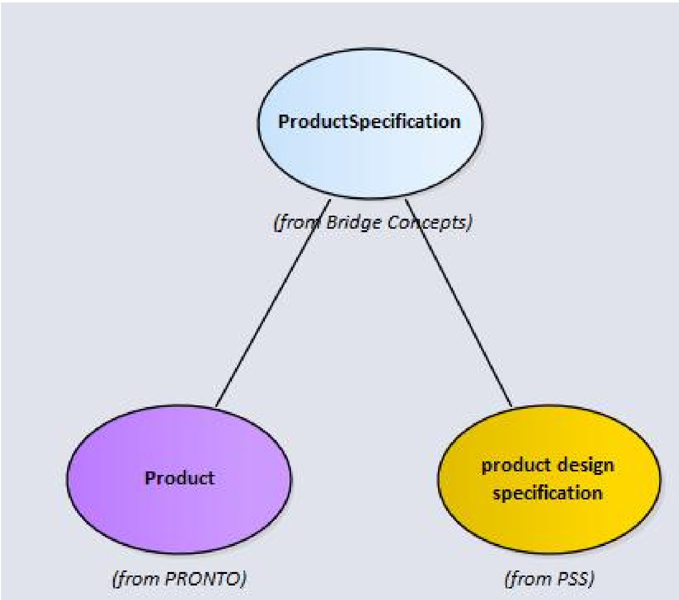

Figure 74: Product Specification Bridge Concepts and closest entities

4.1.1.2 CommercialGood

After analysing further the PSS ontology, such as PSS Product (i.e. IOF-Core:MaterialProduct) as well as other PRONTO ontology related terms such as PRONTO:Family and PRONTO:VariantSet, several relationships were established and the bridge concept Commercial Good was considered as another Bridge Concept.

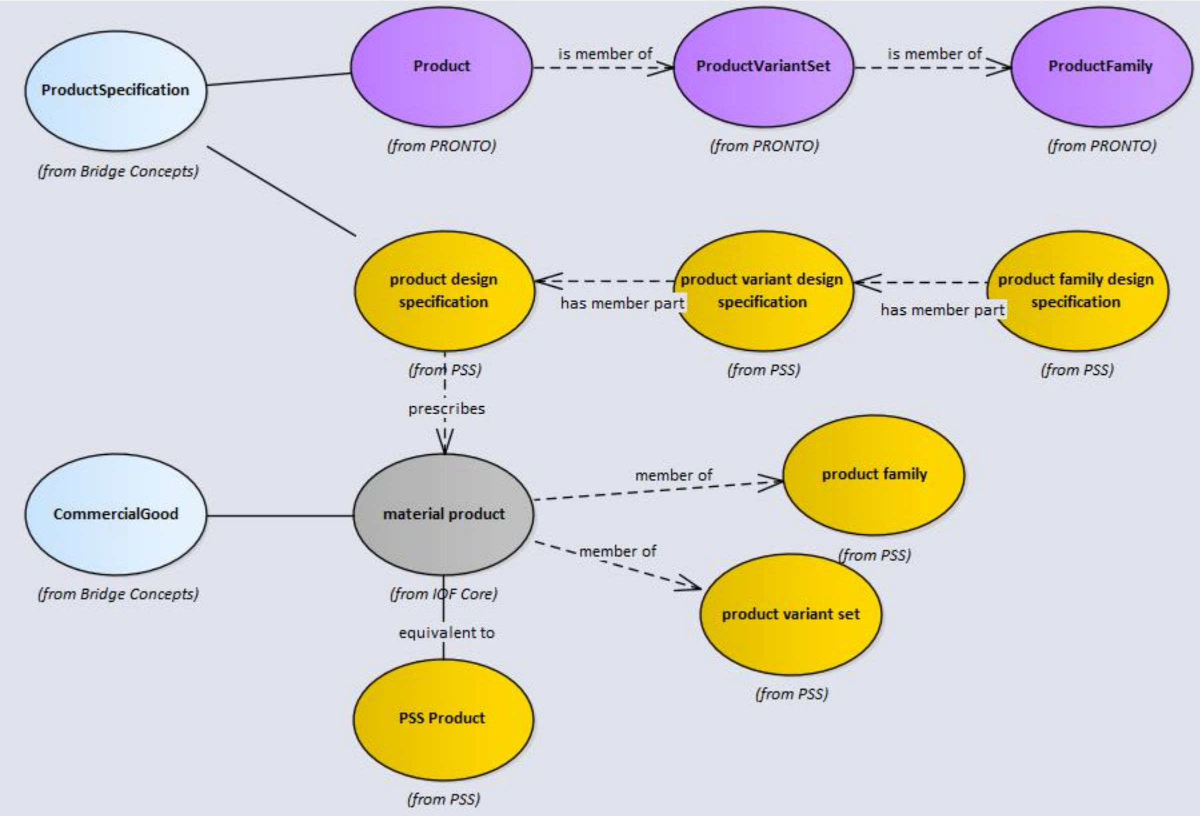

Figure 75: Product Specification and Commercial Good Bridge Concepts and closest entities

Table 16 General concept information for CommercialGood

IRI:	*Suggested entity new IRI.*
OWL Type:	*Class*
Concept Elucidation:	A Commercial Good is something which is explicitly offered on the market for purchase or barter, whose ownership is transferred to the purchaser as a condition for the completion of the transaction, and which is associated with a specific material entity which doesn't merely act as a legal placeholder or as a contingent medium to the end of completing a transaction. Goods are the outcome of some kind of practical activity which needn't have been performed, directly, or indirectly, by the organization or individual offering the Good on the market, and which needn't involve a transformation of the item which is then offered for purchase. It should be noted that an intellectual activity might be prodromic to the performance of a practical activity whose result is a Good.

	Goods can either belong to the purchaser for an indefinite, or predetermined, period of time after the completion of a transaction; the ownership can be transferred at any point during the transaction and needn't grant full legal rights over the owned article. They are generally considered to be tangible and conceptualised as reducible, or identical to specific material entities, though said characteristics do not pertain to the domain of economics, and are at most derivative. Goods can indifferently be artefacts or not artefacts. Likewise, they can indifferently be raw materials or processed materials. Domain: Economics - Business – Marketing
Labels:	*Labels used to address the concept, ordered as:* *skos:prefLabel:* Commercial Good *skos:altLabel: Good (Commercial); Good; Good (Economic); Ware; Merchandise* *skos:hiddenLabel: Product; Service; Article; Purchasable; Transactable Entity; Commodity; Tangible Article; Tangible Product*

Table 17 Knowledge domain resources for CommercialGood

Related Domain Resources:	-*WordNet 3.1:* articles of commerce. -*ISO 9000:* [product] "output of an organization that can be produced without any transaction taking place between the organization and the customer"; "production of a product is achieved without any transaction necessarily taking place between provider and customer, but can often involve this service element upon its delivery to the customer"; "the dominant element of a product is that it is generally tangible"; "Hardware is tangible and its amount is a countable characteristic (e.g. tyres). Processed materials are tangible and their amount is a continuous characteristic (e.g. fuel and soft drinks). Hardware and processed materials are often referred to as goods"; "software consists of information regardless of delivery medium (e.g. computer programme, mobile phone app, instruction manual, dictionary content, musical composition copyright, driver's license)". -ISO 14040: [product] "any goods or service"; "the product can be categorized as follows: — services (e.g. transport); — software (e.g. computer program, dictionary); — hardware (e.g. engine mechanical part); — processed materials (e.g. lubricant)"; "services have tangible and intangible elements. Provision of a service can involve, for example, the following: — an activity performed on a customer-supplied tangible product (e.g. automobile to be repaired); — an activity performed on a customer-supplied intangible product (e.g. the income statement needed to prepare a tax return); — the delivery of an intangible product (e.g. the delivery of information in the context of knowledge transmission); — the creation of ambience for the customer (e.g. in hotels and

	restaurants). Software consists of information and is generally intangible and can be in the form of approaches, transactions or procedures. Hardware is generally tangible and its amount is a countable characteristic. Processed materials are generally tangible and their amount is a continuous characteristic"; "adapted from ISO 14021:1999 and ISO 9000:2005".
Comments:	*This engineered OntoCommons bridge-concept aims to provide a detailed notion capable of helping users to better navigate business practice's logical space, increasing conceptual clarity and reducing ambiguities and misunderstandings. This bridge-concept was developed in accordance with both explicit requests from MLOs' stakeholders given OntoCommons' survey and pragmatic alignment needs.* *The defining trait of the OntoCommons bridge-concept, Good (Commercial), was chosen in a way that would ensure a common-sense & golden-standards friendly handle: association with a material entity. The specification, excluding material entities which act as legal placeholders or contingent mediums (concretisations) to the end of completing the transaction, avoids possible sources of doubt and concern for the users, eliminating ambiguities.* *Tangibility is explicitly mentioned in the definition: a decision warranted by its importance in the relevant literature. However -to the end of avoiding ambiguities and improving conceptual clarity- the related considerations were explicitly stated to be grounded on non-neutral background assumptions, to be alien with respect to the domain of economics, and the trait was specifically stated to be -at most- contingently derivative. Given the high risk of introducing biases by listing paradigmatic (yet not strictly necessary) characteristics and examples, they were kept to a minimum, and are mostly employed to make value gaps explicit.*

4.1.2 Alignments to existing ontologies

4.1.2.1 **Vertical alignments, TLOs**

BFO

Target Ontology:	*<http://purl.obolibrary.org/obo/bfo.owl>*
Related Ontology Entities:	*Material Entity: <http://purl.obolibrary.org/obo/BFO_0000040>*
Mapping Elucidation:	*Given BFO's internal organisation, the most pertinent option for an alignment seems to be BFO:Material Entity. Arguably, the relevant scenarios would be represented in BFO as involving a BFO:Material Entity in which inheres (BFO) a certain BFO:Role, possibly with further specifications about the transaction process and its participants. BFO's documentation is perfectly in line with some*

	of the traits characterising the proposed OntoCommons bridge-concept, Good (Commercial), and the alignment is reinforced by the treatment of supposedly similar concepts in MLOs based on BFO. It might be suggested that a more informative alignment could be established with subclasses of BFO:Material Entity (i.e. BFO:Object, BFO:Object Aggregate, or BFO:Fiat Object); however the classes are not mutually disjoint, as the relevant BFO universals are not rigid. Everything considered, there are good prima facie good reasons to believe that the link between the proposed OntoCommons bridge-concept and BFO:Material Entity is one of rdfs:subClassOf, as the specifications considered act as constraints on BFO:Material Entity.
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:subClassOf*
Mapping Axioms:	*TBD*

DOLCE

Target Ontology:	*<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic>*
Related Ontology Entities:	*Physical Object: <http://www.loa-cnr.it/ontologies/DOLCE-Lite.owl#physical-object>*
Mapping Elucidation:	*Taking into account DOLCE's background philosophical assumptions and internal organisation, DOLCE: Physical Object seems to be the best candidate for a connection, with no real alternatives, if not among its subclasses. The connection is quite straightforward and supported by the relevant documentation. It might appear prima facie plausible to connect the proposed OntoCommons bridge-concept, Good (Commercial) directly to DOLCE:Non-Agentive Physical Object, in order to establish a more informative connection, however nothing in the proposed definition bars goods from having intentions, beliefs and desires (consider for instance pets and livestock); so that link would be too restrictive, and ultimately mistaken.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:subClassOf*
Mapping Axioms:	*TBD*

EMMO

Target Ontology:	*<http://emmo.info/emmo>*

Related Ontology Entities:	*Role: <http://emmo.info/emmo#EMMO_4f226cf3_6d02_4d35_8566_a9e641bc6ff3>*
Mapping Elucidation:	*In EMMO, the holistic perspective represents entities according to their relations to the whole. Given EMMO's framework and background assumptions, it seems appropriate to look for a connection with the proposed OntoCommons bridge-concept,* Commercial *Product, in this branch. EMMO:Role, or one of its subclasses, seems to be an appropriate candidate for a meaningful connection, though it should be noted that the same entity could be represented differently under different guises (and not as something that is being explicitly offered on the market for purchase or barter). For instance, it might be worth considering some goods under the reductionistic or physicalistic perspective, or -within the boundaries of the holistic perspective- investigating the establishment of a connection with EMMO:Whole.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:subClassOf*
Mapping Axioms:	*TBD*

4.1.2.2 Horizontal alignments, MLOs

IOF Core

Target Ontology:	https://spec.inductrialontologies.org/ontology/202301/core/Core
Related Ontology Entities:	https://spec.industrialontologies.org/ontology/core/Core/MaterialProduct
Mapping Elucidation:	*IOFCore is based on BFO. As such, there are extremely good reasons, by analogy with BFO and as a result of the analysis of the pertinent documentation, to believe that the most meaningful connection is mediated by IOFCore:MaterialProduct, subclass of BFO:materialEntity while IOFCore:Material Product Role complements the IOFCore:Material Product class.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:subClassOf*
Mapping Axioms:	*TBD*

Allotrope

Target Ontology:	<http://purl.allotrope.org/voc/afo/merged-OLS/REC/2019/05/10>
Related Ontology Entities:	*Material Entity: <http://purl.obolibrary.org/obo/BFO_0000040>*
Mapping Elucidation:	*Allotrope is based on BFO. As such, there are extremely good reasons, by analogy with BFO and as a result of the analysis of the pertinent documentation, to believe that the most meaningful connection is mediated by Allotrope:Physical Product Role (Economic), subclass of Allotrope:Product Role (Economic) while Allotrope:Product Role is "a false friend". Physical Product Role (Economic) defines subclasses of Allotrope:Independent Continuant (via relations of inherence), and, specifically, of Allotrope:Material Entity, in line with the expectations concerning the relation between the latter and roles which were considered above.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:subClassOf*
Mapping Axioms:	*TBD*

BWMD

Target Ontology:	*<https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid>*
Related Ontology Entities:	*Technological Product: <https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00036>*
Mapping Elucidation:	*Like Allotrope, BWMD is based on BFO. Differently from other BFO-based MLOs, the role branch has not been populated actively with ML terms in this ontology; nonetheless there seems to be a prima facie good candidate for an informative connection directly among the subclasses of BWMD:Material Entity: i.e. BWMD:Technological Product. The relevant documentation and subclasses appear to be compatible, and, while there is an explicit focus on manufacturing aspects, playing a non-definitory role in the proposed OntoCommons bridge-concept, Good (Commercial), the target class stands opposed to BWMD:Engineering Material, highlighting a relevant difference. Nonetheless, the connection remains tentative, as there is no explicit mention of economic aspects, and the tentative semantic link rdfs:superClassOf, since BWMD:Technological Product does not encompass individuals which were not transformed.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:superClassOf*
Mapping Axioms:	*TBD*

4.1.3 Related existing concepts

4.1.3.1 IOFCore:Material Product (equivalent to PSS:PSS Product)

Table 18 General concept information for MaterialProduct

IRI:	https://spec.industrialontologies.org/ontology/core/Core/MaterialProduct
OWL Type:	*Class*
Concept Elucidation:	*material entity which has the material product role* *Examples of Usage:*Any manufactured good when it is offered for sale, supplied or being bought.
Labels:	*material product*

4.1.3.2 IOFCore:Material Product Role

Table 19 General concept information for MaterialProductRole

IRI:	https://spec.industrialontologies.org/ontology/core/Core/MaterialProductRole
OWL Type:	*Class*
Concept Elucidation:	*material product role is a role held by a material entity that is intended to be sold, or has been bought, or has been supplied* *Examples of Usage: a manufactured good has a material product role when a manufacturer offers it for sale; a drug product has a material product role when it is bought by a customer in a pharmacy; sea shells have a material product role when they are collected, packaged and offered for sale;*
Labels:	*material product role*

4.1.3.3 Physical Object (DOLCE)

Table 20 General concept information for physical-object

IRI:	*<http://www.loa-cnr.it/ontologies/DOLCE-Lite.owl#physical-object>*
OWL Type:	*Class*
Concept Elucidation:	*The main characteristic of physical objects is that they are endurants with unity. However, they have no common unity criterion, since different subtypes of objects may have different unity criteria. Differently from aggregates, (most) physical objects change some of their parts while keeping their identity, they can have therefore temporary parts. Often physical objects (indeed, all endurants) are ontologically independent from occurrences (discussed below). However, if we admit that every object has a life, it is hard to exclude a mutual specific constant dependence between the two. Nevertheless, we may still use*

	the notion of dependence to (weakly) characterize objects as being not specifically constantly dependent on other objects.
Labels:	*Physical Object*

Table 21 Knowledge domain resources for physical-object

Related Domain Resources:	*Dolce D18:* "within Physical Objects, a special place have those to which we ascribe intentions, beliefs, and desires. These are called Agentive, as opposite to Non-agentive. Intentionality is understood here as the capability of heading for/dealing with objects or states of the world. This is an important area of ontological investigation we haven't properly explored yet, so our suggestions are really very preliminary".

4.1.3.4 Role (EMMO)

Table 22 General concept information for Role

IRI:	*<http://emmo.info/emmo#EMMO_eb77076b_a104_42ac_a065_798b2d2809ad>*
OWL Type:	*Class*
Concept Elucidation:	In this class the concept of role and part are superimposed (the term part is also used to define the role played by an actor). Here entities are categorized according to their relation with the whole, i.e. how they contribute to make a specific whole, and not what they are as separate entities. This class is expected to host the definition of world objects as they appear in its relation with the surrounding whole (being a part implies being surrounded by something bigger to which it contributes). For example, an output is a part (a role or the final stage) of a process, but its specific nature as a whole (e.g. car, service) is categorized under the whole class branch. An entity that is categorized according to its relation with a whole through a parthood relation and that contributes to it according to an holistic criterion.
Labels:	*Role*

Table 23 Knowledge domain resources for Role

Related Domain Resources:	*No instances.*

4.1.3.5 Material Entity (Allotrope)

Table 24 General concept information for Material Entity

IRI:	<http://purl.obolibrary.org/obo/BFO_0000040>
OWL Type:	*Class*
Concept Elucidation:	A material entity is an independent continuant that at all times at which it exists has some portion of matter as continuant part. A physical product role is a role of some artifact that is produced for the purpose of sale. *Examples of Usage:* a human being, the undetached arm of a human being, an aggregate of human beings.
Labels:	*Material Entity*

Table 25 Knowledge domain resources for Material Entity

Related Domain Resources:	*Building Ontologies with BFO:* "material entity is an independent continuant that has some portion of matter as part. It is thus an independent continuant that is spatially extended in three dimensions, and that continues to exist through some interval of time, however short".

4.1.3.6 Technological Product (BWMD)

Table 26 General concept information for Technological Product

IRI:	*<https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00036>*
OWL Type:	*Class*
Concept Elucidation:	Technological products underwent some kind of manufacturing process and possess some kind of functionality.
Labels:	*Technological Product*

4.2 Materials science

4.2.1 Bridge Concepts

As a recap, the analysis of glossaries coverage in Materials Domain level ontologies reported in the previous Deliverable of Task 3.4 (D3.6) led to a list of potential bridge concepts including the following:

- Material

- Property (of Material)
- Structure (of Material)
- Materials Component
- Atom
- Experiment
- Materials Process

While the concept of ''Materials Process'' did not occur with a high frequency, the ontologies include a wide range of materials processes in a variety of ways, so that a general superclass would be helpful for bridging.

In this deliverable, we include an update of bridge concept developments for these and closely related terms, noting that the Bridge Concept for Materials Component was included in D3.6, i.e. here we elaborated Bridge Concepts for

- Physical Matter
- Material
- Molecular Entity
- Molecule
- Atom
- Physical Quantity
- Materials Property
- Materials Process
- Materials Processing
- Experiment

Since the concept of Material is obviously fundamental, but used relatively inconsistently and in different terminologies across the DLOs we elaborate a bit more in general terms about that and related concepts such as Physical Matter, Molecular Entity etc.

In particular, the questions are how the concept material relates to 'matter', and also how it relates to the field of chemistry, where the term 'chemical substance' has been defined in the IUPAC Goldbook as a ''Matter of constant composition best characterized by the entities (molecules, formula units, atoms) it is composed of''. Furthermore, the question is whether individual atoms and molecules (known as 'molecular entities' in the IUPAC Goldbook) are subclasses of materials or more broadly 'matter'.

The concepts Matter, Material, Substance, Molecular Entity and Chemical Species are closely interrelated and are used in the slightly different ways in the DLOs. While Matter, Material and Substance are sometimes used somewhat interchangeably, it is useful to come to a consensus about how they differentiate and relate to each other. As background we utilise the following elucidations:

(Physical) Matter has been elaborated as a Bridge Concept in OntoCommons WP2 and is included here for reference. It describes Matter as follows:

Physical Matter is that which occupies space and has rest mass.

This is a very wide concept which would include any entity including atoms, molecules, nanoparticles and macroscopic materials and substances. As such it seems justified to place (Physical) Matter at the top of a hierarchy.

Substance: The term substance is sometimes used almost interchangeably with matter or material, but is often defined in a somewhat narrower sense, e.g. in schema.org/substance as "Any matter of defined composition that has discrete existence, whose origin may be biological, mineral or chemical."

Furthermore, the question arises where and how to place elementary particles with rest mass, nuclei, atoms and molecules. This point is (at least partly) addressed by the term 'molecular entity' defined in the IUPAC Goldbook and also adapted in schema.org https://schema.org/MolecularEntity as: "Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity". It is noted in IUPAC Goldbook that a Molecular Entity is distinguish from ensembles of such entities which are termed "chemical species". The latter may also be a set of molecular entities, but we will refrain from providing general mappings of the 'chemical species' concept to Causal Structures (EMMO) and Objects (BFO) or to Collections (EMMO) and Object Aggregates (BFO).

Hence, individual molecular entities and substances are different types of matter. Substance is closely related to the intended OntoCommons Bridge Concept Material. However, Substance is often more restrictive in its use.

Generalising the IUPAC Goldbook definitions to all types of materials, we propose the following for the **OntoCommons Bridge Concepts Matter and Material**:

- Physical Matter is that which occupies space and has rest mass.
    - Note it includes individual atom and molecule entities (in general all 'molecular entities' as defined in IUPAC Goldbook)
- Material is an amount of matter at the super-molecular level.
    - It includes chemical substances or mixtures of substances in different states of matter or phases ('continuum matter'), as well as nanomaterials such as nanoparticles ('mesoscale matter').
- Chemical Substances are materials with defined chemical composition.
- Molecular Entity is an atom_based physical matter defined by an exact number of e-bonded atomic species and an electron cloud made of the shared electrons. It includes a single atom, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity.

Hence, Materials (including Chemical Substances) and Molecular Entities are disjoint types of Physical Matter, as shown in Figure 76 below.

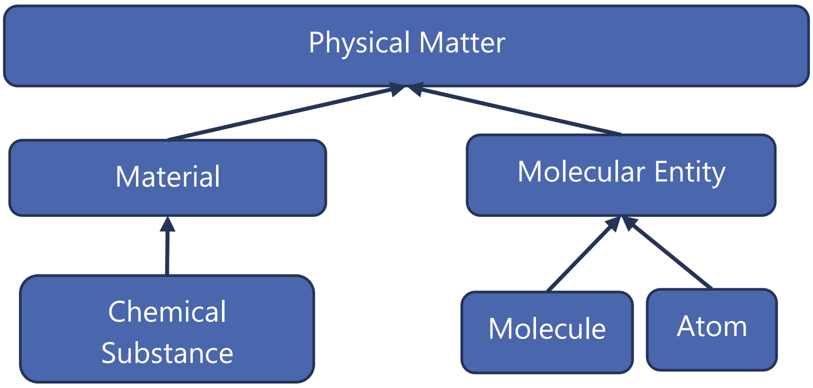

Figure 76 : Taxonomy of types of Physical Matter. Material and Molecular Entity are disjoint. There are other classes of Physical Matter not shown here, e.g. elementary particles. Types of Material and Molecular Entity discussed in Bridge Concepts are also included.

Hence OntoCommons:Material is broader than or superclass of a Chemical Substance, since the latter requires a defined composition, whereas the composition of a material may not even be known. Note that this is in contrast to the usage of materials classes in a number of DLOs.

Finally, we note that this task has contributed to a session on "Data representation in materials and chemicals based on harmonised domain ontologies" at the RDA Plenary 20 in Gothenburg (https://www.rd-alliance.org/data-representation-materials-and-chemicals-based-harmonised-domain-ontologies), a planned and RDA supported Working Group on the same topic (supported by the RDA Tiger scheme, https://www.rd-alliance.org/get-involved/calling-rda-community/rda-tiger) and an update of the activities in RDA Plenary 21 in Salzburg (see https://www.rd-alliance.org/plenaries/international-data-week-2023-salzburg/building-collaborative-bridges-fostering and https://www.rd-alliance.org/engineering-terminology-and-schema-lims).

A publication about this topic is in preparation, for submission to IEEE Access.

4.2.1.1 Physical Matter

General Concept Info:

IRI:	*PhysicalMatter*
OWL Type:	*Class*
Concept Elucidation:	Physical Matter is that which occupies space and has rest mass. The vast majority of everyday physical objects human beings interact with have parts which are quanta with non-zero rest mass, though the reduction of the former to the latter is scientifically inaccurate, and should be considered at most a pragmatic approximation. Physical Matter is not to be confused with Aristotelian Matter -a metaphysical posit- albeit the

	relevant notions are ultimately not unrelated, and common sense's understanding arguably sways in between the two. Domain: Natural Sciences - Physics.
Labels:	*Labels used to address the concept, ordered as:* *skos:prefLabel: Physical Matter* *skos:altLabel: Matter; Amount of Matter; (Amount of) Matter; Portion of Matter; (Portion of) Matter; Ordinary Matter* *skos:hiddenLabel: Stuff*

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	-*Wikipedia:* "matter is the substance of which objects are made"; "In classical physics and general chemistry, matter is any substance that has mass and takes up space by having volume. All everyday objects that can be touched are ultimately composed of atoms, which are made up of interacting subatomic particles, and in everyday as well as scientific usage, 'matter' generally includes atoms and anything made up of them, and any particles (or combination of particles) that act as if they have both rest mass and volume. However it does not include massless particles such as photons, or other energy phenomena or waves such as light or heat". -*Encyclopedia Britannica:* "matter, material substance that constitutes the observable universe and, together with energy, forms the basis of all objective phenomena. At the most fundamental level, matter is composed of elementary particles known as quarks and leptons". -*WordNet 3.1:* "that which has mass and occupies space". -*WikiData:* "substance that has rest mass and volume".
Comments:	The engineered OntoCommons bridge-concept, Physical Matter, aims to provide a general definition of matter focusing on some distinctive traits, while at the same time ruling out possible ambiguities due to the related term's etymology. For the sake of aligning the bridge-concept with stakeholders' demands and standard usage, it was decided to leave ample room to common-sense; clarifications were nonetheless included when they were deemed necessary to strike a balance between intuitiveness and scientific rigorousness. Notably, the chosen core traits play a pivotal role in the vast majority of the well-known and pervasively used domain resources which were consulted. This will ensure immediateness and intuitiveness for domain experts and ontologists, while at the same time improving the usability for non-experts. The risk of meaning/conceptual shift, and thus, obsoleteness, is also reduced. Finally Physical Matter was explicitly distinguished from the metaphysical Aristotelian Matter, as the similarities are not strong enough to ensure interoperability, yet abundantly capable of generating confusions. Nonetheless the two concepts are by all means related, and often con-fused in hybrid concepts.

ALIGNMENTS TO EXISTING ONTOLOGIES: *(1: VERTICAL, TLOS; 2: HORIZONTAL, MLOS)*

1: VERTICAL ALIGNMENTS

BFO

Target Ontology:	*<http://purl.obolibrary.org/obo/bfo.owl>*

Related Ontology Entities:	*Material Entity: <http://purl.obolibrary.org/obo/BFO_0000040>*
Mapping Elucidation:	In BFO, Material Entities are explicitly stated to be independent continuants that have some portions of matter as their part. Given that, the enquiry should be focused on those entities which can be part of BFO's Material Entities. Arguably, there aren't many relevant candidates, all of which are subclasses of BFO:Material Entity. In fact, it seems inappropriate to think of Physical Matter in terms of BFO's Object Aggregates, but that's an interpretation which cannot be entirely ruled out. As such the most informative and appropriate alignment is arguably with the class BFO:Material Entity itself, and, specifically, the union of BFO:Object and BFO:Object Aggregate. The classes are not mutually disjoint as the relevant BFO universals are not rigid, so there is no major loss of informativeness considering a class closer to the root. There do not seem to be evidence in favour of a different alignment.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	TBD

DOLCE

Target Ontology:	<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic>
Related Ontology Entities:	AmountOfMatter: <http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic#AmountOfMatter>
Mapping Elucidation:	Part of what has been said with respect to BFO:Material Entity is relevant when it comes to DOLCE:Physical Endurant. However, the choice of a subclass is in this case possible and, in fact, almost immediate, qua suggested both by the linguistic label and the relevant documentation: DOLCE:Amount of Matter. However, at a closer inspection, DOLCE's concept seems heavily influenced by the metaphysical, Aristotelian/Neo-Aristotelian connotation from which we decided to part in the definition of the OntoCommons bridge-concept, Physical Matter. Nonetheless, it is important to consider the alignment holistically, taking into proper account the background assumptions underlying DOLCE's framework: all things considered, DOLCE's concept arguably falls in the "hybrid" territory, and it doesn't seem necessary to weaken the semantic relation from rdfs:equivalentClass to skos:related, especially since the core traits which were chosen to characterise the proposed bridge-concept are explicitly endorsed.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:equivalentClass
Mapping Axioms:	TBD

EMMO

Target Ontology:	<http://emmo.info/emmo>
Related Ontology Entities:	Matter: <http://emmo.info/emmo#EMMO_5b2222df_4da6_442f_8244_96e9e45887d1>
Mapping Elucidation:	EMMO:Matter seems to be the perfect candidate for a meaningful and informative alignment with the OntoCommons bridge-concept Physical Matter, with no real

	contenders. EMMO:Matter belongs -in line with expectations- to the physicalistic perspective; the concept is explicitly characterised alongside Field and Vacuum referring to a state-of-the-art scientific paradigm, that is the Standard Model of particle physics. It should be noted that the relevant EMMO concept has no direct link with common-sense/intuitiveness, differently from the bridge-concept. However, taking into account EMMO's framework, that is arguably to be expected, and the (applied) sciences-friendly definition provided in EMMO is ultimately perfectly in line with the one put forward by the OntoCommons team. It is worth noting that, while not all the traits are explicitly endorsed in EMMO:Matter's elucidation, they can be all be recovered/inferred by considering the class' superclasses', and taking into account EMMO's overall framework. The most pertinent alignment is thus that of class-equivalence.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:equivalentClass
Mapping Axioms:	TBD

2: Horizontal Alignments

Domain Mechanical Testing (EMMO-MECH-TEST)

Target Ontology:	<http://emmo.info/emmo/domain/mechanical-testing>
Related Ontology Entities:	Matter: <http://emmo.info/emmo/middle/physicalistic#EMMO_5b2222df_4da6_442f_8244_96e9e45887d1>
Mapping Elucidation:	The Domain Mechanical Testing ontology EMMO-MECH-TEST is based on EMMO; as such what has been said above can be applied mutatis mutandis in this case. Given the proposed semantic link, the absence of better candidates should come as no surprise. However, it should be noted that EMMO-MECH-TEST is based on an outdated version of EMMO. Nonetheless, there are no significant differences compromising the alignment, or modifying the semantic relationship between the proposed OntoCommons bridge-concept, Physical Matter, and EMMO-MECH-TEST's Matter.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:equivalentClass
Mapping Axioms:	TBD

RELATED EXISTING CONCEPTS

TLOs

MATERIAL ENTITY (BFO)

General Concept Info:

IRI:	<http://purl.obolibrary.org/obo/BFO_0000040>
OWL Type:	Class
Concept Elucidation:	A material entity is an independent continuant that at all times at which it exists has some portion of matter as continuant part.

	Examples of Usage: a human being, the undetached arm of a human being, an aggregate of human beings.
Labels:	Material Entity

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	Building Ontologies with BFO: "material entity is an independent continuant that has some portion of matter as part. It is thus an independent continuant that is spatially extended in three dimensions, and that continues to exist through some interval of time, however short.".

AMOUNT OF MATTER (DOLCE)

GENERAL CONCEPT INFO:

IRI:	<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic#AmountOfMatter>
OWL Type:	Class
Concept Elucidation:	An Amount Of Matter is a physical endurant which has no unity criterion and is mereologically invariant, that is, all its part are essential parts. Examples of Usage: the gold of my wedding ring, the sand used to make this glass.
Labels:	AmountOfMatter

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	No instances.

MATTER (EMMO)

GENERAL CONCEPT INFO:

IRI:	<http://emmo.info/emmo#EMMO_5b2222df_4da6_442f_8244_96e9e45887d1>
OWL Type:	Class
Concept Elucidation:	A physical system that possesses some fundamental fermionic parts in each of its parts.
Labels:	Matter

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	European Materials Modelling Ontology v. 1.0.0 alpha 2: "Matter: A 'Physical' that possesses some 'Massive' parts".

4.2.1.2 Material

General Concept Info:

IRI:	*Material*
OWL Type:	*Class*

Concept Elucidation:	**Material is an amount of matter at the super-molecular level.** Comment: See also the OntoCommons:PhysicalMatter Bridge Concept, which is elucidated: "Physical Matter is that which occupies space and has rest mass." It includes atoms and molecule. Comment: It includes chemical **substances** or mixtures of substances in different states of matter or phases ('continuum matter'), as well as nanomaterials such as nanoparticles ('mesoscale matter'). Comment: **Substance** in Chebi and Schema.org (https://schema.org/Substance): Any matter of defined composition that has discrete existence, whose origin may be biological, mineral or chemical. Comment: Only the EMMO is specific about the difference between matter and material. There are matter items that are not materials are e.g. electrons, atoms and molecules. Comment: Many ontologies do not define the notion material, but only the concept "material entity" which is the indication of any object of a material rather than abstract nature. Comment: Materials are often classified by either properties (e.g. magnetic materials), structure (e.g. composite material, porous materials), chemistry (e.g. metals, organometallic materials) or application (electronic materials, building materials). Comment: the subclasses of materials like e.g. thermal materials (materials used to conduct or isolate heat) will find a more straightforward alignment as all ontologies have the same intentions with such concepts.
Labels:	*i) Preferred:* **Material** *ii) Alternative labels:* **Substance**: depending on context, Substance is a wider concept meaning all types of matter, or narrower as in Schema.org/substance, being of defined composition. **Matter**: a concept that is wider than material, see above.

Knowledge Domain Resources:

Related Domain Resources:	1. Schema.org Defines 'Substance' (see above). Also defines Material in the context of Products and CreativeWork items as (https://schema.org/material): A **material** that something is made from, e.g. leather, wool, cotton, paper. 2. Wikipedia: Material is a substance or mixture of substances that constitutes an object. Materials can be pure or impure, living or non-living matter. Materials can be classified on the basis of their physical and chemical properties, or on their geological origin or biological function. In classical physics and general chemistry, matter is any substance that has mass and takes up space by having volume. 3. Merriam-Webster: Relating to, derived from, or consisting of matter especially physical; bodily 4. Wikidata:

	material (Q214609): substance that can occur in different amounts, all with some similar [mixture of some] characteristics, and of which objects can be made up. 5. ISO Standards: While there are no definitions of Material, related terms such as Nanomaterial and Substance are defined. ISO/TS 8004: **Nanomaterial:** a "material with any external dimension in the nanoscale or having internal structure or surface structure in the nanoscale". This includes both nano-objects, which are discrete pieces of material, and nanostructured materials, which have internal or surface structure on the nanoscale; a nanomaterial may be a member of both these categories. https://en.wikipedia.org/wiki/ISO/TS_80004 ISO/TS 22703:2021(en), 3.23: **Substance**: matter of defined composition that has discrete existence, whose origin may be biological, mineral or chemical [SOURCE: ISO 11238:2018, 3.84, modified]
Comments:	Materials Science classical textbook, such as Callister and the glossary by Raabe do not include definitions or elucidations of the term 'material' itself. The concept definition orients itself at the overarching features described in the domain resources, while keeping to the most general nature; avoiding unnecessary restrictions such as 'defined composition' while keeping to the generally macroscopic interpretation of a material, hence separating out molecular entities and below (see also the separate Molecular entity Bridge Concept).

Alignments To Existing Ontologies:

1: Vertical Alignments

OntoCommons: Material is a type of Physical Matter. See the Physical Matter Bridge Concept for Vertical Alignments to EMMO, BFO and DOLCE TLOs.

2: Horizontal Alignments (between DLOs)

MaterialsMine

Target Ontology:	*http://materialsmine.org/ns*
Related Ontology Entities:	There is no Material class. Material Entity (http://semanticscience.org/resource/MaterialEntity) A material Entity is defined as "A material entity is a physical entity that is spatially extended, exists as a whole at any point in time and has mass." It is a subclass of Object. Object is defined as in "http://semanticscience.org/ontology/sio/v1.53/sio-subset-labels.owl". Chemical Entity (http://semanticscience.org/resource/ChemicalEntity) Chemical entity is defined as "A chemical entity is a material entity that pertains to chemistry". It is a subclass of Material entity. Chemical substance (http://semanticscience.org/resource/ChemicalSubstance)

	Chemical substance is defined as" A chemical substance is a chemical entity composed of two or more weakly (non-covalently) interacting chemical entities." It is a subclass of Chemical entity.
Mapping Elucidation:	OntoCommons:Material is clearly a kind of Material Entity, but wider than a Chemical Entity and Chemical Substance, as already outlined in the Bridge Concept elucidation
Semantic Relation Level:	Strong hierarchical
Mapping Axioms:	OntoCommons:Material rdfs:subClassOf MaterialsMine:MaterialEntity MaterialsMine:ChemicalSubstance rdfs:subClassOf OntoCommons:Material

Nanomine

Target Ontology:	*http://nanomine.tw.rpi.edu/ns*
Related Ontology Entities:	ChemicalSubstance(http://semanticscience.org/resource/ChemicalSubstance) Nanomaterial (http://nanomine.tw.rpi.edu/ns/Nanomaterial) Nanomaterial is defined as "materials of which a single unit is sized (in at least one dimension) between 1 and 1000 nanometres (10^{-9} meter) but is usually 1—100 nm" It is a Subclass of Chemical Substance that is not defined
Mapping Elucidation:	Comment: only the size is explained but not what a material is.
Semantic Relation Level:	Strong Hierarchical
Mapping Axioms:	NANOMINE:Nanomaterial rdfs:subClassOf Ontocommons:material

NPO

Target Ontology:	*http://purl.bioontology.org/ontology/npo#NPO_147*
Related Ontology Entities:	Material is not defined Comment: Material Entity (http://purl.bioontology.org/ontology/npo#NPO_672" http://purl.bioontology.org/ontology/npo#NPO_672) is defined as "An independent continuant [snap:IndependentContinuant] which is spatially extended and composed of matter. The identity of material entities is independent of that of other entities and can be maintained through time." Chemical entity(http://purl.bioontology.org/ontology/npo#NPO_1973) Chemical Entity is defined as "A material entity which can be identified as an atom, ion, isotope, molecule/compound or particle" Chemical substance (http://purl.bioontology.org/ontology/npo#NPO_1972) Chemical Substance Is a subclass of Chemical Entity defined as "A chemical entity which can be identified based on its physical state, chemical composition or molecular structure; Particle(http://purl.bioontology.org/ontology/npo#NPO_1895) Particle is a subclass of Chemical entity and it is defined as :A material entity which is a minute portion of matter.

Mapping Elucidation:	Chemical entity is closely related to Matter Subclasses of Chemical entity: • Atom, Ion, Molecular entity are types of Matter (not included in OntoCommons:Material; • in EMMO they are included in ParticulateMatter) • Chemical substance and Particle are related to OntoCommons:Material
Semantic Relation Level:	Strong hierarchical
Mapping Axioms:	OntoCommons:Material is superclass of NPO:chemical substance OntoCommons:Material is superclass of NPO:particle

MSEO

Target Ontology:	*https://purl.matolab.org/mseo/mid*
Related Ontology Entities:	Material is not elucidated The following concepts appear: Matter Object (https://purl.matolab.org/mseo/mid/MatterObject) Matter Object is not defined in MSEO. It is a subclass of: Object (http://purl.obolibrary.org/obo/BFO_0000030) Object is defined as “a material entity which manifests causal unity & is of a type instances of which are maximal relative to the sort of causal unity manifested)” It is a subclass of Material Entity. Material Entity (http://purl.obolibrary.org/obo/BFO_0000040" http://purl.obolibrary.org/obo/BFO_0000040) Material Entity is defined as ” A material entity is an independent continuant that at all times at which it exists has some portion of matter as continuant part” ChemicalEntity(http://purl.obolibrary.org/obo/CHEBI_24431) Chemical Entity is a subclass of Matter object ChemicalEntity is defined as “A chemical entity is a physical entity of interest in chemistry including molecular entities, parts thereof, and chemical substances.” Chemical substance is not defined as a class, it participates in the explanatory note of other classes as the class of Agent (role)
Mapping Elucidation:	Apart from OntoCommons:Materials being a subclass of Materials Entity, the concepts in MSEO are insufficiently elucidate to provide semantic relationship levels. Material or Matter is similar to Matter Object.
Semantic Relation Level:	None
Mapping Axioms:	

LPBFO

Target Ontology:	*https://www.emi.fraunhofer.de/ontologies/LPBFO*
Related Ontology Entities:	There are no material, chemical substance or substance classes Material Entity (http://purl.obolibrary.org/obo/BFO_0000040) Material Entity is defined as "A material entity is an independent continuant that has some portion of matter as proper or improper continuant part." Matter Object (https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00132) Matter Object is defined as "Any kind of basic matter object, e.g. atoms, chemical elements, electrons....".Il is a subclass of Object that is defined as in MSEO Ontology Object (http://purl.obolibrary.org/obo/BFO_0000030) Substance, chemical substance are not classes. Substance is only in AmountOfSubstance that is a subclass of QuantityKind. Chemical only in Chemicalelement that is a subclass of Matterobject and it is referred to periodic table. Material is associated to MaterialStructure
Mapping Elucidation:	See comments above
Semantic Relation Level:	See MSEO remarks
Mapping Axioms:	

MatOnto

Target Ontology:	http://matonto.org/ontologies/matonto
Related Ontology Entities:	Material (http://matonto.org/ontologies/matonto#Material) ChemicalSubstance (http://ontology.dumontierlab.com/ChemicalSubstance) Material is defined as "A chemical substance that is studied in materials science." Material is a subclass of Chemical Substance. Chemical Substance is defined as "Any material with a definite chemical composition." It is a subclass of Object Object is defined as" A independent continuant that is spatially extended, maximally self-connected and self-contained (the parts of a substance are not separated from each other by spatial gaps) and possesses an internal unity. The identity of substantial objects is independent of that of other entities and can be maintained through time and through loss and gain of parts and qualities" Comment: The conceptualisation makes use of the ontology and this is a circular statement.
Mapping Elucidation:	Comment: it seems that the intentions are the same as those of ONTOCOMMONS bridge term, but it is not clear how this concept relates to ONTOCOMMONS:PhysicalMatter or ONTOCOMMONS:Material and there is thus no guarantee where all items classified under material will also be a material in ONTOCOMMONS or only a ONTOCOMMONS:PhysicalMatter.
Semantic Relation Level:	Strong hierarchical
Mapping Axioms:	MatOnto:material subclassOf ONTOCOMMONS:PhysicalMatter

EMMO and EMMO-based Domain ontologies

Target Ontology:	http://emmo.info/emmo/1.0.0-beta4
Related Ontology Entities:	Material (http://emmo.info/emmo#EMMO_4207e895_8b83_4318_996a_72cfb32acd94) Substance(http://emmo.info/emmo#57d977ab_0036_4779_b59a_e47620afdb9c) Matter(http://emmo.info/emmo#EMMO_5b2222df_4da6_442f_8244_96e9e45887d1) Matter is defined as "A ' A physical system that possesses some fundamental fermionic parts in each of its parts." Material is defined as " A matter individual that stands for a real world object representing an amount of a physical substance (or mixture of substances) in different states of matter or phases." It is a subclass of Substance, which is not defined
Mapping Elucidation:	OntoCommons:Material is largely inspired by Material elucidation in EMMO.
Semantic Relation Level:	Equivalence
Mapping Axioms:	owl:equivalentClass

4.2.1.3 Molecular Entity

General Concept Info:

IRI:	Molecular Entity
OWL Type:	*Class*
Concept Elucidation:	Molecular Entity is a physical matter defined by an exact number of e-bonded atomic species and an electron cloud made of the shared electrons. It includes a single atom, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity. Comment: This concept is wider than molecule (neutral and excluding a single atom, non-periodic) and includes e.g. periodic structures like nanotube, non-neutral entities like ions and radicals and also the single atom is included. Comment: The definition is not based on properties, nor on composition. Comment: chemical substances are composed of molecular entities Note A conformer is a conformation of a molecule that lies at an energy minimum in a potential energy diagram.
Labels:	*Labels used to address the concept, ordered as:* *iii) preferred (one)* Molecular entity

	iv) alternative (multiple) None

Knowledge Domain Resources:

Related Domain Resources:	4. Schema.org: Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity. 5. Wikipedia: A molecular entity, or chemical entity, is "any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer, etc., identifiable as a separately distinguishable entity". A molecular entity is any singular entity, irrespective of its nature, used to concisely express any type of chemical particle that can exemplify some process: for example, atoms, molecules, ions, etc. can all undergo a chemical reaction. Chemical species is the macroscopic equivalent of molecular entity and refers to sets or ensembles of molecular entities. 2. Merriam-Webster: **Not included** 3. Callister: No definition is given, only molecular chemistry and polymer molecular structure is. 4. Raabe: No definition. 5. Wikidata: molecular entity (Q2393187) : any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer, etc., identifiable as a separately distinguishable entity 6. IUPAC-Goldbook: molecular entity

	Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex,conformer etc., identifiable as a separately distinguishable entity. Molecular entity is used in this Compendium as a general term for singular entities, irrespective of their nature, while chemical species stands for sets or ensembles of molecular entities. Note that the name of a compound may refer to the respective molecular entity or to the chemical species, e.g. methane, may mean a single molecule of CH_4 (molecular entity) or a molar amount, specified or not (chemical species), participating in a reaction. The degree of precision necessary to describe a molecular entity depends on the context. For example 'hydrogen molecule' is an adequate definition of a certain molecular entity for some purposes, whereas for others it is necessary to distinguish the electronic state and/or vibrational state and/or nuclear spin, etc. of the hydrogen molecule. 7. Brittanica dictionary: **Not included** 8 ISO Standards: Not included 9 IOF Core: Not included
Comments:	

Alignments To Existing Ontologies: *(1: vertical, MLOs/TLOs; 2: horizontal, DLOs)*

1: Vertical Alignments

NA

2: Horizontal Alignments

NPO

Target Ontology:	*http://purl.bioontology.org/ontology/npo#NPO_147*
Related Ontology Entities:	Molecular Entity is not included. Chemical Entity (http://purl.bioontology.org/ontology/npo#NPO_1972) Chemical Entity is defined as “A material entity which can be identified as an atom, ion, isotope, molecule/compound or particle” *Chemical substance(http://purl.bioontology.org/ontology/npo#NPO_1973)*

	Chemical Substance is a subclass of Chemical Entity. ChemicalSubstance is defined as "A chemical entity which can be identified based on its physical state, chemical composition or molecular structure". *Pure Substance(http://purl.bioontology.org/ontology/npo#NPO_1974)* *Pure substance is a subclass of Chemical Substance and is defined as "A chemical substance which as a constant, defined composition and cannot be separated into simpler substances by physical methods."* *Molecule is a subclass of Pure Substance. A molecule is a group of atoms bonded together, representing the smallest fundamental unit of a chemical compound that can take part in a chemical reaction."*
Mapping Elucidation:	*ChemicalEntity does not include* radical, radical ion, complex, conformer etc.,
Semantic Relation Level:	• *Strong rdfs Hierarchical* • *Weak skos Hierarchical*
Mapping Axioms:	*NPO:ChemicalEntity rdfs:subClassOf ONTOCOMMONS:MolecularEntity* *NPO:ChemicalEntity skos:narrower ONTOCOMMONS:MolecularEntity*

MSEO

Target Ontology:	*https://purl.matolab.org/mseo/mid*
Related Ontology Entities:	Molecular Entity is not included. Included are the following concepts and these are discussed in the BT doc Molecule Molecule(http://semanticscience.org/resource/Molecule) Cluster(http://semanticscience.org/resource/Cluster) Matter Object (https://purl.matolab.org/mseo/mid/MatterObject) Molecule is not defined, nor is Cluster, nor is Matter Object.

Mapping Elucidation:	As the concepts are not elucidated we can only guess and anticipate that ONTOCOMMONS:MolecularEntity is a subclass of the more generic cluster, matter object and object.

Materialsmine== Nanomine

Target Ontology:	http://materialsmine.org/ns
Related Ontology Entities:	Molecular Entity is not included Included are Molecule (http://semanticscience.org/resource/Molecule) which is discussed in the Bridge Concept Molecule. Also included are Chemical Entity(http://semanticscience.org/resource/ChemicalEntity) Material Entity(http://semanticscience.org/resource/MaterialEntity) Object(http://semanticscience.org/resource/Object) Chemical Entity is defined as "A chemical entity is a material entity that pertains to chemistry." Chemical Entity is a subclass of Material entity, defined as "A material entity is a physical entity that is spatially extended, exists as a whole at any point in time and has mass." MaterialEntity is a subclass of object, defined as "An object is an entity that is wholly identifiable at any instant of time during which it exists."
Mapping Elucidation:	*The elucidation of chemical entity is not very precise and should encompass ONTOCOMMONS:molecular entity*
Semantic Relation Level:	• *Strong rdfs Hierarchical* • *Weak skos Hierarchical*
Mapping Axioms:	*ONTOCOMMONS:molecularEntity rdfs:subClassOf MaterialMine:chemicalEntity* *ONTOCOMMONS:molecularEntity skos:narrower MaterialMine:chemicalEntity*

LPBFO==MSEO

CHEBI

Target Ontology:	http://purl.obolibrary.org/obo/chebi

Related Ontology Entities:	*MolecularEntity* (http://purl.obolibrary.org/obo/CHEBI_23367*)*: Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer etc. identifiable as a separately distinguishable entity. *Molecular Entity is a subclass of Chemical Entity, defined as "*A chemical entity is a physical entity of interest in chemistry including molecular entities, parts thereof, and chemical substances.*"* *Polyatomic Entity is a subclass of Molecular entity, defined as "*Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity.*"* *Molecule is a subclass of PolyatomicEntity and is defined as "*Any polyatomic entity that is an electrically neutral entity consisting of more than one atom.*"* *Molecule is defined as "*Any molecular entity consisting of more than one atom.*"* *Chemical entity(*http://purl.obolibrary.org/obo/CHEBI_24431) *PolyatomicEntity(*http://purl.obolibrary.org/obo/CHEBI_36357) *Molecule(*http://purl.obolibrary.org/obo/CHEBI_25367*)*
Mapping Elucidation:	*Although the ONTOCOMMONS elicidation is stricter it can be assumed that the two concepts are used in the same way.*
Semantic Relation Level:	Equivalence
Mapping Axioms:	owl:equivalentClass

RNXO

Target Ontology:	*http://purl.obolibrary.org/obo/rxno.owl*
Related Ontology Entities:	Molecular Entity is not included, nor is Molecule The concept Macromolecule is included and aligned to CHEBI Ontology MacroMolecule(http://purl.obolibrary.org/obo/CHEBI_33839)

MatOnto

Target Ontology:	*http://purl.obolibrary.org/obo/rxno.owl*

EMMO

Target Ontology:	*http://emmo.info/emmo/1.0.0-beta4*
Related Ontology Entities:	*Molecular Entity (http://emmo.info/emmo#EMMO_21205421_5783_4d3e_81e5_10c5d894a88a)* *Molecular Entity that is defined as "Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity."* *Molecular Entity is a subclass of Matter, defined as "A 'Physical' that possesses some 'Lepton' or 'Quark' parts in each of its temporal parts."* *Molecule is a subclass of Molecular Entity and is further discussed in the Bridge Concept Molecule* *Matter(http://emmo.info/emmo#EMMO_5b2222df_4da6_442f_8244_96e9e45887d1)*
Mapping Elucidation:	
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* • *Equivalence (strong mapping)*
Mapping Axioms:	owl:equivalentClass

4.2.1.4 Molecule

General Concept Info:

IRI:	*Molecule*
OWL Type:	*Class*
Concept Elucidation:	Molecule is a physical matter defined by an exact number of e-bonded atomic species and an electron cloud made of the shared electrons. Comment: periodic entities like nanotubes are excluded Comment: non-neutral entities are excluded. Comment: one atom is not included.

	Comment: the type of bond between constituents is defined as e-bonded, which is more precise than a definition stating "by attractive forces" and less exclusive than a definition based on potential energy. Comment: The definition is not based on properties. Comment: Molecule is one type of Molecular Entity. The last also includes periodic, non-neutral, single atom entities.
Labels:	*Labels used to address the concept, ordered as:* *v) preferred (one)* Molecule (more than one atom) *vi) alternative (multiple)* None

Knowledge Domain Resources:

Related Domain Resources:	6. Schema.org Not included 7. Wikipedia: A **molecule** is a group of two or more atoms held together by attractive forces known as chemical bonds; depending on context, the term may or may not include ions which satisfy this criterion. In quantum physics, organic chemistry, and biochemistry, the distinction from ions is dropped and *molecule* is often used when referring to polyatomic ions. 2. Merriam-Webster: The smallest particle of a substance that retains all the properties of the substance and is composed of one or more atoms. 3. Callister: No definition is given, only molecular chemistry and polymer molecular structure is. 4. Raabe: No definition. 5. Wikidata: molecule (Q11369) electrically neutral entity consisting of more than one atom (n > 1); rigorously, a molecule, in which n > 1 must correspond to a depression on the potential energy surface that is deep enough to confine at least one vibrational state

	6. IUPAC-Goldbook: An electrically neutral entity consisting of more than one atom (n>1). Rigorously, a molecule, in which n>1 must correspond to a depression on the potential energy surface that is deep enough to confine at least one vibrational state.. 7. Britannica dictionary: **molecule**, a group of two or more atoms that form the smallest identifiable unit into which a pure substance can be divided and still retain the composition and chemical properties of that substance. 8 ISO Standards: The singular term molecule is not defined in ISO Standards. Instead, particular molecules or roles that molecules have, or properties of molecules are defined. E.g.: linker molecule, reporter molecule, oligomer molecule. 9 IOF Core: Molecule does not appear as a class and as term in other classes definition 10 MATPORTAL: see
Comments:	

Alignments To Existing Ontologies: *(1: vertical, MLOs/TLOs; 2: horizontal, DLOs)*

1: Vertical Alignments

NA

2: Horizontal Alignments

Nanomine

Target Ontology:	*http://nanomine.tw.rpi.edu/ns*
Related Ontology Entities:	Molecule(http://semanticscience.org/resource/Molecule) Molecule is defined as "A molecule is a single chemical entity composed of fully covalently bonded atoms." Molecule is a subclass of Chemical Entity ((Chemical Entity(http://semanticscience.org/resource/ChemicalEntity)

	defined as "A chemical entity is a material entity that pertains to chemistry." Chemical Entity is a subclass of Material entity (Material Entity(http://semanticscience.org/resource/Molecule) defined as "A material entity is a physical entity that is spatially extended, exists as a whole at any point in time and has mass."
Mapping Elucidation:	
Semantic Relation Level:	Equivalent
Mapping Axioms:	*owl:equivalentClass*

NPO: NanoParticle Ontology for Cancer Nanotechnology Research

Target Ontology:	*http://purl.bioontology.org/ontology/npo#NPO_147*
Related Ontology Entities:	A molecule is a group of atoms bonded together, representing the smallest fundamental unit of a chemical compound that can take part in a chemical reaction." It is a subclass of Pure Substance (see discussion in BT Molecular Entity)
Mapping Elucidation:	*The elucidation is not very precise in its specification of the bonding between the atoms. The elucidation is hinging on a property (chemical).*
Semantic Relation Level:	*Similarity (e.g. skos:related).*
Mapping Axioms:	

MSEO Material Science and Engineering Ontology

Target Ontology:	*https://purl.matolab.org/mseo/mid*
Related Ontology Entities:	*Molecule is not defined.*

Materialsmine== Nanomine

Target Ontology:	*http://materialsmine.org/ns*

Related Ontology Entities:	*Molecule(http://semanticscience.org/resource/Molecule)* *Molecule is defined as "A molecule is a single chemical entity composed of fully covalently bonded atoms."* *Product, isomer, substrate are subclasses of Molecule.* *Molecule is a subclass of Chemical Entity that is defined as "A chemical entity is a material entity that pertains to chemistry."* *Chemical Entity(http://semanticscience.org/resource/ChemicalEntity)*
Mapping Elucidation:	*The elucidation hinges on a property (chemical) , but is otherwise similar. ONTOCOMMONS:molecules might not be chemical.*
Semantic Relation Level:	
Mapping Axioms:	MM:molecule SubClass of ONTOCOMMONS:molecule

LPBFO==MSEO

Target Ontology:	*https://www.emi.fraunhofer.de/ontologies/LPBFO*
Related Ontology Entities:	*LPBFO has the same taxonomy of MSEO but here there are references to concepts of the classes* *Molecule is defined by https://en.wikipedia.org/wiki/Molecule.*

CHEBI

Target Ontology:	http://purl.obolibrary.org/obo/chebi
Related Ontology Entities:	*Molecule(*http://purl.obolibrary.org/obo/CHEBI_25367*)* *Molecule is defined as "*Any polyatomic entity that is an electrically neutral entity consisting of more than one atom.*"* It is a subclass of Polyatomic Entity that is defined as "Any molecular entity consisting of more than one atom." *PolyatomicEntity(*http://purl.obolibrary.org/obo/CHEBI_36357) Polyatomic Entity is a subclass of Molecular entity, defined as "Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity." *MolecularEntity (*http://purl.obolibrary.org/obo/CHEBI_23367*)*

	Molecular Entity is a subclass of Chemical Entity, defined as "A chemical entity is a physical entity of interest in chemistry including molecular entities, parts thereof, and chemical substances." *Chemical entity*(http://purl.obolibrary.org/obo/CHEBI_24431)
Mapping Elucidation:	The bonding between the atoms is not described and the concept is thus wider than the Ontocommons concept.
Semantic Relation Level:	*Strong Hierarchical*
Mapping Axioms:	*ONTOCOMMONS:molecule rdfs:subClassOf CHEBI:molecule*

RNXO

Target Ontology:	*http://purl.obolibrary.org/obo/rxno.owl*
Related Ontology Entities:	*MacroMolecule(http://purl.obolibrary.org/obo/CHEBI_33839)*
Mapping Elucidation:	*Molecule is not a class, and Macromolecule is aligned to CHEBI Ontology*

MatOnto

Target Ontology:	*http://purl.obolibrary.org/obo/rxno.owl*
Related Ontology Entities:	Molecule(http://ontology.dumontierlab.com/Molecule) Molecule is defined as "A collection of atoms of definite composition and connectivity held together by chemical bonds."
Mapping Elucidation:	The bonds need not be e-bonds (electrostatic bonds are also chemical bonds) and the concept is thus wider.
Semantic Relation Level:	*Similarity (e.g. skos:related).*
Mapping Axioms:	

EMMO

Target Ontology:	*http://emmo.info/emmo/1.0.0-beta4*

Related Ontology Entities:	Molecule(http://emmo.info/emmo#EMMO_3397f270_dfc1_4500_8f6f_4d0d85ac5f71) Molecule is defined as "An atom_based state defined by an exact number of e-bonded atomic species and an electron cloud made of the shared electrons." It is a subclass of Molecular Entity that is defined as "Any constitutionally or isotopically distinct atom, molecule, ion, ion pair, radical, radical ion, complex, conformer etc., identifiable as a separately distinguishable entity." Molecular Entity http://emmo.info/emmo#EMMO_21205421_5783_4d3e_81e5_10c5d894a88a Molecular Entity is a subclass of Matter, defined as "A 'Physical' that possesses some 'Lepton' or 'Quark' parts in each of its temporal parts." Matter(http://emmo.info/emmo#EMMO_5b2222df_4da6_442f_8244_96e9e45887d1)
Mapping Elucidation:	*Equivalence*
Semantic Relation Level:	*Equivalence (strong mapping)*
Mapping Axioms:	*owl:equivalentClass*

4.2.1.5 Atom

GENERAL CONCEPT INFO:

IRI:	*Suggested entity new IRI.*
OWL Type:	*Class*
Concept Elucidation:	An atom is a nucleus surrounded by an electron cloud. The nucleus consists of electrically positive protons and electrically neutral neutrons, and carries almost all of the atom's mass; the electron cloud is a quantum system made of one or more bounded electrons, and is pivotal in determining the atom's size and properties. It is the smallest system that has the characteristic properties of a chemical elements and, as such, it is often employed as a unit in the domain of chemistry. Atoms can either be standalone or bonded; they can have an unbalanced number of electrons with respect to their atomic number (the latter being determined by the number of protons in the nucleus) or have a net electric charge. Domain: Natural sciences - Physics / Chemistry.
Labels:	*Labels used to address the concept, ordered as:* *skos:prefLabel: Atom*

	skos:altLabel: Atom (Broad) *skos:hiddenLabel: Chemical Element; Neutral-or-Ion Atom; Standalone-or-Bonded Atom*

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	-*Wikipedia:* "an atom is the smallest unit of ordinary matter that forms a chemical element"; "an atom is a basic unit of matter consisting of a nucleus within a cloud of one or more electrons". -*Encyclopedia Britannica:* "smallest unit into which matter can be divided without the release of electrically charged particles. It also is the smallest unit of matter that has the characteristic properties of a chemical element". -*WordNet 3.1:* "the smallest component of an element having the chemical properties of the element". -*WikiData:* "smallest indivisible unit of a chemical substance" (Q9121). -IUPAC Goldbook: "Smallest particle still characterising a chemical element. It consists of a nucleus of a positive charge (Z is the proton number and e the elementary charge) carrying almost all its mass (more than 99.9%) and Z electrons determining its size".
Comments:	*This engineered OntoCommons bridge-concept aims to provide a general, up-to-date and ambiguity-free characterisation of one of the most employed and successful notions in physics and chemistry. In this case, the lack of a shared common ground might not have immediate consequence for stakeholders, but there is a serious risk of compromising some of the most notable advantages in data exchange via ontologies, and, specifically having to do with reusability and the overall network's predictive potential. Ultimately, as a result of a survey of the related concepts appearing in MLOs, it was decided to put forward a very general Atom bridge-concept, and explicitly specify value gaps with respect to two characteristic traits: net charge and bonds. Thus, a neutral atom and a charged atom (ion) are joint into the concept Atom, and the same goes for Standalone Atoms and Bonded Atoms. It should be noted that this last point solves a serious representational issue whereas atoms are considered as mereological parts of molecules, as many resources (and even golden standards such as the IUPAC, do: <https://doi.org/10.1351/goldbook.M04002>. There was in fact an effort to ensure that the proposed bridge-concept would be aligned with said golden standard, even relatively to the definition/elucidation itself. The trait of "being the smallest particle still characterising a chemical element" was explicitly stated to be domain specific, for the sake of clarity: in line with that, it was decided not to include the trait "basic unit of matter", even though it could point to a taxonomical, hierarchical, informative characteristic. Notably, the resulting definition is also not too far from the ones provided by well known and pervasively employed domain resources, such as Wikipedia, Wikidata, WordNet and the Encyclopedia Britannica. The trait of being "indivisible",*

	appearing in Wikidata's has been deemed obsolete and potentially confusing qua too close too the notion of Mereological Atom, which cannot be ignored due to Mereology's pervasiveness in formal ontologies. It is factually possible to split Atoms into their subatomic components, and Encyclopedia Britannica's definition depicts a vastly more accurate picture.

ALIGNMENTS TO EXISTING ONTOLOGIES: *(1: VERTICAL, TLOS; 2: HORIZONTAL, MLOS)*

1: VERTICAL ALIGNMENTS

BFO

Target Ontology:	*<http://purl.obolibrary.org/obo/bfo.owl>*
Related Ontology Entities:	*Material Entity: <http://purl.obolibrary.org/obo/BFO_0000040>*
Mapping Elucidation:	*Given BFO's internal organization, there do not seem to be many options beside BFO:Material Entity for an alignment. In general, as far as BFO's distinctions are concerned, Atoms do not seem to be vastly different from moderate-sized specimens of dry goods such as tables and bricks. Arguably, the real question concerns whether the proposed OntoCommons bridge-concept, Atom, is a subclass of BFO:Object, BFO:Object Aggregate, or BFO:Fiat Object (which is arguably the rightful categorisation for a restriction of Atom via the bonded trait); however the classes are not mutually disjoint as the relevant BFO universals are not rigid, so the questions is, to a degree, meaningless. In fact, the possibility of the relevant individuals of migrating among the classes seems especially appropriate in this specific scenario. There do not seem to be reasons to consider a different alignment, and the examples of usage appear to be pertinent. Despite the intuitive gap between Material Entities and Atoms, the connection seems informative and appropriate: in fact, it is pivotal to be wary of intuitions which might derive from unrelated considerations pertaining to concepts' prototypes and scale. Finally, it is worth considering whether such an alignment is conductive to an appropriate representation of electron clouds, but -it could be argued- that would be putting the cart before the horse.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:subClassOf*
Mapping Axioms:	*TBD*

DOLCE

Target Ontology:	*<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic>*

Related Ontology Entities:	*NonAgentivePhysicalObject: <http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic#NonAgentivePhysicalObject>*
Mapping Elucidation:	*The vast majority of what has been said with respect to BFO:Material Entity is relevant when it comes to DOLCE:Physical Endurant. However, the choice of a subclass, or, more specifically, of a tree of subclasses is in this case possible and informative. In DOLCE there is no distinction analogous to the one between BFO:Objects and BFO:Objects Aggregates; DOLCE:Arbitrary Sums plays a completely different role. As such, the proposed OntoCommons bridge-concept, Atom, can be seen as a subclass of DOLCE:Physical Object. Given the further distinction between Dolce's Agentive and Non Agentive Physical Objects, based on intentionality and the possess of desires and beliefs, the choice seems straightforward, bizarre philosophical options contrary to common-sense notwithstanding. Thus, the proposed bridge-concept Atom is arguably a subclass of DOLCE:Non Agentive Physical Object; the connection seems informative and appropriate, and it is made even more plausible given the examples of usage provided in the relevant documentation.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:subClassOf*
Mapping Axioms:	*TBD*

EMMO

Target Ontology:	*<http://emmo.info/emmo>*
Related Ontology Entities:	*Atom:* *<http://emmo.info/emmo#EMMO_eb77076b_a104_42ac_a065_798b2d2809ad>*
Mapping Elucidation:	*EMMO:Atom appears to be the perfect candidate for an alignment based on class equivalence with the proposed OntoCommons bridge-concept, Atom. The tentative connection is supported by the relevant documentation, which makes explicit relevant value gaps by means of subclasses. There do not seem to be reasons to consider other alignments, and, in this case, even the problems involving the eventual in-framework representation of electron clouds can be dismissed.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:equivalentClass*
Mapping Axioms:	*TBD*

2: HORIZONTAL ALIGNMENTS

BWMD

Target Ontology:	*<https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid>*
Related Ontology Entities:	*Atom: <https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00131>*
Mapping Elucidation:	*The prima facie obvious candidate for a connection is BWMD:Atom. The alignment is based on the assumption that the relevant Wikipedia page (in German), and specifically the version which was consulted by BWMD's developers, is consistent with its English analogue as of 24/04/22, given what has been said above in the comment to the elucidation of the OntoCommons bridge-concept, Atom. In support of this alignment, it should also be noted that BWMD is based on BFO, and BWMD:Atom is a subclass of BWMD/BFO:Object and of BWMD/BFO:Material Entity, consistently with the relative proposed alignment. Moreover, there do not seem to be other candidates worth considering, nor evidence against a semantic relationship of class equivalence. However there could, and should, be doubts concerning how literally "any kind of atom as described by https://de.wikipedia.org/wiki/Atom" should be interpreted. Due to the lack of alternatives, common-sense was chosen as a guide.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:equivalentClass*
Mapping Axioms:	*TBD*

Domain Mechanical Testing (EMMO-MECH-TEST)

Target Ontology:	*<http://emmo.info/emmo/domain/mechanical-testing>*
Related Ontology Entities:	*Atom: <http://emmo.info/emmo/middle/materials#EMMO_eb77076b_a104_42ac_a065_798b2d2809ad>*
Mapping Elucidation:	*The Domain Mechanical Testing ontology EMMO-MECH-TEST is based on EMMO; as such what has been said above can be applied mutatis mutandis in this case. Given the proposed semantic link, the absence of better candidates should come as no surprise. However, it should be noted that EMMO-MECH-TEST is based on an outdated version of EMMO. Nonetheless, there are no significant differences compromising the alignment, or modifying the semantic relationship between the proposed OntoCommons bridge-concept, Atom, and EMMO-MECH-TEST's Atom.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* *rdfs:equivalentClass*

Mapping Axioms:	*TBD*

RELATED EXISTING CONCEPTS

TLOs

MATERIAL ENTITY (BFO)

GENERAL CONCEPT INFO:

IRI:	*<http://purl.obolibrary.org/obo/BFO_0000040>*
OWL Type:	*Class*
Concept Elucidation:	*A material entity is an independent continuant that at all times at which it exists has some portion of matter as continuant part.* *Examples of Usage:* a human being, the undetached arm of a human being, an aggregate of human beings.
Labels:	*Material Entity*

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	*Building Ontologies with BFO:* "material entity is an independent continuant that has some portion of matter as part. It is thus an independent continuant that is spatially extended in three dimensions, and that continues to exist through some interval of time, however short".

NON AGENTIVE PHYSICAL OBJECT (DOLCE)

GENERAL CONCEPT INFO:

IRI:	*<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic#NonAgentivePhysicalObject>*
OWL Type:	*Class*
Concept Elucidation:	A Non-Agentive Physical Object is a physical object to which intentions, believes and desires are not ascribed. *Examples of Usage:* a pebble, a house, a computer, a human body.
Labels:	*NonAgentivePhysicalObject*

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	*Dolce D18:* "within Physical Objects, a special place have those those to which we ascribe intentions, beliefs, and desires. These are called Agentive, as opposite to Non-agentive. Intentionality is understood here as the capability of heading for/dealing with objects or states of the world. This is an important area of ontological investigation we haven't properly explored yet, so our suggestions are really very preliminary".

ATOM (EMMO)

GENERAL CONCEPT INFO:

IRI:	*<http://emmo.info/emmo#EMMO_eb77076b_a104_42ac_a065_798b2d2809ad>*
OWL Type:	*Class*
Concept Elucidation:	An 'atom' is a 'nucleus' surrounded by an 'electron_cloud', i.e. a quantum system made of one or more bounded electrons.
Labels:	*Atom*

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	*European Materials Modelling Ontology v. 1.0.0 alpha 2:* "Bonded Atom: an Atom that shares at least one electron to the atom-based entity of which is part of. A real bond between atoms is always something hybrid between covalent, metallic and ionic. In general, metallic and ionic bonds have atoms sharing electrons. The bond types that are covered by this definition are the strong electonic bonds: covalent, metallic and ionic. This class can be used to represent molecules as simplified quantum systems, in which outer molecule shared electrons are un-entangled with the inner shells of the atoms composing the molecule"; "Standalone Atom: an atom that does not share electrons with other atoms. A standalone atom can be bonded with other atoms by intermolecular forces (i.e. dipole–dipole, London dispersion force, hydrogen bonding), since this bonds does not involve electron sharing"; "Neutral Atom: A standalone atom that has no net charge"; "Ion Atom: standalone atom with an unbalanced number of electrons with respect to its atomic number".

MLOs

ATOM (BWMD)

GENERAL CONCEPT INFO:

IRI:	*<https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00131>*

OWL Type:	*Class*
Concept Elucidation:	Any kind of atom as described by https://de.wikipedia.org/wiki/Atom
Labels:	*Atom*

Knowledge Domain Resources:

Related Domain Resources:	*<https://de.wikipedia.org/wiki/Atom>*

ATOM (EMMO-MECH-TEST)

General Concept Info:

IRI:	*<http://emmo.info/emmo/middle/materials#EMMO_eb77076b_a104_42ac_a065_798b2d2809ad>*
OWL Type:	*Class*
Concept Elucidation:	An 'atom' is a 'nucleus' surrounded by an 'electron_cloud', i.e. a quantum system made of one or more bounded electrons. A standalone atom has direct part one 'nucleus' and one 'electron_cloud'. An O 'atom' within an O2 'molecule' is an 'e-bonded_atom'. In this material branch, H atom is a particular case, with respect to higher atomic number atoms, since as soon as it shares its electron it has no nucleus entangled electron cloud. We cannot say that H2 molecule has direct part two H atoms, but has direct part two H nucleus.
Labels:	*Atom*

Knowledge Domain Resources:

Related Domain Resources:	*European Materials Modelling Ontology v. 1.0.0 alpha 2:* "Bonded Atom: an Atom that shares at least one electron to the atom-based entity of which is part of. A real bond between atoms is always something hybrid between covalent, metallic and ionic. In general, metallic and ionic bonds have atoms sharing electrons. The bond types that are covered by this definition are the strong electronic bonds: covalent, metallic and ionic. This class can be used to represent molecules as simplified quantum systems, in which outer molecule shared electrons are un-entangled with the inner shells of the atoms composing the molecule"; "Standalone Atom: an atom that does not share electrons with other atoms. A standalone atom can be bonded with other atoms by intermolecular forces (i.e. dipole–dipole, London dispersion force, hydrogen bonding), since this bonds does not involve electron sharing"; "Neutral Atom: A standalone atom that has no net charge"; "Ion Atom: standalone atom with an unbalanced number of electrons with respect to its atomic number".

4.2.1.6 Physical Quantity

GENERAL CONCEPT INFO:

IRI:	Suggested entity new IRI.
OWL Type:	Class
Concept Elucidation:	Physical Quantities are properties associated with a physical entity (qua physical) for which there is a standardized definition capable of supporting quantification, and which can either be observed under practically achievable experimental conditions or predicted by means of a theoretical model apt to generalize observations. It should be noted that Physical Quantities need not necessarily pertain to the domain of physics, understood as a discipline. Domain: Natural sciences - Metrology.
Labels:	Labels used to address the concept, ordered as: skos:prefLabel: Physical Quantity skos:altLabel: Physical Property; Quantity skos:hiddenLabel: Property; Physical Quality; Physical Characteristic; Quality

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	-Wikipedia: "a physical quantity is a physical property of a material or system that can be quantified by measurement. A physical quantity can be expressed as a value, which is the algebraic multiplication of a numerical value and a unit". -WikiData: "quantitative characterisation of an aspect of a physical entity, phenomenon, event, process, transformation, relation, system, or substance" (Q107715). -VIM (3rd edition): "property of a phenomenon, body, or substance, to which a number can be assigned with respect to a reference". -ISO 80000-1/12 provides a general characterisation and an extensional definition of quantities, though it is explicitly stated that "systems of quantities and systems of units can be treated in many consistent, but different, ways. Which treatment to use is only a matter of convention" and that "the quantities and the relations among them are essentially infinite in number and are continually evolving as new fields of science and technology are developed. Thus, it is not possible to list all these quantities and relations in this International Standard; instead, a selection of the more commonly used quantities and the relations among them is presented". -ISO 10303-45: "a type of property of a product where the meaning and value of the property depend on the method and conditions by which it was measured"; "material properties are representative of all engineering properties that are defined by a specified testing method [whereas] an engineering property characterises some aspect of the behaviour of a product"; "The following are the fundamental concepts and assumptions related to the representation of engineering properties: • multiple representations of a property are possible including the use of numeric values, parametric or fundamental equations, graphical representations and non-numeric values (NOTE The distinction between a concept and the representation of a concept is described in ISO 10303-43); • the value of a property may be assigned or measured; • if the value is measured, the resulting value will depend on the method of measurement and on the conditions used in applying the method;

	• if the value is assigned, the conditions under which that assignment is valid may be specified; • in the case of either assignment or measurement, the conditions under which the value is valid are expressed as a set of quantitative and qualitative data which form the data environment".
Comments:	This engineered OntoCommons bridge-concept aims to provide a MLO-friendly, pragmatic restriction of an extremely general family of notions which can be characterised in vastly different ways; notions which generally fall under the labels of 'property', 'attribute', 'quality', 'characteristic', 'quantity'. Given the aim, the characteristics of the target MLOs, and, more importantly, the requests coming from MLOs' stakeholders given OntoCommons' survey, it was decided to focus on a list of features encompassing property quantification, the existence of a standardised and shared definition/procedure ensuring objectivity, and the relevant aspects being grounded -directly or indirectly- in actual, and not just possible (to restrict the number of problematic cases by avoiding merely hypothetical ones), observability. There was an effort to ensure that the proposed bridge-concept would be aligned with golden standards: specifically, it is in line with ISO 80000, which also provides a (nominally partial, yet extremely rich) extensional definition of the class; it is also aligned with ISO10303-45, though we ultimately decided to explicitly include quantities associated with physical objects which do not pertain to the domain of physics, understood as discipline, to ensure coverage of all the relevant MLOs, in line with our goals. Doing so also avoids some well-known issues related to demarcation problems. Notably, the resulting definition is compatible with the ones provided by well known and pervasively employed domain resources, such as Wikipedia, Wikidata, and another golden standard, the International Vocabulary of Metrology. This will ensure immediateness and intuitiveness for domain experts and ontologists, while at the same time improving the usability for non-experts. The risk of meaning/conceptual shift, and thus, obsoleteness, is also reduced. That said, the proposed definition cannot be reduced to said resources, insofar as it attempts to go beyond them explicitly pointing at possible pitfalls and nuances that need to be considered when attempting an alignment.

Alignments To Existing Ontologies: (1: vertical, TLOs; 2: horizontal, MLOs)

1: Vertical Alignments

BFO

Target Ontology:	<http://purl.obolibrary.org/obo/bfo.owl>
Related Ontology Entities:	Quality: <http://purl.obolibrary.org/obo/BFO_0000019>
Mapping Elucidation:	Arguably, BFO's Specifically Dependent Continuants cover the vast majority of the entities commonly labelled as 'properties' etc. -in line with what has been said above- in the guise of a metaphysical commitment to tropes. The ones which are not covered might be seen as falling under Generically Dependent Continuant, yet said class does not seem to be appropriate as an alignment target. BFO's Role class is likewise not a good candidate, since they explicitly do not cover properties whose possession has consequences for the physical make-up of the bearer. As such, the only options left are Disposition and Quality. Given the focus on the observation process outlined in the

	proposed definition of Physical Quantity, it might be tempting to connect the latter to a specific kind of BFO:Disposition, yet that would mean vastly disregarding BFO's background philosophical assumptions, internal organization, and factual approach to the description of similar cases. Taking those into account the proper connection is arguably with BFO:Quality. The Quality class is not restricted to quantities, nor bound by actual-observation grounding or the possibility of supporting quantification; as such the proposed OntoCommons bridge-concept, Physical Quantity, can only be a subclass of the former.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	Example: IRI rdfs:subClassOf <http://purl.obolibrary.org/obo/BFO_0000019>

DOLCE

Target Ontology:	<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic>
Related Ontology Entities:	PhysicalQuality: <http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic#PhysicalQuality>
Mapping Elucidation:	In the TLO DOLCE, the class Quality arguably covers the entirety of the entities commonly labelled as 'properties' etc. -in line with what has been said above-. Analogously to BFO, DOLCE approaches properties via a commitment to tropes, though the relevant theoretical framework is fairly more complex. As such, it seems appropriate to look for a connection in the subclasses of DOLCE:Quality. The most pertinent target is arguably the class Physical Quality, which covers one of the core traits characterising the proposed bridge-concept, Physical Quantity. Since there are no explicit references to actual-observation grounding for the sake of generality, and qualities implicitly include non quantifiable properties, qua qualities, the proposed OntoCommons bridge-concept, Physical Quantity, should be considered a specification of the relevant Dolce class, and, thus, a subclass of the latter. This last point is also supported by the explicit examples of usage provided in DOLCE's documentation.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	TBD

EMMO

Target Ontology:	<http://emmo.info/emmo>
Related Ontology Entities:	QuantitativeProperty <http://emmo.info/emmo#EMMO_dd4a7f3e_ef56_466c_ac1a_d2716b5f87ec>
Mapping Elucidation:	In EMMO, properties are approached from a metaphysically deflationary (even in-framework, and not as a general attitude concerning the relationship between ontology and world), applied-sciences friendly point of view. Despite belonging to the Semiotic perspective, EMMO:Quantitative Property, is perfectly in line with the OntoCommons bridge-concept definition, as the various traits characterising the latter are explicitly covered, either in the relevant elucidation or on the elucidation of its superclasses. In fact, there are extensive references to the same golden standards/domain resources

	(e.g., ISO 80000 and the VIM). Given that, there are good reasons to believe that the class defined by the proposed bridge-concept, Physical Quantity, is equivalent to EMMO:Quantitative Property. The linguistic labels associated with the two concepts arguably offer further support to the proposed alignment.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:equivalentClass
Mapping Axioms:	TBD

2: Horizontal Alignments

Allotrope

Target Ontology:	<http://purl.allotrope.org/voc/afo/merged-OLS/REC/2019/05/10>
Related Ontology Entities:	Quality: <http://purl.obolibrary.org/obo/BFO_0000019>
Mapping Elucidation:	Allotrope is based on BFO, hence sharing its treatment of the entities commonly labelled as 'properties' etc. -in line with what has been said above-. Some subclasses of Allotrope:Quality are obvious candidates as subclasses of the proposed OntoCommons bridge-concept, Physical Quantity, though the discussion of the links should be done via a case by case analysis. Given that, the most informative alignment connection, having to chose only one for the sake of demonstration, is with Quality class itself, in line with alignment with BFO proposed above.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	TBD

BWMD

Target Ontology:	<https://gitlab.cc-asp.fraunhofer.de/EMI_datamanagement/bwmd_ontology/-/blob/master/docs/create_new_domain_ontology_using_BWMD_mid.md>
Related Ontology Entities:	QuantityKind: <https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00011>
Mapping Elucidation:	BWMD, like Allotrope, is based on BFO, hence sharing its treatment of the entities commonly labelled as 'properties' . The subclass of Quality, QuantityKind, adds an explicit requirement which covers one of the traits characterising the proposed OntoCommons bridge-concept, Physical Quantity, namely, being quantifiable. The linguistic labels wear the above point on their sleeves. As such, BWMD:QuantityKind seems to be the most informative target for a meaningful connection/alignment. Some subclasses of BWMD:QuantityKind are obvious candidates as subclasses of the proposed OntoCommons bridge-concept, Physical Quantity, however, as above, the discussion of the links should be done via a case by case analysis. It should be noted that BWMD distinguishes between the class Quantity and the class QuantityKind, and it might prima facie seem that the former is a better candidate for alignment. However, at a closer inspection, that does not seem to be the case, though some subclasses of Quantity seems eminently physical, rather than concerning the mathematical representation/modelling of single possible observations. Direct cooperation with the developers of BWMD to clarify this point is advised.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	TBD

CCO

Target Ontology:	<https://github.com/CommonCoreOntology/CommonCoreOntologies>
Related Ontology Entities:	Quality: <http://purl.obolibrary.org/obo/BFO_0000019>
Mapping Elucidation:	The situation is analogue as in the case of the Mid Level Ontology Allotrope; as such, the same considerations can be applied, mutatis mutandis, in this case.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	TBD

IOF-Core

Target Ontology:	<https://github.com/NCOR-US/IOF-BFO>
Related Ontology Entities:	Quality: <http://purl.obolibrary.org/obo/BFO_0000019>
Mapping Elucidation:	BWMD, like some of the MLOs considered above, is based on BFO, hence sharing its treatment of the entities commonly labelled as 'properties' . Differently from them, the ontology seems to be less focused on providing a categorization of different kinds of properties: the sole subclass of Quality is, in fact, IOF-Core:Relational Quality. As such, the choice of the alignment target is even more straightforward. The considerations

	concerning the nature of the alignment between the proposed OntoCommons bridge-concept, Physical Quantity, and IOF-Core:Quality are analogous as in the cases of Allotrope and CCO.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	TBD

Saref

Target Ontology:	<https://saref.etsi.org/core/v3.1.1/>
Related Ontology Entities:	Property: <https://saref.etsi.org/core/Property>
Mapping Elucidation:	Saref:Property is defined in terms of qualities and features, and the subclasses seem appropriate for a connection. In fact, some a good number of the subclasses of Property are good candidates as subclasses of the proposed OntoCommons bridge-concept, Physical Quantity, though not all of them. In line with what has been said in other cases, Sare:Property remains the preferable target for a meaningful and informative connection and other alignments should be considered case by case. The alternatives to Saref:Property seem less compelling/appropriate.
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities: rdfs:subClassOf
Mapping Axioms:	TBD

RELATED EXISTING CONCEPTS

TLOs

QUALITY (BFO)

GENERAL CONCEPT INFO:

IRI:	<http://purl.obolibrary.org/obo/BFO_0000019>
OWL Type:	Class
Concept Elucidation:	A quality is a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized. Examples of Usage: The colour of a tomato, the ambient temperature of this portion of air, the length of the circumference of your waist, the shape of your nose, the shape of your nostril, the mass of this piece of gold.
Labels:	Quality

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	Building Ontologies with BFO: “specifically dependent continuant is a continuant entity that depends on one or more specific independent continuants for its existence. Dependent continuants exhibit existential dependence in the sense that, in order for a dependent continuant to exist, some other entity in which it inheres (intuitively, an

	entity enjoying a larger degree of concreteness) must exist also"; "there are two types of specifically dependent continuant : quality and realizable entity . Qualities are contrasted with realizables in that the former, if they inhere in an entity at all, are fully exhibited or manifested or realized in that entity. The latter, in contrast, can inhere without being realized, and can be realized to different degrees (including different degrees of likelihood). What all qualities have in common is that they inhere in, and so depend on, other entities; in order for a quality to exist some other entity or entities — specifically, one or more independent continuants, must also exist".

PHYSICAL QUALITY (DOLCE)

GENERAL CONCEPT INFO:

IRI:	<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic#PhysicalQuality>
OWL Type:	Class
Concept Elucidation:	A Physical Quality is a quality that directly inheres to a physical endurant. Examples of Usage: the weight of a pen, the color of an apple.
Labels:	PhysicalQuality

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	Dolce D18: "DOLCE has four top categories: endurant (including object- and substance-like entities), perdurant (event- and state-like entities), quality (individual attributes), and abstracts (mainly conceptual "regions" for structuring attributes)"; "Qualities can be seen as the basic entities we can perceive or measure: shapes, colors, sizes, sounds, smells, as well as weights, lengths, electrical charges. . . 'Quality' is often used as a synonymous of 'property', but this is not the case in DOLCE: qualities are particulars, properties are universals. Qualities inhere to entities: every entity (including qualities themselves) comes with certain qualities, which exist as long as the entity exists. Within a certain ontology, we assume that these qualities belong to a finite set of quality types (like color, size, smell, etc., corresponding to the "leaves" of the quality taxonomy shown in Figure 2), and are characteristic for (inhere in) specific individuals".

QUANTITATIVE PROPERTY (EMMO)

GENERAL CONCEPT INFO:

IRI:	<http://emmo.info/emmo#EMMO_dd4a7f3e_ef56_466c_ac1a_d2716b5f87ec>
OWL Type:	Class
Concept Elucidation:	A 'Quantity' that can be quantified with respect to a standardized reference physical instance (e.g. the prototype meter bar, the kg prototype) or method (e.g. resilience) through a measurement process. "A property of a phenomenon, body, or substance, where the property has a magnitude that can be expressed by means of a number and a reference" ISO 80000-1

	"A reference can be a measurement unit, a measurement procedure, a reference material, or a combination of such." International vocabulary of metrology (VIM) Subclasses of 'QuantitativeProperty' classify objects according to the type semiosis that is used to connect the property to the object (e.g. by measurement, by convention, by modelling).
Labels:	QuantitativeProperty

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	European Materials Modelling Ontology v. 1.0.0 alpha 2: "a quantitative property is always expresssed as a quantity (i.e. a number and a reference unit). For the EMMO, a nominalistic ontology, there is no property as abstract object"; "a property is a sign that stands for an object according to a specific code shared by some observers"; "for quantitative properties, one possible code that is shared between the scientific community (the observers) is the SI system of units".

MLOs

QUALITY (Allotrope)

GENERAL CONCEPT INFO:

IRI:	<http://purl.obolibrary.org/obo/BFO_0000019>
OWL Type:	Class
Concept Elucidation:	A quality is a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized. [BFO] <http://purl.allotrope.org/voc/bfo/REC/2018/04/bfo-2-0> <http://purl.obolibrary.org/obo/bfo.owl> Examples of Usage: the ambient temperature of this portion of air, the colour of a tomato, the length of the circumference of your waist, the mass of this piece of gold, the shape of your nose, the shape of your nostril.
Labels:	Quality

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	No Instances.

QUANTITY KIND (BWMD)

GENERAL CONCEPT INFO:

IRI:	<https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_0001 1>

OWL Type:	Class
Concept Elucidation:	A quantity kind in analogy to the QUDT ontology described by http://www.qudt.org/
Labels:	QuantityKind

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	No instances.

QUALITY (CCO)

GENERAL CONCEPT INFO:

IRI:	<http://purl.obolibrary.org/obo/BFO_0000019>
OWL Type:	Class
Concept Elucidation:	A quality is a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized. (axiom label in BFO2 Reference: [055-001]) <http://purl.obolibrary.org/obo/bfo.owl> Examples of Usage: the ambient temperature of this portion of air, the colour of a tomato, the length of the circumference of your waist, the mass of this piece of gold, the shape of your nose, the shape of your nostril.
Labels:	Quality

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	No Instances.

QUALITY (IOF-Core)

GENERAL CONCEPT INFO:

IRI:	<http://www.loa.istc.cnr.it/dolce/dolce-owl/DOLCEbasic#PhysicalQuality>
OWL Type:	Class
Concept Elucidation:	A quality is a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized. Examples of Usage: the colour of a tomato, the ambient temperature of this portion of air, the length of the circumference of your waist, the shape of your nose, the shape of your nostril, the mass of this piece of gold.
Labels:	Quality

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	No Instances.

PROPERTY (Saref)

GENERAL CONCEPT INFO:

IRI:	<https://saref.etsi.org/core/Property>
OWL Type:	Class
Concept Elucidation:	A quality of a feature of interest that can be measured; an aspect of a feature of interest that is intrinsic to and cannot exist without the feature.
Labels:	Property

KNOWLEDGE DOMAIN RESOURCES:

Related Domain Resources:	No instances.

4.2.1.7 Materials Property

Materials Property is a particular characteristic associated with a material. It is often referred to as a quality, which is inherent in a material, but can also be regarded as the outcome of an observation using a certain method and involving an interpretation of that observation as the property. Materials Property is not necessarily quantitative and not necessarily related to measurement. Nevertheless, some ontologies do not clearly differentiate between materials properties and physical quantities, which require a standardized definition capable of supporting quantification.

General Concept Info:

IRI:	MaterialsProperty
OWL Type:	*Class*
Concept Elucidation:	Materials Property is a property that is associated with a material. Comment: the bridge concept is neutral with respect to a realist or semiotic stance. Realist: a Materials Property is inherent in the continuant, as a kind of “quality”. Semiotics: Material Property is the outcome of an observation making use of a certain method of observation of a material and by an interpreter who interprets the results. Comment: Materials Property is not necessarily quantitative and not necessarily related to measurements; it is not necessarily intrinsic. Note, however, that the term Quantity is sometimes used to refer to a Materials Property.

	Comment: According to the OntoCommons Bridge Concept: Physical Quantities are elucidated as "properties associated with a physical entity (qua physical) for which there is a standardized definition capable of supporting quantification, and which can either be observed under practically achievable experimental conditions or predicted by means of a theoretical model apt to generalize observations." Comment: Often the word "attribute" appears in dictionaries and also as concept in ontologies see e.g. MaterialsMine. Comment: The concept domain is Natural Science, in particular Materials Science. In contrast the label "property" in computer science and ontologies is used to denote attributes and relationships of entities.
Labels:	*vii)* *Preferred:* Materials Property *viii)* *Alternative:* Quality, Attribute, Feature (but see comments above.)

Knowledge Domain Resources:

Related Domain Resources:	8. Wikipedia: A materials property is an intensive property of a material, i.e., a physical property that does not depend on the amount of the material. These quantitative properties may be used as a metric by which the benefits of one material versus another can be compared, thereby aiding in materials selection. A property may be a constant or may be a function of one or more independent variables, such as temperature. Materials properties often vary to some degree according to the direction in the material in which they are measured, a condition referred to as anisotropy. Materials properties that relate to different physical phenomena often behave linearly (or approximately so) in a given operating range[further explanation needed]. Modeling them as linear functions can significantly simplify the differential constitutive equations that are used to describe the property. Equations describing relevant materials properties are often used to predict the attributes of a system. The properties are measured by standardized test methods. Many such methods have been documented by their respective user communities and published through the Internet; see ASTM International. 9. Merriam-Webster:

	MaterialsProperty does not appear **General property** is about ownership only **Chemical property**: a property of a substance relating to its chemical reactivity (as the explosive property of nitroglycerin) **Quality**: an inherent feature : property; a distinguishing attribute : characteristic 3. Wikidata : **Property**: intrinsic, intensive, quantitative property of a material, which can be measured and compared • material properties • material quality • material qualities • materials properties Comment: This is narrowly restricted to intrinsic, intensive and quantitative. **quality (Q1207505) :** distinguishing feature • feature • attribute • nature • trait • characteristic 4. IUPAC-Goldbook: Materials property nor property nor quality appear. **Quantity** (https://doi.org/10.1351/goldbook.Q04982) : Attribute of a phenomenon, body or substance that may be distinguished qualitatively and determined quantitatively. 5. IOF Core/IAOA terms: MaterialsProperty does not appear. **Property** 1 [Natural Language] An attribute, quality, or characteristic of something. (https://www.lexico.com/definition/property) 2 [Logic] A property is a unary predicate in intention. 3 [W3C OWL 2] A property is a binary relation: Annotation Property, Object Property, or Data Property. (https://www.w3.org/TR/2012/REC-owl2-primer-20121211/) The last two refer to the fact that “relation” in W3C speak is called “property” and this is thus not related to our term.
Comments:	

Alignments To Existing Ontologies:

1: Vertical Alignments

N/A since only focus on DLO level alignments

2: Horizontal Alignments

MSEO

Target Ontology:	*https://purl.matolab.org/mseo/mid*
Related Ontology Entities:	*Quality(http://purl.obolibrary.org/obo/BFO_0000019)* **Quality** is defined as "a quality is a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized". Examples of subclasses are material composition , luminous intensity , number density , relational quality (is a subclass of quality and is defined as "b is a relational quality =Def b is a quality and there exists c and d such that b and c are not identical, & b s-depends on c & b s-depends on d".) Comment: It includes besides the applied science concept materials property also quantities, physics terms and more. Comment: Stress is included which according to physics is a physical quantity and not materials properties. **Disposition** definition: "b is a disposition means: b is a realizable entity & b is such that if it ceases to exist, then its bearer is physically changed, & b's realization occurs when and because this bearer is in some special physical circumstances, & this realization occurs in virtue of the bearer's physical make-up" MaterialProperty is a subclass of SpecicallyDependantContinuant. **SpecificallyDependanContinuant** definition: "b is a specifically dependent continuant =Def b is a continuant & there is some independent continuant c which is not a spatial region & which is such that b s-depends on c" **MaterialArtifact.** **It is taken from IoF Core** Natural language definition: object that is deliberately created to have a certain function. First order logic definition: MaterialArtifact(x) ↔ Object(x) ∧ ∃f,∃d(Function(f) ∧ DesignSpecification(d) ∧ bearerOf(x,f) ∧ prescribes(d,f))

	Comment: Examples of how MSEO classifies concepts: Hardness has superclass quality. Electrical conductance has superclass disposition. Mallability the subclass of MSEO:malleability depends on a MSEO:raw material OR on MSEO:material artifact.
Mapping Elucidation:	ONTOCOMMONS:MaterialProperty relates to the MSEO union of quality and disposition. The class quality contains more than what we call Materials Property. The class disposition contains more than what we call Materials Property. The allocation of concepts to each of these classes seems rather random and does not follow physics. As soon as this ontology separates the classes quality and disposition and gives a more precise elucidation we will create a BT to these classes.

BMWD

Target Ontology:	**BMWD** (superseded by MSEO)
Related Ontology Entities:	Quality is defined as “Any kind of mechanical quantity or property” Subclasses of Quality are • Quantity is defined as “Physical or nonphysical quantities” Quantity is a subclass of quality. • QuantityKind is defined as “A quantity kind in analogy to the QUDT ontology described by http://www.qudt.org/” • Relationalquality is defined as “b is a relational quality = Def. for some independent continuants c, d and for some time t: b quality_of c at t & b quality_of d at t. (axiom label in BFO2 Reference: [057-001])” Subclasses of Quantity are • Amount is defined as” A quantity which specifies the amount of entities” • MechanicalQuantity is defined as “Any kind of mechanical quantity or property” • StucturalQuantity is defined as “ Any kind of structural quantity or descriptor to (quantitatively) describe the internal or external structure of an object.” • TemperatureRelatedQuantity is defined as “Any kind of temperature related quantity, i.e. a quantity of kind temperature (e.g. solution annealing temperature, material temperature…)”

	• TimerelatedQuantity is defined as "Any kind of time related quantity, i.e. a quantity of quantity kind time"
Mapping Elucidation:	See MSEO

Materialsmine

Target Ontology:	*http://materialsmine.org/ns*
Related Ontology Entities:	Quality (http://semanticscience.org/resource/Quality) Attribute (http://semanticscience.org/resource/Attribute) Object (http://semanticscience.org/resource/Object) **Property** is not found, but it lists examples as subclasses of quantity like this: Electrical Property is a subclass of Quantity it is defined "A materials property describing the material's behavior under some applied electrical field." **Quality** is defined as "A quality is an attribute that is intrinsically associated with its bearer (or its parts), but whose presence/absence and observed/measured value may vary." It is a subclass of Attribute. **Attribute** is defined as "An attribute is a characteristic of some entity." **Quantity** *Quantity(http://semanticscience.org/resource/Quantity)* is defined as "A quantity is an informational entity that gives the magnitude of a property". *Examples found are* • *Viscosity(http://materialsmine.org/ns/Viscosity)* • *Electrical Property(http://materialsmine.org/ns/ElectricalProperty)* • *Hardness Property(http://materialsmine.org/ns/HardnessProperty)* • *Mechanical Property(http://materialsmine.org/ns/MechanicalProperty)* • *Thermal Property(http://materialsmine.org/ns/ThermalProperty)* • *Viscoelastic Property(http://materialsmine.org/ns/ViscoelasticProperty)* It is a subclass of Object. **Object** is defined as "An object is an entity that is wholly identifiable at any instant of time during which it exists." The other classes (Viscosity etc...) are subclasses of Quantity

Mapping Elucidation:	*Concepts vary significantly from the OntoCommons Bridge Concept, see also the comments in the introduction.*

LPBFO

Target Ontology:	*https://www.emi.fraunhofer.de/ontologies/LPBFO*
Related Ontology Entities:	*Quality(http://purl.obolibrary.org/obo/BFO_0000019)* *Quantity(https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00010)* *QuantityKind(https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00011)*
Mapping Elucidation:	**Quality** is defined as "a quality is a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized. (axiom label in BFO2 Reference: [055-001])" **Quantity** and **QuantityKind** are subclass of Quality and they are defined as in BMWD. (The classes IRI ends with BMWD)
Semantic Relation Level:	See BWMD, MSEO and introduction

MatOnto

Target Ontology:	*http://purl.obolibrary.org/obo/rxno.owl*
Related Ontology Entities:	*Although the term "property" is used in composite terms it is not defined in isolation. But we find:* *Quality (http://www.ifomis.org/bfo/1.0/snap#Quality)* *Atom Property (http://ontology.dumontierlab.com/AtomProperty)* *Chemical Quality(http://ontology.dumontierlab.com/ChemicalQuality)* *Measured Property(http://ontology.dumontierlab.com/MeasuredProperty)* Quality is defined as "A dependent continuant that is exhibited if it inheres in an entity or entities at all (a categorical property). Examples: the color of a tomato, the ambient temperature of air, the circumference of a waist, the shape of a nose, the mass of a piece of gold, the weight of a chimpanzee" Atom property, chemical quality, Measured Property are subclasses of Quality

	• Atom property is defined as " a property of an atom" • ChemicalQuality is defined as "A quality of a chemical." • MeasuredProperty is defined as "A quality of a continuant that can be quantitatively determined."
Mapping Elucidation:	See comments in the introduction and above ontologies

EMMO

Target Ontology:	*http://emmo.info/emmo/1.0.0-beta4*
Related Ontology Entities:	*MaterialsProperty not included* *Property (http://emmo.info/emmo#EMMO_b7bcff25_ffc3_474e_9ab5_01b1664bd4ba)* *Coded(http://emmo.info/emmo#EMMO_7286b164_df4c_4c14_a4b5_d41ad9c121f3)* *Conventional(http://emmo.info/emmo#EMMO_35d2e130_6e01_41ed_94f7_00b333d46cf9)* *Sign(http://emmo.info/emmo#EMMO_b21a56ed_f969_4612_a6ec_cb7766f7f31d)*
Mapping Elucidation:	**Property** is defined as "A coded that makes use of an atomic symbol with respect to the code used to refer to the interaction." It is a subclass of Coded. **Coded** is defined as" A conventional that stands for an object according to a code of interpretation to which the interpreter refers." It is a subclass of Conventional. **Conventional** is defined as "A 'Sign' that stands for an 'Object' through convention, norm or habit, without any resemblance to it." It is a subclass of Sign. **Sign** is defined as "An 'Physical' that is used as sign ("semeion" in Greek) that stands for another 'Physical' through an semiotic process."
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* Emmo:Property if related to materials only would be a rdfs:subClassOf ONTOCOMMONS:materialsProperty
Mapping Axioms:	Emmo:coded if applied to materials would be similar to ONTOCOMMONS:materialsProperty.

4.2.1.8 Materials Process

General Concept Info:

IRI:	*Materials Process*
OWL Type:	*Class*

Concept Elucidation:	Materials process is a set of interrelated tasks with the purpose to do Materials Science and Engineering, where the tasks may be carried out by people, nature or machines using various resources phenomenon by which change takes place in a system.
	A whole that is identified according to a criteria based on its temporal evolution that is satisfied throughout its time extension."
	However, in the EMMO we restrict the meaning of the word process to items whose evolution in time have a particular meaning for the ontologist (i.e. every 4D object unfolds in time, but not every 4D time unfolding may be of interest for the ontologist and categorized as a process).
	
	The concept includes
	• Materials Modelling,
	• Materials Characterisation,
	• Materials Testing,
	• Materials Processing (synthesis)
	• Materials Design and
	• Materials Recycling
	• Materials behaviour (process)
	    o Chemical
	        ▪ Chemical degradation
	    o Electrical
	    o Magnetic
	    o Mechanical
	        ▪ Mechanical degradation breakdown of materials into resp. atoms and/or small molecules and/or simple compounds.
	    o Thermal
	    o Optical
	
	Comment: Process includes Processing (synthesis)
	
	Comment: The expression "materials process" does not appear in any dictionary. But we need it as a concept that includes all operations in Materials Science and Engineering.

Labels:	*preferred label:* Materials Process *alternative labels: Materials Science and Engineering Operations*

Knowledge Domain Resources:

Related Domain Resources:	**Materials Process** *1. [Wikipedia]:* In materials science, a process is a method for producing materials from small molecules. *2. [Merriam-Webster]:* Process in the meaning of proceeding : a series of actions or operations conducing to an end. Comment: restrict by adding "in materials science and engineering" *3. [Callister]:* The term is not defined. *4. [Raabe]:* No definition. Comment: Many papers are listed that use the word "process" but no definition is given. *5. [Wikidata]:* Process is a set of interrelated tasks that transform inputs into outputs, where the tasks may be carried out by people, nature or machines using various resources Comment: Restrict to materials S&E *6. [IUPAC Goldbook]:* Process is a phenomenon by which change takes place in a system. In physiological systems, a process may be chemical, physical or both. Comment: Although the first sentence is general the second sentence seems to restrict "process" to "processing". *7. [Brittanica dictionary]:* Comment: The term "process" alone is not defined but appears in many compounds. However no generic definition can be distilled from this. **(Materials) Technology**

	1. [Wikipedia]: Technology is the application of knowledge for achieving practical goals in a reproducible way. The word technology can also mean the products resulting from such efforts, including both tangible tools such as utensils or machines, and intangible ones such as software. Technology plays a critical role in science, engineering, and everyday life. Comment: Only specific technologies like metallurgy are mentioned, no generic definition is given. Comment: This is concentrating on the application of knowledge and although this is what happens in the first subdomains, it is not a determining aspect for materials behaviour. *2. [Myriam-Webster]: :* Technology is the practical application of knowledge especially in a particular area; The specialized aspects of a particular field of endeavours e.g. educational technology. Comment: This is concentrating on the application of knowledge and although this is what happens in the first subdomains, it is not a determining aspect for materials behaviour. *3. [Callister]:* Comment: the term is not defined. *4. [Raabe]:* No definition. Comment: many papers are listed that use the word" component," but no definition is given. *5. [Wikidata]:* making, modification, usage, and knowledge of tools, machines, techniques, crafts, systems, and methods of organization Comment: see above *6. [IUPAC Goldbook]:* Comment: No definition of the term *7. [Brittanica dictionary]:* **technology**, the application of scientific knowledge to the practical aims of human life or, as it is sometimes phrased, to the change and manipulation of the human environment.
Comments:	

	See above for comments.

Alignments To MatOnto, Material Ontology:

Target Ontology:	http://matonto.org/ontology/matonto
Related Ontology Entities:	**ChemicalReaction** *(http://ontology.dumontierlab.com/ChemicalInteraction)* **Process** (*http://www.ifomis.org/bfo/1.0/span#Process*) ChemicalReaction is defined as "A process in which at least one chemical is converted into another". It is a subclass of Process. Process is defined as "A processual entity that is a maximally connected spatio-temporal whole and has bona fide beginnings and endings corresponding to real discontinuities" It has no intentional aspect (and thus not to materials processing) Taxonomy in MatOnto-ontology: • *ChemicalReaction subclassOf Process* • *Process is a rdfs:subClassOf ProcessualEntity* • *ProcessualEntity is a rdfs:subClassOf Occurrent* In MatONTO "Synthesis" is defined as " A synthesis reaction is an organic reaction in which two or more molecules are chemically bonded together to produce a single product." This is a subclass of an (unintentional) process , thus not of materialsprocessing.
Mapping Elucidation:	Comment: ChemicalReaction seems to be a subclass of Process
Semantic Relation Level:	
Mapping Axioms:	*[ONTOCOMMONS]:Process rdfs:superclassOf [MATOnto]:Chemical Reaction*

Alignments To ENM, ENANOMAPPER Ontology:

Target Ontology:	*http://enanomapper.github.io/ontologies/enanomapper.owl*
Related Ontology Entities:	*Process (http://purl.obolibrary.org/obo/BFO_0000015)*

Mapping Elucidation:	"Process" is "An occurrent that has temporal proper parts and for some time t, process depends on some material entity at t." Comment: Process seems to have only SynthesisPart as subclass. Comment: Although Enanomapper only concentrates on materials processes the definition is all encompassing (and materials processes are a subclass of processes) Taxonomy in ENM Ontology: • Synthesis Part (no elucidation) rdfs:subClassOf Process • Adsorption rdfs:subClassOf Process • Process rdfs:subClassOf Entity
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* Despite the different philosophical commintments in emmo and enanomapper we can postulate that if we
Mapping Axioms:	*[ONTOCOMMONS]:Materials Process* rdfs:subClassOf *[ENANOMAPPER]: Process* And in practice *[ENANOMAPPER]: Process IsEquivalentOf [ONTOCOMMONS]:Materials Process*

Alignments To MatOnto, Material Ontology:

Target Ontology:	http://matonto.org/ontology/matonto
Related Ontology Entities:	*Process(http://www.ifomis.org/bfo/1.0/span#Process)* *ProcessualEntity (http://www.ifomis.org/bfo/1.0/span#ProcessualEntity)*
Mapping Elucidation:	Processual Entity is defined as " A processual entity that is a maximally connected spatio-temporal whole and has bona fide beginnings and endings corresponding to real discontinuities." Examples of Processual Entity are. "The life of an organism, the process of sleeping, the process of cell-division." A Process is a subclass of processual_entity that is defined as An occurrent that exists in time by occurring or happening, has temporal parts and always involves and depends on some entity.

	"Examples: the life of an organism, the process of meiosis, the course of a disease, the flight of a bird " . Comment:Process seems to include any type of process. Taxonomy in MatOnto: • Process is a rdfs:subClassOf ProcessualEntity • ProcessualEntity is a rdfs:subClassOf Occurrent Comments: The same as enanomapper
Semantic Relation Level:	See enanomapper
Mapping Axioms:	

Alignments To MM, MATERIALSMINE Ontology:

Target Ontology:	*http://materialsmine.org/ns/1.0*
Related Ontology Entities:	*Process (http://semanticscience.org/resource/Process)*
Mapping Elucidation:	*The Process is defined as" A process is an entity that is identifiable only through the unfolding of time, has temporal parts, and unless otherwise specified/predicted, cannot be identified from any instant of time in which it exists."* *Comment: Process is a wide encompassing concept.* *Process is a subclass of entity that it is not defined.* In MaterialsMine "Synthesis" is defined as " A synthesis reaction is an organic reaction in which two or more molecules are chemically bonded together to produce a single product." This is a subclass of an (unintentional) process *Taxonomy in MM Ontology:* • *Process is subclass of "'exists at' only 'time interval'"* • *Process is subclass of "'has proper part' only process"* • *Process is a subclass of "entity"*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* Same as above

Mapping Axioms:	*[*

Alignments to EMMO

Target Ontology:	*https://emmo.info/emmo* Example DLO: http://emmo.info/emmo/domain/mechanical-testing
Related Ontology Entities:	*Process* *(http://emmo.info/emmo#EMMO_43e9a05d_98af_41b4_92f6_00f79a09bfce)* To see how this ontology uses the concept process *we look at the only subclass IntentionalProcess (http://emmo.info/emmo#EMMO_bafc17b5_9be4_4823_8bbe_ab4e90b6738c) and its only subclass Manufacturing (http://emmo.info/emmo#EMMO_a4d66059_5dd3_4b90_b4cb_10960559441b)*
Mapping Elucidation:	The mechanical testing ontology is a DLO that has imported the EMMO as MLO and TLO. The MidLevel concept Emmo:Process is elucidated as "A whole that is identified according to a criteria based on its temporal evolution that is satisfied throughout its time extension." Comment "Following the common definition of process, the reader may think that every whole should be a process, since every 4D object always has a time dimension. However, in the EMMO we restrict the meaning of the word process to items whose evolution in time have a particular meaning for the ontologist (i.e. every 4D object unfolds in time, but not every 4D time unfolding may be of interest for the ontologist and categorized as a process). For this reason, the definition of every specific process subclass requires the introduction of a primitive concept." The EMMO chooses to look at process in a persistence perspective. EMMO:Process is a subclass of Persistence Perspective Item, which in turn is a subclass of Perspective Item. Persistence is a perspective of an ontologist who divides things into object and process . Comment on the EMMO itself. In the EMMO, most processes (e.g. intentialProcess, experiment etc) are

	often described in a holistic perspective, since they are seen in a whole/role perspective. Furthermore, it is possible to describe processes by strict tessellation which makes the description reductionistic, as is often done for example 'SequentialProcess' in EMMO. IntentionalProcess is "A process occurring with the active participation of an agent that drives the process according to a specific objective (intention)." SequentialProcess is " xxx ". Taxonomy in EMMO Ontology: • Process *rdfs:subClassOf* Physical • IntentionalProcess *rdfs:subClassOf* Process • SequentialProcess *rdfs:subClassOf* IntentionalProcess Comment: Materials Process includes both intentional and unintentional (e.g. degradation) processes, unlike manufacturing.
Semantic Relation Level:	
Mapping Axioms:	*[ONTOCOMMONS]: MaterialsProcess (rdfs:subClassOf) [EMMO]:Process*

CHEBI

Target Ontology:	*http://purl.obolibrary.org/obo/chebi.owl*
Related Ontology Entities:	
Mapping Elucidation:	*CHEBI: doesn't present classes about process.*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* ***None***
Mapping Axioms:	*NA*

RNXO Ontology

Target Ontology:	*http://purl.obolibrary.org/obo/rxno.owl*
Related Ontology Entities:	*Process(http://purl.obolibrary.org/obo/BFO_0000015)*
Mapping	*Process is alligned with BFO Process.*

Elucidation:	*Taxonomy of RNXO:* • *Process is a subclass of owl: Thing*

4.2.1.9 Materials Processing

General Concept Info:

IRI:	*Suggested entity new IRI:* Materials Processing
OWL Type:	Class
Concept Elucidation:	Elucidation: In materials science, processing is an intentional process for the creation (producing), transformation or decomposition of materials (recycling) from and/or into atoms and/or small molecules and/or simple compounds. Comment: aging is not an intentional process and is thus not included in materials processing. Comment: The effort can involve tangible tools such as utensils or machines, and intangible ones such as software. Comment: Materials Processing is a specific Process. Comment: The use of the term in Materials Science is different from its use in Manufacturing and/or Materials Engineering where processing are the techniques to create components from various materials and where the shape is important and where changes in the material are an unwished-for side effect. Comment: The decomposition of products is not included in the Manufacturing and Materials Engineering Term, but it is in the Materials Science Term. The ONTOCOMMONS concept “process” includes both intentional and unintentional processes, while “processing” is intentional. Some knowledge resources use the two labels “process” and “processing” differently. Therefore both are investigated. E.g. Wikipedia: Sol-Gel Process is an intentional process. Examples are material synthesis, material treatment (such as thermomechanical processing like annealing) and recycling.

	Comment: The expression "materials processing" does not appear in any dictionary, but the label "chemical process industry" is commonly used. Materials processing is wider than chemical processing. Forming and casting are subclasses of manufacturing as they concern the aspect shape.
Labels:	*i) preferred* Materials Processing *ii) alternative labels* Materials Synthesis, Materials Transformation and Materials Recycling

Knowledge Domain Resources:

Related Domain Resources:	**Materials Processing** 10. Wikipedia The term does not appear. But many compound entries do contain either "process" or "processing" and are relevant for our Bridge Term. Sol-Gel Process : In materials science, a process is a method for producing materials from small molecules. Different materials require different processing or synthesis methods. Comment: This definition is adapted from the definition of sol-gel process. The restriction to small molecules is not appropriate as one can also start from atoms. Integrated Computational Materials Engineering: In materials science, a process produces material structures which give rise to material properties, based on the selected materials. Chemical Process: In a scientific sense, a chemical process is a method or means of somehow changing one or more chemicals or chemical compounds. 2. Merriam-Webster: The term does not appear other than a form of the verb process. 3. Callister: Although it is a major topic in the book as part of the paradigm processing -structure-properties -performance the term is not defined.

	4. Raabe: No definition. 5. Wikidata: The term does not appear but this is the closest: food processing (Q627371): transformation of raw ingredients into food, or of food into other forms. 6. IUPAC-Goldbook: The term does not appear but the closest is Sol-Gel processing in which a network of precipitated colloidal particles is treated by a conventional processing technique, such as cold pressing, hot pressing or sintering, in order to produce a ceramic article. Comment: The definition demonstrates the intentionality of this term (in order to). **7. Brittanica dictionary:** Materials processing is the series of operations that transform industrial materials from a raw-material state into finished parts or products. Industrial materials are defined as those used in the manufacture of "hard" goods, such as more or less durable machines and equipment produced for industry and consumers, as contrasted with disposable "soft" goods, such as chemicals, foodstuffs, pharmaceuticals, and apparel. Comment: This definition specifies what we call manufacturing processing, while the production of materials is excluded (!). 9 IOF Core: IOF Core Iof covers the processing of materials intended for manufacturing. They process that is prescribed by a plan specification. It includes in Manufacturing Process one that presupposes that the outputs of a manufacturing process are in every case material artifacts or manufactured substances, so excludes processes that have as their primary output, something immaterial or informational in nature (digital outputs), such as found in the production of software, will be considered separately at a later stage. It provides for a transformation of the material. 10 Matportal: Comment: The term processing is only cited by three ontologies: • In DEB Ontology there is a class name properly Material

	Processing that is defined as "A planned process which results in physical changes in a specified input material." • In MaterialsMine Ontology there is the Processing class. • In MSEO (Material Science and Engineering Ontology) there is the class Post Processing which is a subclass of Simulation. 11. MATONTO: Comment: The term processing is not mentioned, neither as material processing nor in any other context. There is only the term process. 12. ISO standards Comment: The term processing is used in the field of electronics and in the field data, then systems. ISO 19844:2018 "Processing Material" is defined as "Type of material essential to the manufacturing process that is not incorporated into the resultant material", so Processing is thought to be an adjective. ISO 16762:2016(en): "Material in process" is defined as "Products or materials that have had processes applied to them but are still awaiting further additional processes to be applied — for example packing, varnishing" **Materials Transformation** 1. Wikipedia Comment: The compound term does not appear; only chemical reaction refers to chemical transformation which is a narrower concept than our Bridge Term. 2. Merriam Webster Transform: to change in composition or structure **Synthesis** 1. Wikipedia chemical synthesis (or combination) is the artificial execution of chemical reactions to obtain one or several products. 2. Merriam Webster The production of a substance by the union of chemical elements, groups, or simpler compounds or by the degradation of a complex compound. Comment: Degradation is included!

	3. Callister No definition 4. Raabe No definition. 5. Wikidata The chemical reactions and pathways resulting in the formation of substances 6. IUPAC Goldbook Biosynthesis: production of a chemical compound by a living organism 7. Brittanica dictionary Chemical synthesis is the construction of complex chemical compounds from simpler ones. 8. ISO standards Comment: in standard ISOs, the concept of synthesis is more applied to acoustics than to manufacturing or materials processing, but at the chemical level it approaches the concept of materials, applied to graphene. ISO/IEC 2382:2015(en), 2123784 **Synthesis:**<artificial intelligence> generation, by a functional unit, of artificial voice, text, music, and images. ISO/TS 80004-13:2017(en), 3.2.1.7 **chemical synthesis:** <graphene> bottom-up graphene production route using small organic molecules that become linked into carbon rings through surface-mediated reactions and elevated temperatures.
Comments:	In ONTOCOMMONS we propose (see comments above) MaterialsProcess superClassOf MaterialsProcessing MaterialsProcessing superClassOf Synthesis MaterialsProcessing superClassOf MarterialsTranformations MaterialsProcessing superClassOf MaterialsDecomposition ChemicalTransformation subClassOf MaterialsProcessing

Alignments To ENM, ENANOMAPPER Ontology:

Target	*http://enanomapper.github.io/ontologies/enanomapper.owl*

Ontology:	
Related Ontology Entities:	Processing is not defined SynthesisPart (http://purl.bioontology.org/ontology/npo#NPO_1944)
Mapping Elucidation:	The class "Synthesis Part" is not described and the label "part" is not explained. The concept is just synthesis. It is defined as a Subclass of "Process". Synthesis Part has two subclasses. macroscopic synthesis part and microscopic synthesis part. In macroscopic part processes that involve the mechanical and thermal treatment of material, such as freezing, heating colling, mixing, extrusion. For the microscopic part. Indeed, there are all processes at microscopic level, such as agglomeration, dispersion. etc. Taxonomy in ENM Ontology: • SynthesisPart (no elucidation) rdfs:subClassOf Process • Process rdfs:subClassOf Entity
Semantic Relation Level:	ONTOCOMMONS:materialsProcessing has a weak hierarchical semantic relation to enanomapper: synthesisPart.
Mapping Axioms:	*ONTOCOMMONS:MaterialsProcessing (skos:broader)* *ENANOMAPPER:SynthesisPart*

Alignments To MatOnto, Material Ontology:

Target Ontology:	http://matonto.org/ontology/matonto
Related Ontology Entities:	ChemicalReaction (*http://ontology.dumontierlab.com/ChemicalInteraction*) Process (*http://www.ifomis.org/bfo/1.0/span#Process*) ChemicalReaction is defined as "A process in which at least one chemical is converted into another". It is a subclass of Process. Process is defined as "A processual entity that is a maximally connected spatio-temporal whole and has bona fide beginnings and endings corresponding to real discontinuities" It has no link to the intentional materials processing and there is thus no matching concept related to

	MaterialsProcessing. Taxonomy in MatOnto-ontology: • *ChemicalReaction subclassOf Process* • *Process is a rdfs:subClassOf ProcessualEntity* • *ProcessualEntity is a rdfs:subClassOf Occurrent*
Mapping Elucidation:	None

Alignments To MM, MATERIALSMINE Ontology:

Target Ontology:	*http://materialsmine.org/ns/1.0*
Related Ontology Entities:	*Processing (http://materialsmine.org/ns/Processing);* *Filler Processing (http://materialsmine.org/ns/FillerProcessing);* *Matrix Processing (http://materialsmine.org/ns/MatrixProcessing);* *Surface Chemistry Processing (http://materialsmine.org/ns/SurfaceChemistryProcessing);*
Mapping Elucidation:	The term Processing is not elucidated. Processing is not a subclass of Process. Process and Processing are sibling classes. Filler/Matrix/SurfaceChemistry Processing are subclasses of Processing. They are not elucidated. The term seems to include all kind of processing (chemical, mechanical etc). Taxonomy in MM Ontology: • Process subClassOf Entity • Processing subClassOf Entity • FillerProcessing subClassOf Processing • MatrixProcessing subClassOf Processing • SurfaceChemistryProcessing subClassOf Processing
Semantic Relation Level:	The level of semantic relationship between the Concept and the Target Ontology entities seems to be weak
Mapping Axioms:	*[MATERIALSMINE]:*Processing *rdfs:subClassOf* *[ONTOCOMMONS]:* MaterialProcessing

Alignments to EMMO (Top Level and Mid Level)

https://emmo.info/emmo

Alignments to EMMO

Target Ontology:	http://emmo.info/emmo/1.0.0-beta4
Related Ontology Entities:	*Materials Processing (http://emmo.info/emmo#EMMO_71d1c8f0_c6e3_44b5_a4b6_1b74ff35698a)* *IndustrialTechnologyProcess (http://emmo.info/emmo#EMMO_2b9cbfb5_dbd0_4a68_9c6f_acc41b40dd72)* *IntentionalProcess (http://emmo.info/emmo#EMMO_bafc17b5_9be4_4823_8bbe_ab4e90b6738c)* *Process (http://emmo.info/emmo#EMMO_43e9a05d_98af_41b4_92f6_00f79a09bfce)* *MaterialSythesis (http://emmo.info/emmo#EMMO_fa9cfc5d_9c3c_4856_a708_28be3858917e)* *MaterialTreatment (http://emmo.info/emmo#EMMO_fc859d37_408d_44b6_b345_a0ea0b65121e)*
Mapping Elucidation:	The class MaterialsProcessing is elucidated as "A manufacturing process aimed to modify the precursor objects through a physical process (involving other materials, energy, manipulation) to change its material properties". It is a subclass of IndustrialTechnologyProcess that is commented as "This class represents processes that are related to industrial approach, that appeared after XIX century". The IndustrialTechnologyProcess is a subclass of IntentionalProcess, elucidated as "A process occurring with the active participation of an agent that drives the process according to a specific objective (intention)". The class IntentionalProcess is a subclass of Process that is elucidated as" A whole that is identified according to a criteria based on its temporal evolution that is satisfied throughout its time extension". MaterialsProcessing hosts classes such as MaterialTreatment, elucidated as" The processing of a material aimed to transform its structure by means of any type of treatment, without involving relevant synthesis phenomena", and MaterialSynthesis, elucidated as "The creation of a material entity

	starting from fundamental substances, involving chemical phenomena (e.g., reaction, bonding)". *Taxonomy in EMMO Ontology:* • *MaterialProcessing is a rdfs:subClassOf of IndustrialTechnologyProcess* • *IndustrialTechnologyProcess is a rdfs:subClassOf of IntentionalProcess* • *IntentionalProcess is a rdfs:subClassOf of Process* • *MaterialSynthesis is a rdfs:subClassOf of MaterialProcessing* • *MaterialTreatment is a rdfs:subClassOf of MaterialProcessing*
Semantic Relation Level:	***Strong Hierarchical semantic relation and equivalence.***
Mapping Axioms:	*[ONTOCOMMONS]:MaterialsProcessing rdfs:equivalentTo [EMMO]: MaterialsProcessing*

CHEBI

Target Ontology:	http://purl.obolibrary.org/obo/chebi.owl
Related Ontology Entities:	
Mapping Elucidation:	CHEBI: doesn't present classes about processing.
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* None
Mapping Axioms:	NA

RNXO Ontology

Target Ontology:	http://purl.obolibrary.org/obo/rxno.owl
Related Ontology Entities:	*plannedSynthesis (http://purl.obolibrary.org/obo/RXNO_0000329)*
Mapping Elucidation:	RNXO: A Planned Synthesis is defined as: " An experimental procedure with the aim of producing a portion of a given compound or mixture." Taxonomy of RNXO: • plannedSynthesis subClassOf plannedProcess RNXO:plannedSynthesis is very close to EMMO:materialsSynthesis

Semantic Relation Level:	Strong hierarchical link
Mapping Axioms:	*[RNXO]:plannedSynthesis rdfs:subClassOf [ONTOCOMMONS]: MaterialsProcessing*

4.2.1.10 Experiment

General Concept Info:

IRI:	*Experiment*
OWL Type:	*Class*
Concept Elucidation:	An experiment is a scientific process that investigates a physical phenomenon that is intended to support, refute, or validate a hypothesis or make a discovery. Comment: One can do experiments in controlled or uncontrolled environments with or without preconceived explanations (hypothesis). Comment: it is a type of observation Comment: An experiment might be designed to replicate a phenomenon Comment: the discovery might be an explanation or theory. Comment: An experiment often contains a measurement. Domain: Natural Sciences including Materials Science.
Labels:	*Preferred:* Experiment *Alternative:* Experimental study, Test

Knowledge Domain Resources:

Related Domain Resources:	*Existing domain resources (e.g. standards, books, articles, dictionaries) that defines or are related to the concept (provide reference to the resource and quote the relevant informational content).* *More than one resource can be reported.* *These resources are aimed to support the choice of the above concept choice and elucidation.* 1. Wikipedia: An **experiment** is a procedure carried out to support or refute a hypothesis, or determine the efficacy or likelihood of something previously untried. Experiments provide insight into cause-and-effect by

	demonstrating what outcome occurs when a particular factor is manipulated. Experiments vary greatly in goal and scale but always rely on repeatable procedure and logical analysis of the results. There also exist natural experimental studies. Experiments typically include controls, which are designed to minimize the effects of variables other than the single independent variable. This increases the reliability of the results, often through a comparison between control measurements and the other measurements. Scientific controls are a part of the scientific method. Ideally, all variables in an experiment are controlled (accounted for by the control measurements) and none are uncontrolled. In such an experiment, if all controls work as expected, it is possible to conclude that the experiment works as intended, and that results are due to the effect of the tested variables. 2. Merriam-Webster: test, trial ; a tentative procedure or policy ; an operation or procedure carried out under controlled conditions in order to discover an unknown effect or law, to test or establish a hypothesis, or to illustrate a known law 3. Wikidata: **experiment (Q101965)** :scientific procedure carried out to support, refute, or validate a hypothesis 4. Britannica dictionary Not defined but **natural experiment (observational study)** : natural experiment, observational study in which an event or a situation that allows for the random or seemingly random assignment of study subjects to different ... 5. ISO Standards: ISO/TR 13195:2015(en), 2.1 purposive investigation of a system through selective adjustment of controllable conditions and allocation of resources Note 1 to entry: Adapted from ISO 3534-3:2013, definition 3.1.1. (The notes are not reproduced here.) 6. IOF Core: In the IOF core ontology, core.rdf file, experiment appears only in one of the examples, in the documentation of "observesAtSomeTime" object property (relation). The example is documented as"a scientist observing a chemical reaction in an experiment recognizes an explosion, an operator observes a

	machining process recognizes a defect in a part, a doctor observes a group of COVID patients and recognizes that majority of them have difficulty breathing<"

Alignments To Existing Ontologies: *(1: vertical, MLOs/TLOs; 2: horizontal, DLOs)*

1: Vertical Alignments

Focus is on horizontal alignments

2: Horizontal Alignments

LPBFO

Target Ontology:	*https://www.emi.fraunhofer.de/ontologies/LPBFO*
Related Ontology Entities:	*Experiment* (https://www.materials.fraunhofer.de/ontologies/BWMD_ontology/mid#BWMD_00151) *Process (*http://purl.obolibrary.org/obo/BFO_0000015*)* **Experiment** is defined as "Any kind of experimental process" It is a subclass of Process and Process is defined as in MSEO: Process is defined as "p is a process means p is an occurrent that has some temporal proper part and for some time t, p has some material entity as participant at t" Comment: circular definition
Mapping Elucidation:	Comment: the concept is probably meant to be identical, but the Ontocommons Bt is much more precisely elucidated. It is ths safer to declare it to be a subclass.
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* • *Strong Hierarchical rdfs:subClassOf,* Comment: probably meant to e equivalent
Mapping Axioms:	*Proposed mapping axiom (or axioms) between the Concept entity and the Target Ontology entities in a OWL2 compliant syntax (e.g. Turtle, Manchester, RDF/XML, Functional-Style, OWL/XML).*

MSEO

Target Ontology:	*https://purl.matolab.org/mseo/mid*

Related Ontology Entities:	*Experiment(*https://purl.matolab.org/mseo/mid/Experiment*)* *MeasurementProcess(*https://spec.industrialontologies.org/ontology/core/Core/MeasurementProcess*)* *PlannedProcess(*https://spec.industrialontologies.org/ontology/core/Core/PlannedProcess*)* *Process (*http://purl.obolibrary.org/obo/BFO_0000015*)* **Experiment** is defined as "In engineering and the physical sciences, experiments are a primary component of the scientific method. They are used to test theories and hypotheses about how physical processes work under particular conditions (e.g., whether a particular engineering process can produce a desired chemical compound). Typically, experiments in these fields focus on replication of identical procedures in hopes of producing identical results in each replication. Random assignment is uncommon." Comment: This concept elucidation contains "controlled" and "hypothesis" and is thus narrower. It is a subclass of MeasurementProcess **MeasurementProcess** is defined as "planned process to determine the value of an attribute (specifically dependent continuant or temporal region or process characteristic) of an entity of interest". It is a subclass of Planned Process. Comment: This concept is always quantitative, while the BT is wider as it can also contain behavioral experiments. Comment: measurement is part of an (characterisation) experiment. **PlannedProcess** is defined as "process that is prescribed by a plan specification PlannedProcess(x) ↔ Process(x) ∧ ∃s (PlanSpecification(s) ∧ prescribes(s, x)) every instance of 'planned process' is defined as exactly an instance of 'process' that is 'prescribed by' some 'plan specification'" It is a subclass of Process **Process** is defined as "p is a process means p is an occurrent that has some temporal proper part and for some time t, p has some material entity as participant at t"
Mapping Elucidation:	See comments above
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* • *MSEO:experiment skos:narrower ONTOCOMMONS:experiment* Note: A MSEO class is an instantiation of the OWL class, thus the skos statement can operate on classes. Skos statements are not logical

	statements, thus a mapping can be both strongly hierarchical and weak hierarchical • *MSEO:experiment rdts:subClassOf ONTOCOMMONS:experiment*
Mapping Axioms:	

MaterialsMine

Target Ontology:	*http://materialsmine.org/ns*
Related Ontology Entities:	Experiment (http://semanticscience.org/resource/Experiment) Investigation (http://semanticscience.org/resource/Investigation) Procedure (http://semanticscience.org/resource/Procedure) **Experiment** is defined as "An experiment is an investigation that has the goal of verifying, falsifying, or establishing the validity of a hypothesis." Comment: hypothesis, controlled and uncontrolled. It is a subclass of Investigation: **Investigation** is defined as "investigation is the process of carrying out a plan or procedure so as to discover facts or information about the object of study." Comment: very close to ONTOCOMMONS:experiment It is a subclass of Procedure. **Procedure** is defined as "A procedure is a process that attempts to achieve one or more objectives by following an established set of actions."
Mapping Elucidation:	Similar to above
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* • *Strong Hierarchical (rdfs:subClassOf,* • *Weak Hierarchical (skos:narrower*
Mapping Axioms:	*Proposed mapping axiom (or axioms) between the Concept entity and the Target Ontology entities in a OWL2 compliant syntax (e.g. Turtle, Manchester, RDF/XML, Functional-Style, OWL/XML).*

MatOnto

Target Ontology:	*http://purl.obolibrary.org/obo/rxno.owl*

Related Ontology Entities:	*Does not include Experiment*

EMMO

Target Ontology:	*http://emmo.info/emmo/1.0.0-beta4*
Related Ontology Entities:	*Experiment(http://emmo.info/emmo#EMMO_22522299_4091_4d1f_82a2_3890492df6db)* *Process(http://emmo.info/emmo#EMMO_43e9a05d_98af_41b4_92f6_00f79a09bfce)* *Persistence(http://emmo.info/emmo#EMMO_e04884d9_eda6_487e_93d5_7722d7eda96b)* **Experiment** is currently defined as "An experiment is a process that is intended to replicate a physical phenomenon in a controlled environment." But this will be updated to be in line with the above thoughts that is to include uncontrolled and no hypothesis. It is and remains a subclass of Process. Process is defined as "A whole that is identified according to a criteria based on its temporal evolution that is satisfied throughout its time extension." It is a subclass of Persistence. Persistence is defined as "The union of the object and process classes."
Mapping Elucidation:	*It will be equivalent after the planned update of the EMMO*
Semantic Relation Level:	*The level of semantic relationship between the Concept and the Target Ontology entities:* • *Equivalence (strong mapping) (e.g. owl:equivalentClass, owl:equivalentProperty)*
Mapping Axioms:	

4.2.2 Alignment between EMMO and MDO

An alignment between EMMO and the MDO ontology has been carried out. Specifically, the MDO-core module has been considered, available at https://w3id.org/mdo/core/. EMMO's version used in the alignment is 1.0.0-beta4.

The alignment involves a number of elements (classes and properties) of the two ontologies, as summarized in Table 27 . Details of EMMO's elements involved are reported in Table 28. The semantic connections used for the alignment mainly include relationships of equivalence, subsumption and their corresponding inference, defined in accordance with the elucidations for the respective elements found in the two ontologies.

Table 27: Details of the elements from MDO and EMMO involved in their alignment.

MDO element	EMMO element	Details
mdo-core:Calculation	Computation	Calculation is defined as a subclass of EMMO's Computation
mdo-core:Material	Material	Material is deemed equivalent to EMMO's Material
mdo-core:Property	Property	Property is a subclass of EMMO's Property, as inferred via the equivalence relationship between qudt:Quantity and EMMO's Quantity
qudt:Unit	MeasurementUnit	Unit is deemed equivalent to EMMO's MeasurementUnit
qudt:Quantity	Quantity	Quantity is deemed equivalent to EMMO's Quantity
qudt:QuantityValue	Data	QuantityValue is defined as subclass of EMMO's Data
mdo-core:Structure	Information	Structure is defined as subclass of EMMO's Information
mdo-core:hasInputProperty	hasInput	hasInputProperty is defined as a subproperty of EMMO's hasInput
mdo-core:hasInputStructure	hasInput	hasInputStructure is defined as a subproperty of EMMO's hasInput
mdo-core:hasOutputCalculatedProperty	hasOutput	hasOutputCalculatedProperty is defined as a subproperty of EMMO's hasOutput
mdo-core:hasOutputStructure	hasOutput	hasOutputStructure is defined as a subproperty of EMMO's hasOutput
mdo-core:relatesToMaterial	hasSign	relatesToMaterial is defined as a subproperty of EMMO's hasSign
rmdo-core:elatesToStructure	hasSign	relatesToStructure is defined as a subproperty of EMMO's hasSign

Table 28: URIs and modules of the elements from EMMO involved in the alignment with MDO.

EMMO label	EMMO URI	EMMO module
Computation	EMMO_eff42cb3_208e_4768_9a39_f8b6b3c3d7a2	disciplines-models
Data	EMMO_1e877c70_3b01_45a8_a8f6_8ce4f6a24660	perspectives-data
Information	EMMO_64c72d00_7582_44ea_a0b5_3a14e50acc36	multiperspective-information
Material	EMMO_4207e895_8b83_4318_996a_72cfb32acd94	disciplines-materials
MeasurementUnit	EMMO_b081b346_7279_46ef_9a3d_2c088fcd79f4	disciplines-metrology
Property	EMMO_b7bcff25_ffc3_474e_9ab5_01b1664bd4ba	perspectives-semiotics
Quantity	EMMO_f658c301_ce93_46cf_9639_4eace2c5d1d5	disciplines-metrology
hasInput	EMMO_36e69413_8c59_4799_946c_10b05d266e22	multiperspective-persholistic
hasOutput	EMMO_c4bace1d_4db0_4cd3_87e9_18122bae2840	multiperspective-persholistic
hasSign	EMMO_60577dea_9019_4537_ac41_80b0fb563d41	perspectives-semiotics

The alignment is available at the following GitHub repository: https://github.com/emmo-repo/mdo-emmo-alignment.

4.3 Manufacturing

4.3.1 Introduction

We introduce a preliminary alignment between two pivotal middle-layer ontologies in the realm of manufacturing engineering: DolceEng and IOF Core. The first one is developed by extending the DOLCE ontology; it is designed and maintained by research groups at the National Research Council (CNR) of Italy, and is still under development. The second ontology is based on the BFO ontology and is collaboratively developed and maintained by efforts within the Industrial Ontology Foundry (IOF).

The two ontologies have been developed independently from each other; the classes we either align or comment upon in the following sections are the ones that are shared among the ontologies, although – as we will see – with some differences in their intended meanings. The list of classes taken into account is reported in the tables below (Table 29, Table 30). The presented alignments revolve around the delineation of taxonomic and equivalence relationships between these classes. The alignments are introduced as proposals for further research and discussion. Informally, we write **is-a** for an axiom of subsumption, and **equiv-to** for an axiom of equivalence between the considered classes. The alignments can be then formally represented in the desired formal language.

DolceEng's classes
Technical Artefact
Technical Artefact Description
Activity Occurrence
Activity
Capability
Transformation System

Table 29 Classes of DolceEng selected for the comparison

IOF Core's classes
Material Artifact
Design Specification
Planned Process
Plan Specification
Capability
Engineered System
AgentRole

Table 30 Classes of DolceEng selected for the comparison

4.3.2 *Presentation of the ontologies*

4.3.2.1 Introduction to DolceEng

The ontology DolceEng has been developed for research and application purposes by specializing the DOLCE foundational ontology with modeling elements for the domain of manufacturing. Research work leading to DolceEng has been presented in various venues ([10]; [19]; [21]; [13]).

Similarly to other research efforts related to DOLCE, the design methodology for DolceEng makes a distinction between at least two core phases of the design process, that is, the ontological analysis of manufacturing-related notions, and the development of models which can be usable for tasks related to data management through computational systems. Accordingly, DolceEng is developed in first-order logic whereas Semantic Web languages are used for its computational representations. Because of the restricted formal expressivity of the latter languages, one needs to find compromises between conceptual modeling choices and their effective computational representation. For instance, DOLCE strongly relies on relationships with *n*-ary cardinality, especially when time indexes are necessary to make sense of the dynamic nature of the phenomena under analysis. How to render these relationships and other aspects of DOLCE that do not squarely fit into OWL in a way that is coherent with the theoretical grounding of DOLCE is a topic for research ([21]). As a consequence, the OWL formalization of DolceEng is still under development. Figure 77 shows the main classes of DolceEng subsumed by DOLCE (only partially represented here).

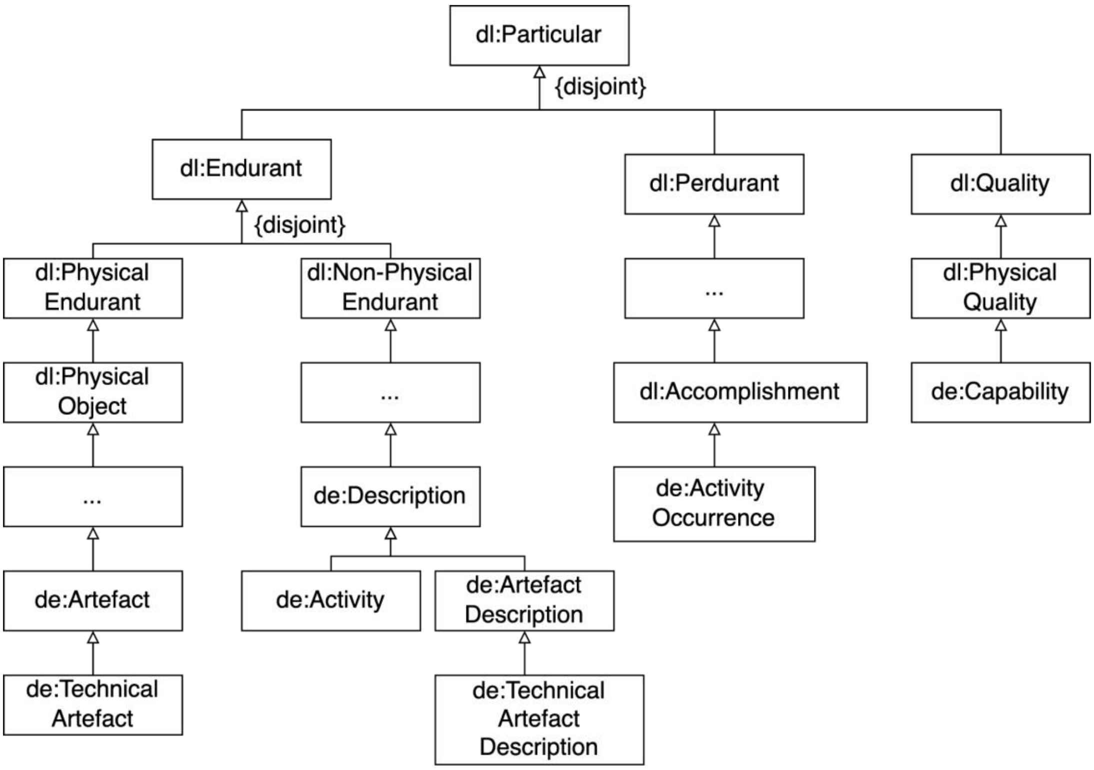

Figure 77: Core classes of DolceEng (with prefix 'de') subsumed by classes in DOLCE (with prefix 'dl')

4.3.2.2 Introduction to IOF Core

IOF Core[7] is a "mid-level" ontology that resides at the top of the suite of ontologies in the Industrial Ontology Foundry (IOF) ([22]); it seeks to fulfil its mission of supporting digital manufacturing by standardizing industrial terminology and improving consistency and interoperability across many operational areas of manufacturing and the product life cycle. As a mid-level ontology, Core contains terms used by, or anticipated to be used by, a plurality of ontologies in the suite. Additionally, as the IOF bases all its ontologies on a single foundational or top-level ontology, for which the IOF has chosen the Basic Formal Ontology (BFO), the Core ontology contains generic terms that build upon BFO and provide a consistent foundation for introducing industrial domain-specific terminologies.

The IOF Core Ontology is developed and formalized as an ontology using both first-order logic (FOL) ([20]) and version 2 of the Web Ontology Language (OWL). The use of logic ensures that each term is defined in a way that is least ambiguous to humans, remains applicable across industrial domain uses, and can be processed by computers. The Core Ontology is curated by the Core Working Group and attempts were made to validate and ground terms utilizing use cases from industry. It should be noted however that while the ultimate purpose of including FOL is to provide a more precise formal semantic definition than can be expressed in version 2 of OWL, the FOL annotations provided in the current release merely parallel those of the OWL expressions. The IOF intends to enrich the FOL formalizations in future releases to align more closely with their natural language definitions.

The released beta version of the IOF Core ontology consists of 57 OWL classes and 38 OWL properties ([14]). There are two types of classes: primitive and defined. Primitive classes are either 1) so basic to our understanding that it is impossible to define them without circularity, 2) we currently cannot identify a useful set of necessary and sufficient conditions, 3) there are insufficient terms in our current scope to formulate such conditions, or 4) there is still insufficient agreement among domain experts as to what such conditions should be. Primitive classes, in most cases, are provided with necessary conditions, along with examples to help users understand the intended meaning. On the other hand, defined classes provide a true definition of the term, formulating both a set of necessary conditions and a set of sufficient conditions. Of the IOF Core's current 57 classes, 37 are primitive while 20 are defined. It should be noted that the number of primitive classes can be reduced by introducing new properties as primitives. Nevertheless, the IOF Core development team seeks, as far as possible, to reuse existing properties.

[7] https://spec.industrialontologies.org/ontology/core/Core/

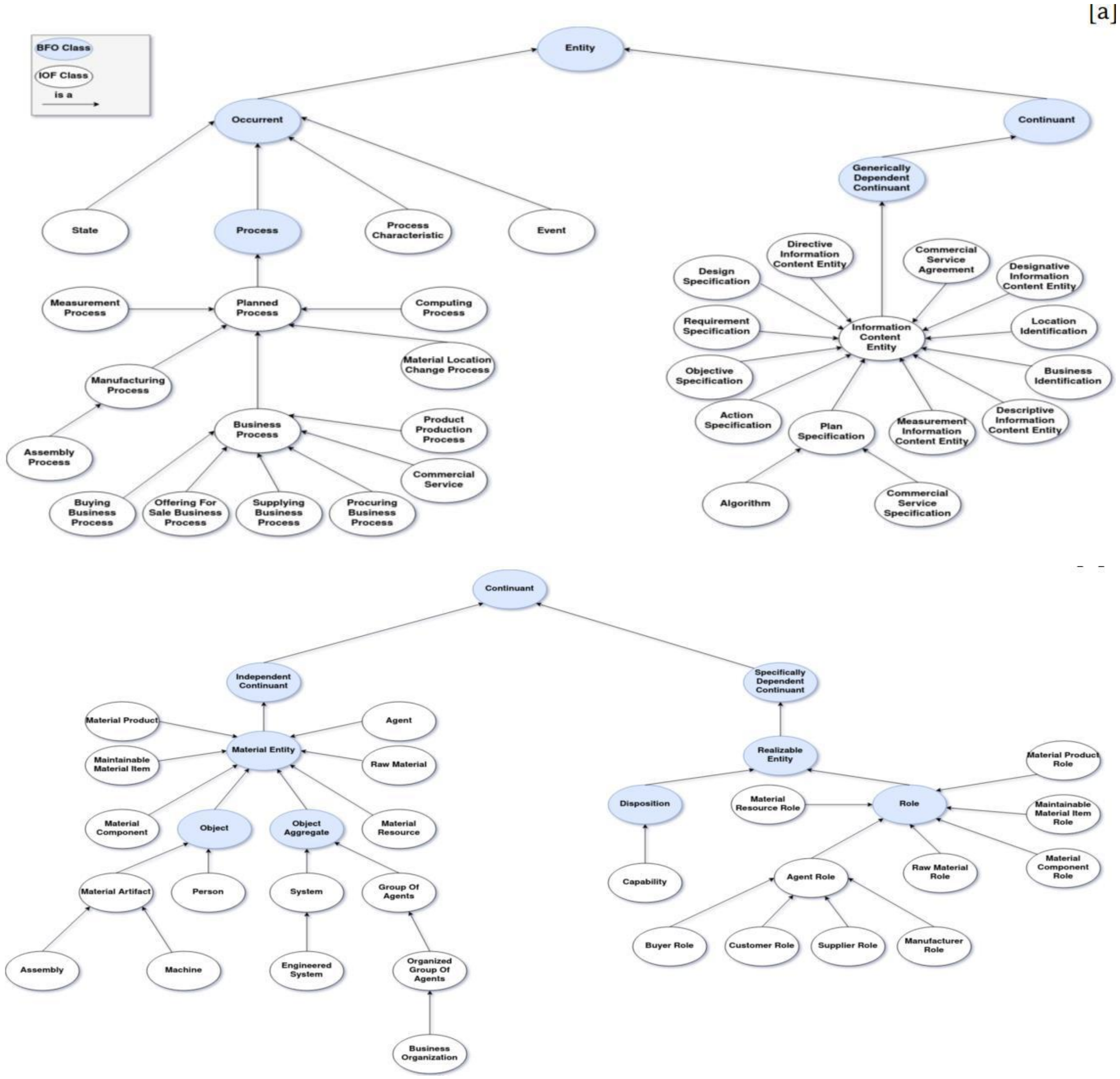

Figure 78: Fragment of the BFO class hierarchy aligned with IOF Core classes. [a] depicts alignment with the occurrent and generically dependent continuant branches of BFO. [b] depicts alignment with the independent continuant and specifically dependent continuant branches of BFO.

4.3.3 List of alignments

4.3.3.1 **Alignment between the classes: de:TechnicalArtefact and iof:MaterialArtifact**

Instances of de:TechnicalArtefact are intentionally human-made entities. Also, differently from instances of the more general de:Artefact class, technical artifacts satisfy (*comply with*) technical specifications, at least when they are fabricated.

Compliance is a complex notion; for instance, it is a matter of debate whether an artifact that (partially) loses compliance with the corresponding specification can be still considered as an artifact of the kind described by the specification ([18]).

Similarly to the more general class de:Artefact, instances of de:TechnicalArtefact are not necessarily made of material.

Material artifacts in the IOF are objects that are intentionally created to have a certain function. In particular, every instance of iof:MaterialArtifact is the bearer of some functionality which is prescribed by a certain design specification. In addition, as the label for this class suggests, material artifacts are made of materials.

Proposed alignment: iof:MaterialArtifact **is-a** de:TechnicalArtefact

de:TechnicalArtefact is more general than iof:MaterialArtifact: they are both intentionally, human-made entities but only the latter takes an explicit commitment to material constitution and functionality.

Through this alignment and the formal structure of the ontologies, iof:MaterialArtifact is subsumed by the more general de:Artefact class in DolceEng.

4.3.3.2 Alignment between the classes: de:TechnicalArtifactDescription and iof:DesignSpecification

Instances of de:TechnicalArtifactDescription in DolceEng are technical descriptions in the engineering sense, e.g., models for the geometric specification of a product, bills of materials, etc. On the other hand, the more general de:ArtifactDescription captures descriptions of artefacts that are not necessarily human-made.

Instances of iof:DesignSpecification set requirements about the properties that material artifacts need to satisfy.

At first glance, de:TechnicalArtefactDescription and iof:DesignSpecification are equivalent classes aimed at representing descriptions of intentionally human-made artifacts.

Proposed alignment: de:TechnicalArtifactDescription **equiv-to** iof:DesignSpecification

4.3.3.3 Alignment between the classes: de:Activity and iof:PlanSpecification

The class de:Activity in DolceEng is based on the Process Specification Language (PSL; [15]) where it is meant as an *activity type*. In terms of DOLCE, we interpreted this class as standing for plans which are not necessarily realized.

Plan specifications in the IOF Core are engineering specifications that when realized lead to processes to achieve predetermined objectives.

At first glance, de:Activity and iof:PlanSpecification are equivalent classes in that they are both meant to represent a specification (description) that can be possibly carried out in a perdurant realizing the prescribed goals.

Proposed alignment: de:Activity **equiv-to** iof:PlanSpecification

4.3.3.4 Alignment between the classes: de:ActivityOccurrence and iof:PlannedProcess

The class de:ActivityOccurrence in DolceEng has been based on the PSL ontology ([15]) where it models events occurring in time and space, possibly satisfying the constraints of activities. In terms of DOLCE, de:ActivityOccurrence specializes the more general class Accomplishment which models occurrences ending in the achievements of certain goals.

A planned process in the IOF Core is an event that satisfies a plan specification.

Proposed alignment: iof:PlannedProcess **is-a** de:ActivityOccurrence

In the proposed alignment iof:PlannedProcess is subsumed by de:ActivityOccurrence since the former, by explicit reference to plan specifications, is more specific than the latter class.

For the sake of clarity, recall that DOLCE's accomplishments are meant to be anti-cumulative, that is, the (mereological) sum of two accomplishments of the same type is not an entity of that type. Consider, for example, a *manufacturing type MT* collecting accomplishments aimed at producing an item with certain characteristics. The sum *s* of two instances of MT is not an instance of MT because *s* does not aim *per se* at producing a specific item.

IOF and BFO classes do not explicitly commit on (anti-) cumulativity for occurrences, hence the proposed alignment above does not conflict with any background assumptions.

4.3.3.5 Alignment between the classes: de:TransformationSystem and iof:System and iof:PieceOfEquipment

In DolceEng, de:TransformationSystem is a subclass of de:TechnicalArtefact that carries out transformations of a product in terms of form, composition, space, etc. It is a general class that can be further specialized for manufacturing systems, assembly systems, transportation systems, etc.

The IOF Core covers the classes iof:System and iof:EngineeredSystem, the latter being subsumed by the former. Both classes are object aggregates in the BFO's sense, i.e., material entities consisting exactly of a plurality of (material) objects as member parts which together form a unit. In this ontological view, systems are "limited to natural, social and technical systems that are tangible and whose "elements" are also tangible". Engineered systems on the other hand are systems that are deliberately created to have certain functions.

Proposed alignment: de:TransformationSystem **is-a** iof:EngineeredSystem

In this manner de:TransformationSystem cannot include immaterial items like holes among its constituents. Recall that entities like holes are understood in DOLCE as (immaterial) features, i.e., physical endurants that require other objects (the features' *hosts*) in order to exist. It is common view in formal ontology that holes are not *parts* of their hosts (Casati and Varzi 1994). In this sense, a transformation system may host features which are not however understood as their components. At first glance, this is coherent with the framework of BFO, hence with the understanding of object aggregates as being composed by material entities only. However, further analysis is required to understand whether these considerations match with both engineering knowledge and the foundational ontologies taken into account, as well as to consider other entities with immaterial nature (e.g., algorithms).

We finally comment on the other two couples of classes. At the current state, they are not aligned because the alignment requires further investigation, including more analytic insights into the foundational and engineering theories upon which DolceEng and IOF Core rely.

4.3.3.6 Comment on the classes: de:Capability and iof:Capability

The modeling of capabilities is a challenging and hot topic for research in ontology engineering for industry ([13]), and their representation in DolceEng and IOF Core is only preliminary at the current state.

In DolceEng, a capability is a quality that is intentionally designed to allow its bearer to participate in certain types of events. For instance, a drilling machine has the capability of drilling certain types of materials with a specific geometry because of the manner in which the driller was designed, i.e., because of its capability. Hence, since the driller owns this quality, it can participate in events of type *drilling* to achieve certain results.

According to the IOF Core ontology, a capability is a disposition possessed by a material entity whose realization is of interest for certain agents, e.g., for the designers who develop that entity. IOF introduced the property isAvailableToAtSomeTime instead of "interest in" (specifically it's reverse), holding between the bearer of a capability and the agent who took interest in its realisation.

We refrain from aligning the two classes because they are grounded in broader views on how to conceive functionalities in engineering. Further research and engagement with the teams behind DolceEng and IOF Core is necessary.

4.3.3.7 Comment on the classes: de:Role and iof:AgentRole

The class of Role in research about DOLCE has been introduced for the first time by [16]. Roles are here intended as concepts that are *anti-rigid* and *founded*, i.e., (i) they have a dynamic nature in that an entity may lose or acquire a role without undergoing radical changes in its nature, and (ii) they have a relational nature, i.e. they depend on other roles and on contexts. For instance, the role of teacher applying to, say, John for a certain interval of time, express an anti-rigid property that John can acquire and lose in time; moreover, it depends on a broader relational context, for instance, that John is employed at a school, got a specific job qualification, etc. As a concept, the same role can apply to multiple entities even at the same time. For instance, the formulas CF(John,teacher,t) and CF(Mary,teacher,t) with Role(teacher) say that both John and Mary are classified (CF) by the role of *teacher* at time *t*. Recall that the relation of classification (CF) is used to bind a concept (including roles) to the entities to which it applies.

In the BFO ontology, each instance of role is a realizable entity that (1) exists because the bearer is in some special physical, social, or institutional set of circumstances in which the bearer does not have to be (optionality), and (2) is not such that, if this realizable entity ceases to exist, then the physical make-up of the bearer is thereby changed (external grounding) ([9]). The optionality clause states that role is a realizable entity whose manifestation brings about some result or end that is not typical of its bearer’s physical structure, its design, or original design intent. The bearer may have a physical structure that gives it capability to bring such change while it is bearing the role but definitely not something it was originally built for or why it came about. A car is built to be driven around for transport but the same car may play a role of prop while being on display in a museum. The car was not built for being displayed as a prop in a museum but plays the role perhaps because of its aesthetics or some historicity associated with it. The externality clause states that the reasons why the role is played by an instance are some special natural, social, or institutional set of circumstances. Many prominent types of roles involve social ascription. A person can play the role of lawyer or of surrogate to a patient because of causes or circumstances that are external to the person. Because of such external grounding of role, a role can cease to exist without the physical make-up of the bearer thereby being changed.

To comment on de:Role and bfo:Role, first, they both admit that the ascription or removal of role do not change the physical nature of an entity. In the case of DOLCE, the condition on anti-rigidity focuses on the change of classification of an entity without changing its identity; on the other hand, external grounding in BFO is based on the absence of any substantial cause in the entity for its behavior. Secondly, the optionality clause for bfo:Role is similar to the relational property of dolce:role. The original idea is drawn from Husserl's notion of foundation, which intuitively states "a property a is founded on a property b if, necessarily, for every instance x of a there exists an instance y of b which is not 'internal' to x". Clearly these are external influences as prescribed by BFO's optional clause. But BFO does not prescribe any definitional dependency of these external causes to the role.

However, the logical mapping between de:Role and bfo:Role suffers from its position in the corresponding taxonomies of DOLCE and BFO. First, a bfo:Role exists only when some specific independent continuant serves as its bearer. bfo:Rrole in this sense, like qualities, are bfo:"specifically dependent continuant" (SDC), which cannot migrate from one bearer to another. An entity can play the same de:Role several times, simultaneously and different entities can play the same de:Role, simultaneously or at different times. DOLCE's roles therefore do not depend specifically on their players. At first glance, BFO's roles are similar to qua-entities as described by [16]; [17]. A more robust comparison including these notions requires however further analysis which is behind our purposes here.

Secondly, bfo:"generically dependent continuant" (GDC) is subclass of NPED (see the alignment between DOLCE and BFO in Deliverable 2.7, dbd5, ddb17-18). Therefore, IOF may extend the "information content entity" (ICE) (subtype of BFO) to introduce specific types of ICE to represent the bfo:role, e.g., iof:"Role Specification", which may be a candidate for mapping to de:Role. Lastly, but most importantly, there is no equivalent property for DOLCE's relationship of classification in BFO or IOF. This will again need some extension at the IOF side to introduce a way to state that the classification of an entity by its inherence of a role is equivalent to the entity following the specification of the role (at the ICE side).

5.Discussion

The overall outcome of this report is to study intra and cross-domain data interoperability through domain ontologies, feedback from stakeholders and cross-domain use cases. By providing the status of four new ontology developments and alignments of domain ontologies in various topics, this report updates on the progress but makes several valuable insights on the concerns of ontology-based interoperability, best practices in ontology development, the practice in the community, and gaps to be addressed. While these advancements undeniably contribute to enhancing industrial data interoperability through the creation of new ontologies and the harmonization of existing ones, perhaps the most significant takeaway is the practical knowledge and observations gained throughout this endeavour. These experiences hold immense value for shaping future standards and methodological guidelines within this domain. This section highlights some of these key observations as crucial takeaways from our efforts.

As presented in Section 1.1 (summary of the detailed methodology presented in D3.6), a high-level workflow for the development of new ontology and alignment of existing ontology is presented. This workflow is a specialisation of the "ontology implementation" phase of the Linked Open Terms (LOT) methodology customised to apply to the context and need of OntoCommons. The design of three phases: domain coverage analysis, harmonisation of existing DLOs, and development of new ontologies, as described in Table 1, is a unique contribution of T3.4, in which the first phase identifies the areas existing domain ontologies may cover as well as areas where no ontologies are found, based on the ontology requirement specification. Next, the second phase is applied to align the existing ontologies and the third phase to cover the gaps. Naturally, the result of these activities is a network of harmonised ontologies that provides data interoperability for one more broad domain area. Although this methodology is devised especially for catering to vast subject areas in manufacturing and materials in an organised manner, the same could be applied to any large-scale ontology development projects aiming to address data interoperability across multiple domains, sectors, and applications.

However, the effort in the application of this methodology was not without hindrance, especially, two of which are worth mentioning. First, it was observed that the existing ontologies selected by the domain coverage have varying degrees of coverage to the requirements as well as similarity among them. Most problematically, highly similar ontologies may have limited coverage for the requirement, and vice versa. E.g., both ontology A and ontology B may have a high number of similar terms (therefore could be aligned to great extent) but only few of these similar terms are similar to the terms in the glossary (from requirement). Consequently, many existing ontologies identified in the first version of the report (D3.5) were not subjected to alignment in this version of the report. Secondly, members of different working groups faced considerable difficulty in applying some of the steps of the methodology, e.g., matching similarities among terms in ontology and glossary, testing CQs against ontologies, and preparing bridge concepts, due to the complexity of these steps multiplied by the volume of work. Furthermore, the preparation of bridge concepts demanded substantial domain knowledge from the members with a lot of time spent on analysis of state-of-the art and understanding the context of the existing ontologies to propose mappings. These two difficulties need to be addressed to make the methodology more effective. The first problem may be mitigated by applying automated tools for finding similarities to some extent. However, the second problem has no immediate solution, although, LOT4OCES has proposed a template, best practice guide and strategies, e.g., trait analysis, to provide some level of assistance. Still, it is evident from some of the efforts on mappings presented in this report, e.g., alignments for Manufacturing (Section 4.3).

The harmonisation of ontologies conducted in T3.4 and reported in this deliverable only addresses intra-domain harmonisation, i.e., ontologies aligned are from the same domain. In the next step, cross-domain mappings need to be addressed. It can be observed however that the methodology guiding the intra-domain mappings resolves the cross-domain mappings to a great extent. The two most important catalysts are the use of some top-level ontology and the use of bridge concepts. Naturally, semantic interoperability between concepts of ontologies under the same top-level ontology is guaranteed. Thanks to the alignment among top-level ontologies as part of Top-reference ontology also helps in mapping concepts from ontologies under two different top-level ontologies, e.g., DolceEng and IOF-Core (Section 4.3). As in the cases of product and services, and materials science, if both or one of the ontologies being aligned do not follow any top-level ontology, then the bridge concepts come into play. In case both of the ontologies are not under any top-level ontology, the bridge concepts provide the common grounding for the concepts of these two ontologies to anchor to. Furthermore, the mapping of domain concepts to bridge concepts makes it easier for the bridge concepts to be less abstract and closer to the domain. As the bridge concepts are mapped to every top-level ontology, some concepts from non-TLO-based ontology mapped to some bridge concepts can be mapped to the concepts of the ontology that is under one of the TLO. In the future, these cross-domain mappings need to be inferred based on the conditions described above. A strategy also needs to be developed to encode these mappings and make them available so that they can be exploited for practical use.

For the OCES to enable intra and cross-domain data interoperability, new ontologies must be developed in alignment with the ecosystem's stack of ontologies from the beginning. This is also a prudent decision as without such alignment, these new ontologies are required to be reworked to enable harmonisation. Most of the newly developed ontologies presented in this report however do not adhere to top-level ontologies or bridge concepts rigorously. It is also observed that these ontologies adopt different standards and formats for naming conventions, annotations, metadata, encoding and storage. Apart from the crucial semantic interoperability that the adherence to TLO or bridge concepts ensures, interoperability needs to be warranted at structural, syntactical and format levels. As described in Section 2.1, LOT is prescribed as the methodology for ontology development in its standard form and except for Model-based systems engineering modelling tool ontology, other new ontology development claimed to follow LOT. It points to a need of some specialisation and customisation to be implemented on top of LOT to mitigate these shortcomings. On this front, LOT for OntoCommons Ecosystem (LOT4OCES) being developed as part of D2.9 is an ideal candidate.

Lastly, one may ask how to evaluate the quality of the harmonisation that was reported in this report. It can be argued that such can be derived from the quantitative and qualitative assessment of the level of interoperability that can be achieved by the aligned ontology stack. The development of a quality framework of data interoperability is long-standing research in the data and ontology community. A review of domain interoperability reported in D3.8 addresses many aspects in this regard.

6.Conclusions

The final report on harmonized and developed DLOs, together with the first report, achieved the following goals. First, a harmonization workflow was designed as a general guideline to guide the harmonization process with an emphasis on adopting the bridge concept approach. Second, five focus areas in the NMBP domain was shortlisted and the existing DLOs in which were identified and analysed. Third, preliminary harmonization of DLOs was attempted through bridge concept elucidation. Fourth, gaps was revealed through domain coverage analysis which pointed to the needs for new DLO development. Finally, four new DLO were developed.

However, the harmonization activity also raised some important questions that need to be addressed. One question is related to the approach used to select candidate-bridge-concept terms. It is unclear whether the establishment of a unique and standardized methodology is advantageous, given the plurality of focus areas that need to be tackled. Another question is related to the use of the template to define the bridge concepts, as it requires involvement, contribution, and collaboration from both domain experts and ontologists to ensure a thorough analysis and a formal representation of the knowledge. However, the presented bridge concept elucidation sometimes lacks sufficient inputs from both sides. As a result, these predefined domain-level bridge concepts have to be reviewed and evaluated by more stakeholders to ensure its completeness and feasibility. Nevertheless, the report has proven to be a significant milestone in the harmonization and development of DLOs, which will pave the way for further improvements in this area.

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