Report D3.8

"Report on the finalized Review of Domain Interoperability"

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"Report on the finalized Review of Domain Interoperability"

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1.3	29/10/2023	A. Simperler, S. Chiacchiera	Added: text in Sec. 3.2, references. Updated App. D. Removed Sec. 3.2.1, its content integrated in other sections. Updates and

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Glossary of terms and acronyms

Item	Description
BFO	Basic Formal Ontology
DL	Description Logic
DLO	Domain Level ontology
DOLCE	Descriptive Ontology for Linguistic and Cognitive Engineering
EMMO	Elementary Multiperspective Material Ontology
FAIR	Findable, Accessible, Interoperable, Reusable
FOL	First-order Logic
ICT	Information and Communication Technology
IoT	Internet of Things
LD	Linked Data
LCA	Life Cycle Analysis
LOV	Linked Open Vocabularies
MLO	Mid Level ontology
OC	OntoCommons
OCES	OntoCommons EcoSystem
OWL	Web Ontology Language
RDB	Relational database
RDF(S)	Resource Description Framework (Schema)
RoDI	Review of Domain Interoperability (the present document)
SSSOM	Simple Standard for Sharing Ontological Mappings
SWRL	Semantic Web Rule Language

TLO	Top Level ontology
TRO	Top Reference Ontology
UC	Use Case
WG	Working Group

Note: For acronyms of initiatives, please see dedicated table and references section. For acronyms of technical components (including formal languages not included above), please see dedicated table in appendix B.

Keywords

Ontology; Data; Interoperability; Data integration

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Executive Summary

This document addresses interoperability in a broad sense, in the context of data, in particular for materials and manufacturing. It is meant for developers (at domain level) of ontologies and platforms, tools or components that use them. To set the stage and give an overview of the various facets of the topic, the document collects existing definitions and classifications of interoperability (its types, layers, levels) and points to recommendations from various entities and communities. Next, it provides an analysis of a set of interoperability scenarios, proposes a classification of broad interoperability requirements and components to address them. Finally, it summarizes advice from OntoCommons on interoperability issues.

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1. Introduction

In our quickly transforming and global society, where digitalization and the world-wide-web are entering more and more aspects of our lives, "interoperability" is an omnipresent term and a precious (time and money-saving) feature[1], if not a necessity[2]. As often happens, the term is used with slightly different meanings in different communities, but as a first approximation most people will agree that is has to do with the capacity of two (or more) things to meaningfully function together. So, when we say that "an artifact is interoperable", we implicitly mean "interoperable *with*" something else (usually, with a certain reference framework). Typical distinctions we encounter are syntactic *vs* semantic interoperability and separations of *concerns*. The objects of interoperability might be data, software, data spaces, semantic artifacts, web-based platforms, and so on, or even ourselves (say, researchers from different backgrounds). One can also "measure" interoperability, to a certain extent: metrics for interoperability have been proposed (e.g., within FAIRness evaluation tools, available for both data and ontologies). While these measurements in themselves will vary a lot across tools, they can indicate what are the directions for improvement. Achieving interoperability is not trivial, there are *barriers* to be overcome, and various solutions have been proposed.

In this document we give a broad overview of the topic with two main purposes: first, to present the various facets of interoperability that one might want to consider and second to provide advice from OntoCommons and the wider community. In this process, we also identify a set of key concepts, classifications, technical components to address interoperability, relevant initiatives and references.

The rest of the document is structured as follows. In Section 2 we summarize how the work of OntoCommons Task 3.5, "Develop the Review of Domain Interoperability (RoDI)", leading to the present report, was organized, then in Sec. 3 we give an overview of the **state of the art** of interoperability, considering both the literature and recent initiatives. To set the stage, we first analyze the terminology, giving an overview of **existing definitions** (Sec. 3.1) **and classifications of interoperability** (Sec. 3.2): this allows us to grasp the broadness of facets (cf. also Appendix D) that have been considered over time and also point out the coexistence of slightly different understandings of what "interoperability" actually is. Then, we provide **pointers to initiatives and organizations** (Sec. 3.3) whose activities are relevant for interoperability in materials and manufacturing and **draw a picture of the recommendations** (from literature and community, cf. App. C for input gathered at OntoCommons events) identifying common points and differences between them (Sec. 3.4). We conclude the section by touching on the issues of **assessing and measuring interoperability** (Sec. 3.5). In Sec. 4, using insight and concepts from the literature, we analyze a set

[1] Think for example of the time that is still spent in trivialities as re-formatting text documents across (e.g., proprietary and open-source) formats or different implementations of the same software tool (e.g., web-based and desktop versions). Or, in a more serious level, to the processes to get academic qualifications recognized across countries and continents (it is improving, used to be more difficult some decades ago).

[2] Think for example of data integration needs for (global) digital product passports.

of interoperability **scenarios** from OntoCommons demonstrators; in turn, this allows to highlight typical requirements. Accordingly, in Sec. 5 we propose a **structuring of interoperability requirements** in a very broad sense (Sec. 5.1), **and of means of addressing them** (Sec. 5.2), and briefly touch on **data lifecycle** aspects (Sec. 5.3). OntoCommons focuses on **ontologies as a means to address interoperability**: in Sec. 6 we summarize the **OntoCommons' project approach** (cf. with Sec. 3.4 to understand its positioning in the bigger landscape), especially in relation to solving interoperability between ontologies themselves. There we recall major results of the project, as the OCES and Bridge Concept template, and give pointers to dedicated deliverables. Finally, we draw our conclusions in Sec. 7.

The **references** (Sec. 8) include both **references to documents** (Sec. 8.1) and **to projects/initiatives** (Sec. 8.2). To help the reader navigating the literature, in App. A we give a **list of tagged references** (with tags telling, e.g., whether they contain a glossary or not, what interoperability types they address, etc). In App. B we give some examples of specific tools addressing the requirements of Sec. 5.

2. Methodology

The OntoCommons Task 3.5 work, after an initial phase, was split into three interconnected working groups, namely: WG1: "Terminology & Classifications of interoperability", WG2: "Technical components to support interoperability" and WG3: "Interoperability scenarios". WG1 provided to WG2 and WG3 initial sets of terms (e.g., to be used for tagging of their resources), WG3 provided input for requirements to WG2. Beside the regular global meetings, the WGs would call for focused ones when needed.

The references (publications, documents) and initiatives mentioned in this document were found by a combination of methods:

- Systematic search on **Web of Science catalogue** for entries having "interoperab*" in the title. This search was run on 10 Feb 2023, and gave 7948 results from All Databases[3]; of these results, 184 were of type "review"; in turn, of these, 20 had "systematic" in the title. To narrow down the set, we focused on the reviews and selected relevant ones for OntoCommons scope, based on the resources title and abstract.
- Resources pointed out by the **Task 3.5 participants and OntoCommons colleagues**
- Resources pointed out by **participants of OntoCommons events**, either in their presentations, or when answering surveys (cf. Appendix C)
- For the resources related to technical components, a requirements matrix was drawn, and served as guidance to identify further references (cf. Section 5.2 and Appendix B)

Given the broadness of the topic, we identified priority criteria, including:

- Start with a focus on data interoperability *via* ontologies
- Start with outputs of EU initiatives
- Prioritize methods relating to the domain level, both intra-domain and inter-domain
- Prioritize recent / active efforts
- Prioritize use-cases from OntoCommons and sister projects.

The main activities that were performed by the WGs are: the tagging of a set (and analysis of a sub-set) of references and initiatives, extraction of independent Definitions of interoperability and Classifications of interoperability[4], identification and structuring of Interoperability requirements, and the analysis of OntoCommons 22 demonstrators from the interoperability point of view.

[3] Roughly, there have been on average 400 such publications per year since 2006. The top four research areas are: Computer Science (5608), Engineering (3006), Telecommunications (1584), Health Care Sciences Services (1021). As per Web of Science, 10 February 2023.

[4] We made our best effort to always look for the original sources, where definitions / classifications were first introduced. See also tags T4 and T6 in Table 12, Appendix A.

3. State of the art

In this section we collect and analyze existing **definitions/terminologies, classifications, etc of interoperability, pointers to initiatives** (that can **possibly disagree with each other**), and metrics. We also give a broad overview of the common points and differences in the existing recommendations.

3.1 Overview of existing interoperability definitions

In this section we collect independent definitions of interoperability that we have identified from our literature analysis. Note that here we restrict to interoperability itself, without further specifiers (e.g., not "syntactic interoperability").

While this list won't be complete (the literature is huge and we haven't expanded all secondary sources, like reviews, to see all their individual primary sources[5]), we are confident it covers some authoritative definitions and gives a reasonable overview of other proposed / published ones.

Source ID	Definition of interoperability
[IEEE, 1990]	"ability of systems to exchange information and use the information that has been exchanged"
[Panetto, 2007]	"Interoperability is the ability of different types of computers, networks, operating systems, and applications to work together effectively, without prior communication, in order to exchange information in a useful and meaningful manner."
[ISO 16100-1:2009]	"manufacturing software interoperability": "ability to share and exchange information using common syntax and semantics to meet an application-specific functional relationship across a common interface"
[Janssen et al., 2014]	"At the data level [...] interoperability is the ability of two or more datasets to be linked, combined, and processed."
[ISO 2382:2015]	<fundamental terms> "capability to communicate, execute programs, or transfer data among various functional units in a manner that requires the user to have little or no knowledge of the unique characteristics of those units"
[Wilkinson 2016]	"the ability of data or tools from non-cooperating resources to integrate or work together with minimal effort"
[ISO 19941:2017]	"ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged"
[EIF 2017]	"[For the purpose of the EIF,] interoperability is the ability of organisations to interact towards mutually beneficial goals, involving the sharing of

[5] Just to give an example, by analyzing one of our references, [Gürdür & Asplund, 2018], we have found another [Ford et al., 2007] which includes 34 definitions of interoperability, 64 interoperability types, and other useful comparisons.

	information and knowledge between these organisations, through the business processes they support, by means of the exchange of data between their ICT systems."
[IEC 2019]	"capability of two or more functional units to process data collaboratively or cooperatively"
[EMMC 2019]	"define interoperability (from latin, inter = between and operari = to work) as the ability of two or more systems to exchange information between them through a common representational system to perform a complex work that cannot be done by each single system alone."[6]
[Guizzardi, 2020]	"interoperability is not about finding ways to connect data artifacts but ultimately about affording the interoperation of humans mediated by these artifacts"[7]
[Nagel & Lycklama, 2021]	"The ability of different systems to work in conjunction with each other and for devices, applications or products to connect and communicate in a coordinated way, without effort from the person."
[Data Act 2022]	"'interoperability' means the ability of two or more data spaces or communication networks, systems, products, applications or components to exchange and use data in order to perform their functions"
[Gupta et al., 2022]	"Interoperability is defined as the process of exchanging data accurately and effectively between different communication systems and software applications and the correct interpretation of this exchanged data by the system is termed as data interoperability."

Table 1 - List of interoperability definitions (Ordering is by year)

Most definitions above agree that interoperability is an "ability" or a "capability" (with a single outlier defining it as a "process" [Gupta et al., 2022]). The *subjects* involved in the definitions varies from "(ICT) systems", "functional units", to "organizations", "devices", "applications", "products", "datasets" and "manufacturing software". About the counting of the subjects, we see they are "two or more", plural forms are used, and we note that in three cases it is pointed out that the subjects are "different (types)" ([Panetto, 2007], [Nagel & Lycklama, 2021], [Gupta et al., 2022]) and in one that they are "from non-cooperating resources" [Wilkinson 2016]. Focusing on the *predicates,* we find that **"exchange" and "communication"** are prominent, however mostly accompanied by or finalized to an **action**, as "use", "work", "interact", "execute". The *objects* involved in the core of the definitions are "information", "data", "knowledge", "programs". We note in passing that the focus on action and on plural nature of the subjects are in line with the etymology of "interoperability" (cf. EMMC definition above).

[6] While many authors use them as synonyms, we point out that [EMMC 2019] considers "compatibility" distinct from "interoperability". It "defines compatibility (from latin, cum = with and passus = to suffer) as the ability of two or more systems to establish a one-to-one connection between them".
[7] More than a definition, an interesting point of view for the present discussion. Please note that technical definitions of semantic interoperability are included in the reference.

Various specifiers are used to underline the deep collaboration: "(work) together effectively", "useful and meaningful (manner)", "(process) collaboratively or cooperatively", "(work) in conjunction".

Interestingly, other specifications that are added refer or imply the use of a language that is somehow general ["without prior communication", "(in a manner that) requires (the user to have) little or no knowledge of the unique characteristics of those units", "through a common representational system"].

3.2 Overview of existing interoperability classifications

In general, interoperability means that different "systems" can interact and seamlessly exchange "things". Depending on what these systems are, how they interact, and what things they exchange, we can define different types of interoperability. Table 2 below lists interoperability classifications found in the literature.

Source ID	Classification of interoperability
[Ouksel & Sheth, 1999]	"[leads us to discuss] different levels of interoperability--system, syntax, structure, and semantic"
[Euzenat, 2001]	"levels of interoperability": "encoding", "lexical", "syntactic", "semantic", "semiotic".[8]
[Chen & Doumeingts, 2003]	"inter-enterprise coordination, business process integration, semantic application integration, syntactical application integration, and physical integration"
[Asuncion & van Sinderen, 2010]	"three layers: syntactic, semantic, and pragmatic" (based on linguistic approach by Morris).
[Koussuris 2011]	Interoperability "scientific areas": "Data interoperability", "Process interoperability", "Rules interoperability", "Objects interoperability", "Software systems interoperability", "Cultural interoperability", "Knowledge interoperability", "Services interoperability", "Social networks interoperability", "Electronic identity interoperability", "Cloud interoperability", "Ecosystems interoperability".
[Euzenat & Shvaiko, 2013](*)	"We consider here the most obvious types of heterogeneity": "Syntactic heterogeneity", "Terminological heterogeneity", "Conceptual heterogeneity [, also called semantic heterogeneity]", "Semiotic heterogeneity [, also called pragmatic heterogeneity]"

[8] Focusing on *interoperability of ontologies,* [Euzenat, 2001] identifies 5 levels of interoperability, so defined: "encoding: being able to segment the representation in characters; lexical: being able to segment the representation in words (or symbols); syntactic: being able to structure the representation in structured sentences (or formulas or assertions); semantic: being able to construct the propositional meaning of the representation; semiotic: being able to construct the pragmatic meaning of the representation (or its meaning in context)."

[Janssen et al., 2014]	"interoperability [, which is commonly seen as occurring at four levels]: "Technical interoperability", "syntactic interoperability", "semantic interoperability", "pragmatic interoperability"
[EIF 2017]	"four layers of interoperability: legal, organisational, semantic and technical"
[ISO 19941:2017]	Interoperability terms: "cloud interoperability", "transport interoperability", "syntactic interoperability", "semantic data interoperability", "behavioural interoperability", "policy interoperability"
[Gürdür & Asplund, 2018]	Interoperability types: "System interoperability", "Technical interoperability", "Enterprise interoperability", "Functional interoperability", "Programmatic interoperability", "Operational interoperability", "Process interoperability", "Information interoperability", "Data interoperability", "Constructive interoperability"
[Andročec et al., 2018]	Data, service, network, application (see its Fig. 4).
[Noura et al., 2018]	"[We divide the existing interoperability solutions in the literature according to the] level of interoperability [that has been achieved] between IoT platforms or systems: device level, networking level, syntactic level, semantic level, cross-platform level, and cross-domain interoperability."
[EMMC 2019]	five levels of semantic interoperability, ordered by abstraction, are identified: "scientific community level, material user case level, characterization level, modelling level and at solver level."[9]
[IEC 2019]	"Syntactic", "Semantic data", "Transport" (intended as communication), "Behavioural" and "Policy".
[Nagel & Lycklama, 2021]	"[Requirement E: Data-sharing interoperability is about providing the ability for all applications in data spaces to create, use, transfer and effectively exchange data. This requires the definition of data exchange APIs and data models supporting] semantic interoperability [...], behavioural interoperability [...], and policy interoperability."
[DSSC SK 2022]	"High-level classification of interoperability categories: technical, semantic, and organisational (including legal) interoperability"
[Gupta et al., 2022]	Levels: ["No Interoperability",] "Technical Interoperability", "Syntactic Interoperability", "Semantic Interoperability", "Pragmatic Interoperability", "Dynamic Interoperability", "Conceptual Interoperability"

Table 2 - List of existing interoperability classification (Ordering is by year)

[9] These can be rephrased as: "Human level, Use case level, Characterization level, Description, Modelling level, Numerical level" see talk by J. Friis at DOME 4.0 Hackathon, Bologna 2023. More in detail, these were described as: "Human level: Communication between and within scientific communities; Use case level: Univocal description of the problem of interest; Characterization level: Description of materials properties, characterisation procedure/workflows; Modelling level: Description of model input/output and modelling workflows; Numerical level: Numerical representation, values, units, …".

In some cases, the focus of the Authors in on the variation of *subject* (e.g., [Andročec et al., 2018]), whereas in others it is actually on the *quality* of interoperability (e.g., [Euzenat, 2001]), and others combine the two. Also, the fact that a certain term is used by multiple authors does not necessarily imply they all agree on its meaning. With these two *caveat* in mind, we record in Appendix D all the prefixes for interoperability found above. They are: Behavioural, Cloud, Conceptual, Constructive, Cultural, Data, Dyacronic, Ecosystems, Electronic Identity, Encoding, Enterprise, Functional, Human, Information, Knowledge, Legal, Lexical, Network, Numerical, Objects, Operational, Organizational, Platform, Policy, Pragmatic, Process, Programmatic, Rules, Semantic, Semiotic, Service, Social, Software, Structure, Synchronic, Syntactic, System, Technical, Terminological, and Transport.

(*) We note that [Euzenat & Shvaiko, 2013] gives a classification of "heterogeneity" rather than "interoperability" types. However, we report it here as the two concepts are strongly related.

3.3 Pointers to initiatives and organizations

In the table below we list major initiatives, organizations and projects that are primarily relevant to interoperability in the context of materials and manufacturing. Note: With "active" we mean that the initiative / organization continues to produce results, organize events in 2023.

Initiatives / organizations					
Acronym	**Full name**	**Geo range (world, EU, national)**	**Domain (if none use "generic")**	**Entity type (as self-stated, whenever possible)**	**Active in year 2023**
AMI2030	Advanced Materials 2030 Initiative	EU	Advanced materials	Initiative	Yes
CEN	European Committee for Standardization[10]	EU	Multi sector (standardization)	Association	Yes
CENELEC	European Committee for Electrotechnical Standardization	EU	Electrotechnical	Association	Yes
DDI	Data Documentation Initiative[11]	world	Social sciences, human activities	initiative, collaboration	Yes
DSC	Data Sharing Coalition	EU/world	cross-sector	"open initiative"	Yes
DSSC	Data Spaces Support Centre	EU	Generic / cross-sector	project	Yes

[10] Acronym from the French name: *Comité Européen de Normalisation*

[11] One of their products under development is DDI-CDI (Cross Domain Integration).

ELIXIR[12]		EU	Life sciences	infrastructure	Yes
EMMC ABSL	European Materials Modelling Council ABSL	EU	Materials modelling	Association	Yes
EMMC-CSA[13]	European Materials Modelling Council CSA	EU	Materials modelling	(H2020) project	No
EOSC[14]	European Open Science Cloud	EU	Science	Initiative	Yes
ETSI	European Telecommunications Standards Institute	World (name is a relic)	ICT	"not-for-profit Institute"	Yes
FAIR-DO (FDO)	FAIR Digital Objects (Forum)	World	Generic / cross-sector	"neutral [...] international network "	Yes
IDSA	International Data Spaces Association	EU/world	Generic / cross-sector	association ("not-for-profit organization"	Yes
IE	Interoperable Europe	EU	Public sector	EC initiative	Yes
IEEE	Institute of Electrical and Electronics Engineers	US/world	Engineering and technology	(technical professional, not-for-profit) organization	Yes
Interop (NoE)	Interoperability research for networked enterprises applications and software (Network of Excellence)	EU	Enterprises	Project	No
INTEROP-VLab	International Virtual Laboratory for Enterprise Interoperability	EU	Enterprises	(not-for-profit) association	Yes
IOF	Industrial Ontologies Foundry[15]	World	Industry	Initiative	Yes
OAEI	Ontology Alignment Evaluation Initiative	World	Generic (alignment)	Initiative	Yes

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[12] Includes resources as FAIRCOOKBOOK (https://faircookbook.elixir-europe.org/content/home.html), and a list of Recommended interoperability resources (for life sciences).

[13] One of the outcomes of the EMMC-CSA project is a set of recommendations regarding metadata-based semantic interoperability, in the context of materials modelling [EMMC 2019]. Five levels of semantic interoperability, ordered by abstraction, are identified: "scientific community level, material user case level, characterization level, modelling level and at solver level." Focusing on software and Open Simulation Platform (OSP), a three-dimensional taxonomy of interoperability for OSPs is proposed in the same document. The three dimensions are: Physics, Scale and Entity, all of which can take values "Single" or "Multi".

[14] See also the EOSC Interoperability Framework, EOSC-IF [Corcho 2021].

[15] At the time of writing (October 2023), the IOF is becoming a legal entity under the OAGi consortium.

OAGi	Open Applications Group (Inc)	US based - World	Enterprises	(non-profit standards) organization	Yes
OAI[16]	Open Archives Initiative	World	Generic (Pre-prints)	Initiative	No
OPEN-DEI	OPEN-DEI: Aligning Reference Architectures, Open Platforms and Large-Scale Pilots in Digitising European Industry	EU	Industry (Manufacturing, agriculture, energy and healthcare)	(H2020) project	No
RDA[17]	Research Data Alliance	world	Generic / cross-sector	("non-profit charitable") organisation	Yes
SDMX	Statistical Data and Metadata eXchange	World	Statistics	Initiative	Yes
SOA4All	Service Oriented Architectures for All	EU	Generic (Web services)	Project	No
W3C	World Wide Web Consortium	World	Cross sector (Web)	consortium	Yes

Table 3 - List of initiatives / organizations relevant to interoperability in materials and manufacturing

Concerning very recent and activities starting soon, we point out the **international Semantic and FAIR Knowledge Graph Alliance (KGA)**, which is a no-profit association to continue OntoCommons work, and **DigiPass CSA** (HORIZON-CL4-2023-RESILIENCE-01-39), which will start in 2024 and focus on product digital passports.
In particular, in relation to organization-organization interoperability, we point out the Enterprise Interoperability Framework proposed by David Chen in the scope of InteropVlab (see e.g., [Chen, 2009] and [Ullberg et al., 2009]) and which is an ISO standard (ISO 11354-1).

3.4 Overview of existing recommendations: common points and differences

Below we summarize the overall picture on recommendations from the analysis carried out on the literature and the discussions at OntoCommons events.

[16] Among others, have produced the Protocol for Metadata Harvesting (OAI-PMH).
[17] The Research Data Alliance (RDA) contains several interest Groups (IGs) and Working Groups (WGs) investigating either intra-domain interoperability or cross-domain interoperability.

To support interoperability, there are a set of **common "ingredients"** (principles, recommendations) on which most initiatives / authors will agree, but there are also **some "branching points"** where opinions can differ and typically a design decision needs to be made.

Common recommendations for (data) interoperability include:

- Adoption of standards (for terminologies, formats, ...)
- Use of vocabularies (human and / or machine readable) [including ontologies, ontologies networks / ecosystems, modelling patterns]
- Openness of standards and protocols – Avoidance of vendor lock-in
- Community building [collaboration, communication, co-creation (cross-enterprise and ideally at global level]
- (Data) Provenance tracking
- Data structuring
- Data linking
- Provide documentation and guidance - Document, curate, share and maintain assets
- Establish a (solid) governance
- Establish, share and adopt (solid) methodologies
- Value demonstration - Show (commercial) benefits

Broadly, these fall under the topics of **data and knowledge structuring, community building**, **value demonstration.**

Common (design) principles for technical components supporting interoperability include:

- Composability
- Concreteness (e.g., use-case driven, need-driven development)[18]
- Explicitness (of used knowledge)
- Adaptability, Extendibility, Scalability
- Human readability and machine readability
- Maintainability (Related: "Sustainability")
- Measurability (Example: ability to assess compliance / interoperability)
- Modularity[19] - Hierarchical structure (e.g., by abstraction levels)
- Parsimony
- Reuse
- Rigour
- Separation of concerns
- Stability
- Usability (Related: "Ease of uptake").

[18] Could also be a branching point, with its opposite being "comprehensiveness".

[19] See also related discussions from systems-of-systems approaches, e.g., [Weichhart et al., 2021] where the "ABCDE" model (Autonomy, Belonging, Connectivity, Diversity, Emergence) is mentioned.

Of these, many are generally applicable to software artefacts, however we would point out "**Explicitness**" as an important principle that is specific to knowledge representation.

Typical design "branching points" we identified include:

- Logical expressivity level (low *vs* high) [Related: Precision needs, e.g. of mappings, reasoning needs]
- Automation level (manual *vs* automatic) [E.g., when generating mappings between models]
- Single *vs* pluralistic model
- Centralized *vs* decentralized governance
- Monolithic *vs* modular approaches
- Open-world vs close-world assumption.

Of course, it is possible to have solutions that sit in-between these extremes in each dimension (e.g., combining different expressivity levels for different tasks, or using manual and automatic processes at different stages of development), what we mean is that these are very likely points where design decisions need to be made and they will have strong implications down the development line.

Each option has, naturally, advantages and disadvantages. Concerning expressivity levels (cf. Sec 6.3), simpler models can facilitate integration with existing workflows (see, e.g. [Matenzoglu 2022], where a model for mappings is proposed), while more complex languages enable richer / more expressive statements and inferences (see, e.g., the related discussion in [IEC 2019], on levels of formalization for data exchange, focusing mainly on XML and OWL languages. Simpler models are typically less computationally demanding and easier to develop and maintain. So, one can see that there could be arguments to choose the simplest language with enough complexity to address the tasks at hand; instead, a future-proofing solution would be to select a more powerful one. In this respect, it is important to be aware of the existing options, their capabilities / limits, and how they relate to each other: for example, what languages are sub-sets of others, and so on. The availability of tools is also an important factor to consider. Another important point to consider when choosing an expressivity level are needs in terms of automatic reasoning[20]: for example, reasoning is a core part in decision support systems and whenever explainability features are needed.

Concerning pluralism in knowledge representation, some initiatives opt for having a single view at the highest level of knowledge abstraction (one single top-level or foundational ontology), whereas others allow for multiple views by construction. An example of first type is the IOF (cf. Sec. 3.3), where BFO is the common top-level ontology for all the rest of models, while an example of the second type is OntoCommons itself, where at present three top-level ontologies (BFO[21], DOLCE[22] and

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[20] Reasoning capability: Ability to automatically infer new (true) statements from given ones. Reasoning is mainly deductive in semantic data models and inductive in data-driven ones. [Alexopolous, 2020]

[21] See, e.g., [Arp et al., 2015].

[22] See e.g., [Borgo et al., 2022]

EMMO) are connected (cf. Sec. 6.4). For a historical reference on pluralism in this context, see also the WonderWeb[23] project.

The governance and pluralism dimensions are often entangled together; also, clearly, the arguments and needs that apply to a single-enterprise data model are different from those of a cross-enterprise (or global one). As an example we mention the position of the FDO Forum (cf. Sec. 5.3) in their Leiden declaration: “Support distributed solutions where useful to achieve robustness and scalability, but recognise the need for centralised approaches where necessary”.

In the semantic web, the “Open-world assumption” is a fundamental one, whereas databases typically function within the “Close-world assumption”: when bringing together different disciplines and practitioners it is important to have in mind these opposite views to be able to integrate them and avoid fundamental pitfalls [Alexopoulos, 2020].

In general, guidance in the design / decision phase will also come from a thorough analysis of the case at hand and its requirements: for example, in security or safety-critical applications (say, medical and pharmaceutical sector), the needs in precision of mappings will be different from, say, those in the entertainment sector.

Finally, focusing on the specificity of the inter-domain interoperability challenge, we highlight these suggestions:

- Use “common design principles” and “consistent practices” across data spaces for different domains ([Nagel & Lycklama, 2021], text and Figure 3, and IDSA Reference Architecture cited therein)
- Implement “the same minimal set of functional, legal, technical, operational agreements and standards” ([Nagel & Lycklama, 2021], Figure 3)
- Use “rich granular metadata” (from DDI draft documentation for CDI[24], Cross Domain Interoperability)
- Use a “set of agreed domain-agnostic standards” (from DDI draft documentation for CDI, Cross Domain Interoperability)
- Develop “Cross-domain semantic foundations” [IEC 2019]

As a key difficulty when integrating data are “context”, “use-case”, or “perspective” dependence, we point out that:

- The EMMO[25] ontology has a built-in approach to multiple perspectives including “reductionistic”, “physicalistic”, “holistic”, “symbolic” among others. (By taking different (possibly combined) perspectives, the same object can be seen in different ways. E.g., a book

[23] WonderWeb project, https://cordis.europa.eu/project/id/IST-2001-33052 (For results, see also: http://wonderweb.man.ac.uk/index.shtml)
[24] The Cross-Domain Interoperability Framework: A Proposed Lingua Franca for FAIR Data Reuse (Discussion Draft), https://ddi-alliance.atlassian.net/wiki/spaces/DDI4/pages/2843475970/Cross-Domain+Interoperability+Framework
[25] https://github.com/emmo-repo/EMMO

can be broken down in pages (physicalistic-reductionistic), but also in chapters and sentences (symbolic-reductionistic).)

- In [Matenzoglu 2022] it is proposed to create **mappings commons**, as "a public registry that enables users to find mappings for a clearly defined use case". Such a mapping registry is currently being developed in the context of the FAIRCORE4EOSC project[26] and should become part of the core EOSC services as mentioned in EOSC-IF.

3.5 Pointers to existing interoperability metrics and related assessments

Before considering the capabilities of two or more entities to function in conjunction, it is advisable to assess each of them individually. With this in mind, concerning interoperability "measurement" and related assessments, we point out the following topics and references:

- At the qualitative level, and for historical reasons, we point out the **"five stars" approaches** of linked data (LD) [Berners-Lee, 2006] and of linked data vocabulary use (LDVU) [Vatant 2012], [Janowicz et al., 2014]. At the lowest end of the overall spectrum there are data available on the web, and at the highest end, LD using vocabularies that use/are used by other vocabularies.[27]As pointed out by Janowicz, the goal of such ratings, more than technical, is to encourage adoption, provide a "reward" system, and indicate the directions for incremental improvements. [Janowicz et al., 2014]
- The "I" of FAIR data. In the FAIR principles [Wilinson 2016], four facets are separated, and for the "interoperability" one, three guiding principles are identified.[28]
- **Data maturity / digitalization level** assessments (see e.g., [Janssen et al., 2014], the "FAIR Data Maturity Model" [RDA 2020], the "FAIRplus Dataset maturity model" [DSM 2023].)
- **Interoperability assessment at organization level.** For a comprehensive review of enterprise interoperability assessment approaches, see [da Silva Serapião Leal et al., 2019], which

[26] https://faircore4eosc.eu/

[27] The classification from [Berners-Lee, 2006] reads: 1-star LD: "Available on the web (whatever format) but with an open licence, to be Open Data"; 2-stars LD: "Available as machine-readable structured data (e.g. excel instead of image scan of a table)"; 3-stars LD: "as (2) plus non-proprietary format (e.g. CSV instead of excel)" ; 4-stars LD: "All the above plus, Use open standards from W3C (RDF and SPARQL) to identify things, so that people can point at your stuff" ; 5-stars LD: "All the above, plus: Link your data to other people's data to provide context". Similarly, in [Vatant 2012] and [Janowicz et al., 2014], 5-stars LD is further classified based on the LDVU, with slightly different view on the priorities between the two approaches. E.g., for Vatant, 5-stars LDVU requires to "Link to other vocabularies by re-using elements rather than re-inventing", whereas for Janowicz, it requires that "The vocabulary is linked to by other vocabularies."

[28] "To be Interoperable: I1. (meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation. I2. (meta)data use vocabularies that follow FAIR principles I3. (meta)data include qualified references to other (meta)data" [Wilkinson 2016]

analyses 72 papers and 22 INAS approaches. The Authors take a holistic view of interoperability, covering these “concerns”: Business, process, software, data. (We note in passing that [Panetto, 2007] is an earlier reference where enterprise maturity models are compared.)

- Other references we have identified are: [Ouksel & Sheth, 1999], [Parent 2000], [Noura et al., 2018], [Gupta et al., 2022]
- On a somewhat different but related line, [Gürdür et al., 2016] proposes to visualize interoperability (in tool chains, *via* node-link diagrams).

In the list of tagged references, please look for entries with the “metric” tag in the reference (primary) content.

4. Analysis of a set of interoperability scenarios

The 22 OntoCommons demonstrators have been analyzed from the interoperability perspective. Below we report the results for those having an interoperability component[29]. For more details on the demonstrators, please see WP5 deliverables.

For each demonstrator/use-case, we answered the following 6 questions:

- Q1. What is the interoperability "pain" in the UC? (High level view)
- Q2. Interoperability of what kind(s) of systems? (humans, communities, databases, softwares, "things"[30] (IoT), ontologies, ...)
- Q3. Single or cross-domain?
- Q4. Type(s) of heterogeneity addressed? (syntactic, terminological, conceptual, semiotic)
- Q5. What is the purpose of interoperability? (Un=Understand, F=Find, O=Operate, Up=Update, OTHER)
- Q6. Technological solution/component used to enable interoperability

Note on Q4: Heterogeneity types taken from [Euzenat & Shvaiko, 2013]. They are originally developed for ontologies, here we use them in a broader sense.[31]

[29] Within WP5 – Demonstration, a preliminary analysis was done, to assess for each demonstrator what activities they develop, among: Ontology use, Ontology Development, Reference ontology alignment, Interoperability.
[30] Here (and in similar questions/options below in the document), ”thing” is intended as ”physical device” (cf. Internet of Things, IoT).
[31] In brief: Syntactic heterogeneity: Different form (e.g. file formats, etc); Terminological heterogeneity: variations in names when referring to the same entities (e.g., due to different natural language or synonyms); Conceptual (or semantic) heterogeneity: differences in modelling the same domain of interest (e.g., different granularity, coverage, perspective); Semiotic (or pragmatic) heterogeneity: concerned with how entities are interpreted by people.

Note on Q5: Purposes "Understand", "Find", "Operate", "Update" are taken from [IEC 2019]

Credit: Strong collaboration with OntoCommons WP5 (Demonstration)

Analysis of the scenarios: UC1, UC2, UC3, UC4				
Use case ID	UC1 Airbus	UC2 Bosch	UC3 Aibel	UC4 Tekniker
Use case Title	IRIS - Industrial co-design Support	SeDIM: Semantic Data Integration for Manufacturing	Engineering for Procurement	Materials Tribological Characterisation
Q1	Interoperability between different manufacturing processes and stakeholders	Data interoperability between different departments	Interoperability between departments -- interoperability between applications	Interoperability between different Tribological experiment terminology
Q2	data, processes and humans	data and software	organizations and software	data
Q3	cross-domain	single	single	single
Q4	syntactic, terminological, conceptual	terminological, conceptual	syntactic, terminological, conceptual	syntactic, terminological
Q5	Un, F, O, Up	Un, O	Un, F, O, Up	Un, F, O
Q6	Neo4j for hosting a knowledge graph. Cypher query language and python libraries.	An internally developed system called SemML	OTTR templates	Modular ontology aligned with TribAIn and TriboDataFAIR in the tribological domain and CHAMEO (work in progress) in the material characterisation domain using Protégé. Instantiation with information of experiments stored in the MongoDB database using GraphDB connector. API REST in Python used for data querying.[32]

Table 4 – Analysis of UC1-UC4

[32] Additional note from UC4: Currently the Knowledge graphs must be materialized in the semantic repository to apply reasoning. An identified gap is to be able to match a non-relational database (e.g. MongoDB) into RDF to support SPARQL including reasoning.

Analysis of the scenarios: UC5, UC6, UC9, UC10				
Use case ID	UC5 EVMF	UC6 OAS	UC9 Adige	UC10 ElvalHalcor
Title	European Virtual marketplace framework	Ontology based yard management	Ontology-based Maintenance	Data Integration and Interoperability in Manufacturing
Q1	The development of a semantic framework for platforms and services requires the matching of different semantics and syntatics.	· Ontologies from different domains need to be used and work together harmonized · Different hardware/software systems need to be able to process the ontologies used · Actors with different skills (e.g., software engineers, hardware maintenance experts, project managers, etc.) or domain expertise (e.g., logistics, machine or material manufacturing, business management/administration etc.) need to be able to use the ontology	· Heteregenous data formats and channels (natural language, forms with open/closed entries, phone calls, sensors...) · Data may refer to different views: machinery structure, function, behaviour	· Data format too diverse · Disconnected or poorly connected Information Systems · Semantic data relations missing
Q2	Platforms and services of virtual material marketplaces with their individual databases, softwares, ontologies,...	Different types of systems (hardware, software) and humans	Humans, databases, softwares, "things" IoT	Human, databases, software
Q3	cross-domain	cross-domain	Single domain	Single domain
Q4	All of them	Syntactic, semantic and terminological (material, logistics, equipment)	syntactic, terminological, conceptual	syntactic, terminological, conceptual
Q5	Un, F, O, Up	Un, F, O, Up	Un, F, O, Up	O, Up
Q6	Development of a system of ontologies, aligned with the EMMO, to organize knowledge on	Set of ontologies under IoF, Protege for ontology editing	• development of domain ontology (with Protégé) • An ad hoc search engine developed by a third party plus	- application ontology building (using Protégé) - Neo4J to visualize the knowledge graph derived from the

	virtual material marketplaces. Used as metadata in the VIMMP platform, for data ingest, storage, search and browsing.		Adige's existing software • An ad-hoc interface, developed by a third party used to insert the data in the ontology	application ontology

Table 5 – Analysis of UC5, UC6, UC9, UC10

Analysis of the scenarios: UC11, UC12, UC13, UC14				
Use case ID	U11 Siemens	U12 Basajaun	U13 BASF	U14 COMAC-BATRI
Title	Digital Manufacturing / Automation Engineering	Basajaun	Lifecycle Sustainability Assessment of a Chemical Product	Architecture, design and ontology definition for Onboard Maintenance System of Aircraft
Q1	- Different data format (PDF, TXT, emf...), storage structure and locations (unit systems)	Interoperability between different actors in the supply chain	aligning data structure and conceptually integrate data across the different sustainability topics	Interoperability among different modelling tools
Q2	Humans, databases, softwares, "things" IoT	Humans and the software systems that they are using	Databases and software	Software, ontologies
Q3	Cross-domain (within Siemens)	cross-domain (but in the same supply chain)	Single domain (for now)	Single (aircraft design and manufacturing but all in the aircraft domain)
Q4	syntactic, terminological, conceptual	syntactic and terminological	syntactic and terminological	terminological
Q5	Un, F, O, Up	(Un), F, O, Up	O, Up	O, Up
Q6	• Protégé for ontology editing • Widoco for ontology documentation	In-house development tools	Use of in-house SW development to be able to use the developed LCA ontology that is then used to align	- Ontologies can be efficiently applied into development of the SOI, where the knowledge will

	• SIMPL CLI for ontology release • SHACL engines for validation • R2RML for mapping relational data • Custom made python ETL libraries[33]		data structure and conceptually integrate data across the different sustainability topics	eliminate ambiguities during the modelling and simulation for the system, potentially reducing the lifecycle cost and duration - Knowledge graph can be explored to find surprisingly new links among ontologies, which currently needs more AI and big data technique adoptions.

Table 6 – Analysis of UC11-UC14

Analysis of the scenarios: UC15, UC16, UC18			
Use case ID	U15 - CPSosaware	U16 - Food Knowledge Graph	UC18 Inter Ikea Systems
Title	Monitoring human operators' safety	Food Knowledge Graph	IKEA Knowledge Graph
Q1	Integration of different data streams (static cameras, wearables, machine position data,...) for the positioning of a robotic system within a shared assembly line with human operators. (or) The development of a framework for the safe interaction between a human operator and a robotic system within an assembly line.	Automatic mapping of different ontologies with their individual concepts, vocabularies.	Serving the ontologies via API endpoints requires a lot of software development work to set up a robust cloud-based platform for scalable storing and serving the knowledge graph and manage any deltas from stakeholder input or data sources
Q2	Static camera systems and wearables (IoT) for the position and movement of the human operator and	The system aims to auto-match, auto-map and auto-manage ontologies on a semantic level.	Humans, databases, diverse data sources from stakeholders

[33] Additional note on UC11: Heterogeneous data sources of Siemens will be mapped to the ontologies in this library and stored in the data layer for Siemens applications to access.

	machine data for the movement and position of the robot.		
Q3	Single domain	Cross-domain	Single domain
Q4	Semantic data integration	Semantic	terminological
Q5	(Un), F, O, Up	Un, F, O, Up	O, Up
Q6	Setup and integration of external (cameras, wearables) and internal (machine positioning sensors) systems for different data streams and their integration within a Semantic Data Integration Framework (CASPAR).	Incorporate relationships with other concepts, ontologies, vocabularies.	· Frontend for authoring and discussing modelling changes (classes, properties) · Frontend for managing taxonomies · Visualisation of IKG · Visual editing

Table 7 – Analysis of UC15, UC16, UC18

Of the demonstrators that have interoperability "pains", most report human or data (databases) interoperability either within the company or with stakeholders of the supply chain (especially in the use cases where the focus is on cross-domain, e.g. UC1, UC6, UC12, etc.). Also, some report interoperability issues of software used in the company where data formats are an issue (e.g., UC11, UC14). Regarding the heterogeneity addressed, there is no common pattern, the use cases mostly address syntactic, terminological and conceptual issues, only few semiotic.

Most of the demonstrators have solved (or are in the process of solving) the interoperability issues by developing an ontology or a set of ontologies (mostly reusing previous taxonomies or as application ontologies aligned with a TLO, e.g. UC5, UC6, UC9) and applying these ontologies in either currently used software (e.g. UC2, UC5, UC6, UC9, UC10, UC12, UC13), in knowledge graphs to handle the data applications in the use case (e.g. UC1, UC10, UC12, UC18) or simply by extending the relationships to other vocabularies and ontologies (e.g. UC16).

To broaden the view on use-cases beyond this set of OntoCommons scenarios, one can look at the results of the survey run during OntoCommons Second Global Workshop (Oslo, June 2023), extracts of which are included in Appendix C, in particular to questions MQ6, MQ7 and MQ10. Asked "What type(s) of heterogeneity do you mainly address? (Via use cases or solutions)", the audience[34] mostly chose "all types" of heterogeneity, followed by terminological one. About " What kind(s) of systems do you make more interoperable?": combining the answers, the first one results data ("databases" and "datasets"), followed by humans ("humans" and "communities"), then "software" and

[34] In Oslo event, the answers to the question "In which role are you here today?" were: Ontologist (54%), Database expert (0%), Application developer (7%), End user (21%), Business developer (4%), Other (14%). The main application domain of their institutions was "manufacturing", and in most of them semantic technologies start to be used (76%) or are heavily used (20%). The sample for these questions was 28, 27 and 25 respectively.

"ontologies", and finally "things". Finally, about technical components, those who were ranked as most crucial for interoperability are "Data models and formats", "Ontologies", followed by "Data Exchange APIs", "Standards" and "Mappings".

Concerning the selection of references that we tagged (cf. App. A), we note in passing that, there, in line with the focus of this document, "data" is the most commonly found, whereas "software", "things", "ontologies" and "organizations" are similarly represented and "human" is less common.

5. Technical components for semantic interoperability and beyond

In this section we propose a systematic structuring of interoperability requirements, in a very broad sense (Sec. 5.1), then see what technical components address them (Sec 5.2), focusing on the role ontologies can play in this. Finally, we touch on the data life-cycle and semantization pipeline (Sec. 5.3).

5.1 Interoperability requirements matrix

Based on the input from WG1 (Terminology) and WG3 (Scenarios), the WG2 decided to structure interoperability requirements as a matrix, as follows. We selected a small set of relevant system types and interoperability types, and then considered all possible combinations of X-Y interoperability of type Z, with symmetry in the first two arguments. More precisely:

{Data, Human, Software, Organization} X {Data, Human, Software, Organization} X {Syntactic interoperability, Terminological + Semantic interoperability, Pragmatic interoperability}, with symmetry in the first two arguments. Taking into account the said symmetry, this gives up to 30 cases, and we asked ourselves how ontologies can support / enable each of those interoperabilities. The question we are asking in each case is: "How can interoperability-related technical components help an *x* and a *y* (*e.g.*, a software package and a dataset) interoperate better?" For clarity, we give below the structure of the table, then fill it in the following ones.

Requirements (Note: Cell (X,Y) refers to "X-Y interoperability")				
	Data	**Human**	**Software**	**Organization**
Data	DD	DH	DS	DO
Human		HH	HS	HO
Software			SS	SO
Organization				OO

Table 8 – Structure of the interoperability requirements matrix

As an additional dimension, we consider three interoperability levels (simplification of (Euzenat 2013]):

- SYN=Syntactic
- TSE=Terminological + Semantic
- PRA=Pragmatic.

For the present purpose, we here define:

Data: "A representation of facts, concepts, or instructions in a manner suitable for communication, interpretation, or processing by humans or by automatic means." [IEEE, 1991]

Human: "a bipedal primate mammal" (From Merriam-Webster, on-line dictionary)

Software: "Software designed to fulfil specific needs of a user; for example, software for navigation, payroll, or process control."("Application software" in [IEEE, 1991])[26]

Software: “Bit-sequences that are machine-interpretable and belong to a type for which operations have been specified” (from “machine actionable” in FDO Machine Actionability version 2.2, doi:10.5281/zenodo.7825650.)

Organization: "an administrative and functional structure (such as a business or a political party)" (Merriam webster, on-line dictionary)

We note in passing that Section 4.1 of [IEC 2019] also discusses general requirements for semantic interoperability (in the context of the scenarios presented in that reference).

Requirements (Note: Cell (X,Y) refers to "X-Y interoperability")				
	Data	**Human**	**Software**	**Organization**
Data	**SYN:** convert data formats; **TSE:** Integrate data from different sources, integrate data having different data models; **PRA:** integration of access/IP rights. Integration of data contexts (context aspects)	**SYN:** Read/write data; **TSE:** understand data, annotate data, find data, compare data, document data; **PRA:** protocol to modify data. Context aspects.	**SYN:** Read/write data; **TSE:** understand data, annotate data, find data, compare data, document data; **PRA:** APIs to exchange data.	**SYN:** Conversion to/compliance with in-house data formats and schemas; **TSE:** Landscaping / analysis of community / organizational terminology and cross-organizational alignment, conceptual engineering; **PRA:** Data management; data certification; compliance with legal requirements

Human		**TSE:** Shared understanding; **PRA:** communication, collaboration; long ago circulated idea of a "pragmatic web" (how can ontologies/the semantic web help establish standardized human practices).[35]	Software usability, user experience, automatic natural language processing (text, audio), human-computer interaction at large; this also includes observation of humans by software. **TSE:** Mapping human languages and human activities to a formal representation and vice versa.	**TSE:** Definition of roles (e.g., for recruitment, wedges)[36] **PRA:** See Human-Human PRA entry.
Software				**SYN:** Documentation of programming language and compiled / cross-compiled binaries on institutional long-term storage / reproducibility-oriented data preservation systems; **TSE**: Requirements and feature specification; **PRA:** Multilinguality, Licensing, IPR protection, access management to software within the organization, SaaS, cybersecurity
Organization				[Note: Legal/organizational interoperability would be the suitable one here] Organisational Interoperability according to [Panetto, 2007] requires defining business

[35] There would be endless examples, e.g., based on roles (lecturer should answer all emails by students within a day; if you are a journalist please contact XY, etc.)

[36] Beside human resources, other examples include marketing, dissemination, surveying.

				goals, modelling business processes and bringing about the collaboration of administrations that wish to exchange information and may have different internal structures and processes.

Table 9 – Interoperability requirements matrix

5.2 Technical components addressing the requirements

Here, following the same structure used for requirements, we organize technical components addressing interoperability. We note in passing that [Jardim-Goncalves et al., 2013] in its table 2 provides "formal methods" from different disciplines that can be relevant to enterprise interoperability.

Components addressing the interoperability requirements (see Table above)				
	Data	Human	Software	Organization
Data	**SYN:** Format converter, file format/grammar definitions such as BNF (Backus-Naur Form); **TSE:** mappings, crosswalks, ontologies; **PRA:** Protocol for data integration; mappings including context aspects	**SYN:** Human-readable format, **TSE:** human-readable metadata, rich annotations, Data annotator / tagger.	**SYN:** (Digital) data format; **TSE:** Machine-readable metadata, Automatic annotator.	**SYN:** Format converter, file format / grammar definitions such as BNF; **TSE:** Tools for landscaping language and for conceptual engineering; **PRA:** Data management plans, ontologies with appropriate categories matching legal requirements; certificates and systems providing certificates
Human		**SYN:** Text processing, typesetting systems, etc. **TSE:** domain-specific vocabulary / glossary, ISO standard,	**PRA:** User interface, User manual / documentation. **TSE:** Ontologies for what can be measured and understood about humans.	Website (inward and outward facing), organizational guidelines / documents, Surveys, Dissemination material (text, audio, video), Recommender system, Access regulations, security and authentication (even for trivialities such as

		ontology; **PRA:** Note: this is underdeveloped and has the potential of becoming an Industry 5.0 bottleneck or facilitating technology	Ontologies of human emotion, or of signals / data from wearable devices, about agency and intentionality, about video observation of humans.	who can access a building and e.g. manufacturing equipment).[37]
Software			Wrapper (interface). **SYN:** tool for porting across programming languages. **TSE:** Process model topologies; **PRA:** APIs, web services	**SYN:** Long-term storage, compiler, research data infrastructure, ontologies / taxonomies of programming languages, OS, and hardware architectures; **TSE:** Organizational registers of available software, requirements analysis tools, ontology / taxonomy of software features; **PRA:** Standards and recommendations on cybersecurity, roles / rights to access software, ontology / taxonomy of services covering SaaS
Organization				Legal / formal contract / agreement. Business process models.

Table 10 – Matrix of components addressing interoperability requirements (from Table 9)

Guided by this analysis, below we list components/assets that are particularly relevant for the scope of the present report. The components marked with [*] are the interoperability-related building blocks of a data space, following [DSSC SK 2022] and [Nagel & Lycklama, 2021].

Generic component / asset	Comment [Optional]	Interoperability requirement mainly addressed by the component	Related reference(s) [Optional]

[37] E.g., ESCO - European Skills, Competences, Qualifications and Occupations (https://esco.ec.europa.eu/en/classification) can be a relevant model.

Data models[38] & formats [*]	Data documentation	Data-data interop., syntactic and semantic level	[DSSC SK 2022], [Nagel & Lycklama, 2021]
Data exchange APIs [*]	Data sharing / publication	Data-software, software-software	[DSSC SK 2022], [Nagel & Lycklama, 2021]. See also [Verborgh 2014, Cremaschi 2017]
Data provenance and traceability components [*]	Data documentation, data publication	Data-data interoperability	[DSSC SK 2022], [Nagel & Lycklama, 2021]
Metadata & discovery protocol		Data-human	[DSSC SK 2022], [Nagel & Lycklama, 2021]
Compilers		All related to software	
Conceptual engineering tool or practice		Data-organization	
Cross-walks	Sequences of mappings	Data-data, terminological + semantic level	E.g., within EOSC interop. task force
Cybersecurity standards and recommendations		Software-organization	
Data annotators/taggers	data enrichment	Data-human	
Data assessment tools	FAIR/digitalization maturity etc assessment	N/A[39]	
Data format converters	Relates to formal grammars that specify the conversion	Data-data, syntactic level	
Data validators	E.g., for compliance with a format or with a schema, or	All related to data	

[38] We note in passing that "meta-model" is a related term with community-dependent meaning: in some cases is a synonym of "model" (as in SysML), in others of "language" (See https://en.wikipedia.org/wiki/Metamodeling)

[39] Interoperability assessment is in-scope, however we note that these components do not address interoperability per se, they *assess* it.

	domain-specific content validation		
Human activity recognition tools and standardization		Software-human	E.g., [Elkobaisi et al., 2022], [Demrozi et al., 2020], [Singh et al., 2023]
Languages (for mappings, ontologies, queries, constraints, knowledge representation, ...)	E.g.: OWL, LINK-ML, SHACL, ...	All related to syntax	
Long-term storage		**ALL**	
Mappings	Broadly, meant as "correspondences". In mathematics has a stricter meaning.[40]	All related to terminological + semantic level	E.g., [Matentzoglu et al., 2022] and [Euzenat & Shvaiko, 2013]
(Schema) Mediators	Related to mappings and interfaces[41]	All related to software and data at syntactic, terminological and semantic levels	[Euzenat & Shvaiko, 2013]
Natural language dictionary, vocabulary, glossary	Includes technical glossaries	Human-human	
Ontology		**ALL**	
Ontology network	"are made of a set of ontologies and a set of alignments	ALL	[Euzenat & Shvaiko, 2013]

[40] E.g., in SSSOM [Matentzoglu et al., 2022] the Authors focus on mappings "between different representations of the same or similar objects in different databases". In [Euzenat & Shvaiko, 2013] it has a more stringent use: "Mapping is the oriented, or directed, version of an alignment...", and is between ontologies.

[41] "Mediation consists of interfacing two software components by dynamically altering the information stream between these. By extension, a mediator is a program performing mediation. In web service composition, a mediator translates the output of a service into the input of another one: it thus performs data translation. In query answering applications it is a dual pair of translations that transforms the query from one ontology to another and that translates the answers back." [Euzenat & Shvaiko, 2013]

	between these ontologies." [42]		
Recommender system		Human-organization	
Research data infrastructure, data space		**ALL**	[DSSC SK 2022], [Nagel & Lycklama, 2021]
Serializations	E.g., JSON-LD[43]	Software-software, syntactic level	
(Machine) Software interfaces	Includes wrappers	Software-software	
Specification of communities and roles	E.g, OAIS concept of a "designated community"	All organization/human practice related	E.g., [Bicarregui 2013]
Syntax / grammar specifications	BNF (Backus-Naur Form), formal grammars, etc.	All related to syntax	
Taxonomy		**ALL**	
Typesetting and text processing tools	LaTeX, Libreoffice, etc.	Human-human	
User interfaces		Software-human	
Widely used / standard (generic) vocabularies / semantic artefacts; repositories of those	E.g., SKOS[44], DCAT, etc. LOV[45] is an example source. Subset of other categories.	(From human-human to ALL, depending on the asset)	

Table 11 – List of main (generic) components / assets for the scope of this report

[42] "The ontologies may be related for several reasons: they may be complementary; they may be two independent domain ontologies, e.g., sales and tyres, refinement; there may be a domain ontology specialising a top-level ontology; or they may be supplementary, e.g., a version replacing another version or two ontologies about the same domain." [Euzenat & Shvaiko, 2013]
[43] https://www.w3.org/TR/json-ld/
[44] https://www.w3.org/2009/08/skos-reference/skos.html
[45] https://lov.linkeddata.es , see also [Vandenbussche et al., 2016].

5.3 Data life-cycle and semantization pipeline

In this section we give a different perspective for the requirements and technical components, namely in terms of data lifecycle and "data semantization" pipeline. Following AMI 2030 Roadmap[46] (cf. Fig. 2 in the reference: "Four priority topics to achieve the data life-cycle of advanced materials"), one can identify four macro activities and corresponding phases in the life-cycle of materials and manufacturing data:

- *Generate new data*
- *Document data*
- *Manage data space*
- *Use and exploit data.*

For the scope of this report, "Document data" is the most relevant one, followed by "Manage data space". Focusing on data documentation, clearly different levels of depth can be identified. For example, following [Friis et al, 2024], one can break data documentation down into four types:

- *Cataloguing documentation*: *e.g.,* describe how data can be found and accessed
- *Structural documentation*: *e.g.,* describe how the data is structured and represented numerically
- *Contextual documentation*: e.g., make data reusable by providing context and provenance
- *Semantic documentation*: e.*g.,* enhance data semantically by mapping it to ontologies.

We emphasize that, in realistic scenarios (e.g., in materials modelling), not all the data and its metadata will be represented semantically (say, as RDF triples), but only a part of it; exactly how much depends on the needs of the specific use-case at hand and on computational limits.

With this *caveat* in mind, we can ask what, in the view of semantic web practitioners, are the steps to go from existing "data" (in any form), and turn it into "linked data"? For example, in [Radulovic et al., 2015] the ***linked data generation process*** is organized in eight main steps/tasks (see also Fig. 2 of the reference)[47]:

- *Step G1: Select data source*
- *Step G2: Obtain access to data source*
- *Step G3: Analyze licensing of the data source*
- *Step G4: Analyze data source*
- *Step G5: Define resource naming strategy*
- *Step G6: Develop ontology*
- *Step G7: Transform data source (intended as: transformation of the data into the RDF format)*
- *Step G8: Link with other data sets.*

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[46] https://www.ami2030.eu/wp-content/uploads/2022/12/2022-12-09_Materials_2030_RoadMap_VF4.pdf

[47] The step titles are from [Radulovic et al., 2015], we have added step identifiers G1, …, P4.

This is followed by four steps for the ***linked data publication process*** [Radulovic et al., 2015] (see also Fig. 3 of the reference):

- *Step P1: Ensure legal compliance*
- *Step P2: Publish the data set and the ontology on the Web*
- *Step P3: Publish metadata and online documentation*
- *Step P4: Enable data set discovery.*

In particular, steps G7, G8, P1, P2, P3, P4 are relevant for the present document, and for more details and examples we point the reader to the respective sections in [Radulovic et al., 2015], where sub-tasks are identified, tools are pointed out and a complete scenario is given.

Clearly the references cited above have different scopes, with AMI 2030 and [Friis et al, 2024] addressing materials modelling and manufacturing data in general, whereas [Radulovic et al., 2015] focuses on how to share data (from any domain) on the Web using RDF-like formats. Of course, depending on the confidentiality of the data at hand certain steps of the latter will need adapting, but the technologies and tools suggested will still be relevant.

From these references we can identify various common activities[48]. However, the concrete steps will depend on the scenario at hand (e.g., adding a semantic layer to an existing database, creating a new data and knowledge storage for an enterprise, etc), and a complete overview and structuring of all possible data semantization scenarios is beyond the scope of this document. Further references can be found in the cited sources and concrete scenarios can be found in Sec. 4.

6. OntoCommons's approach

In this section we summarize core aspects of OntoCommons' proposal regarding ontology-based interoperability (which in turn requires tackling interoperability between ontologies themselves), and point the reader to other project deliverables for further details. In particular, we describe the project original results, as the **OCES** (including decisions regarding pluralism and expressivity) and the **Bridge Concept templates.** This enables us to highlight the design decisions made in the project and understand how they are positioned with respect to the existing literature and interoperability solutions discussed above. We thank colleagues from WP2 - Top Reference Ontology for their support, which allowed us to provide here a summary of their work that is accessible to non-ontologists as well.

[48] Clearly, one should keep in mind the different concerns when combining different views on data pipelines: for example, "Data validation" and "Data transformation" at the domain-level typically refer to domain-specific validations and format conversions, whereas from the semantic web perspective the focus is on RDF aspects.

6.1 Pluralism

Generally speaking, interoperability can be achieved through one of two approaches: (1) by imposing a unique universal standard/protocol on all components, making them mutually compatible by default, or (2) by establishing mechanisms for transitioning from one standard/protocol to another, which can be either standardized or ad hoc themselves. The boundaries between these two approaches are much less defined than it might initially seem; nonetheless, the distinction will suffice for the sake of the following discussion.[49]

As anticipated, OntoCommons' adoption of a pluralistic stance sets it apart from other initiatives, particularly in matters concerning interoperability. Given this, one might assume that the project heavily leans towards approach (2). However, before delving into the details of OntoCommons' stance on specific aspects of interoperability, it is pivotal to clarify the scope, and the modalities in which the project is pluralistic.

Firstly, OntoCommons embraces pluralism in knowledge representation. Its ecosystem comprises diverse ontologies, spanning various domains and perspectives, often tailored to specific application scenarios. Even more radically, it includes different TLOs, each expression of a different perspective/worldview: BFO, DOLCE & EMMO. In line with what has been said above, this approach facilitates technology exploitation, empowering stakeholders to choose the most suitable ontologies for their use cases, and allows for the inclusion of existing ontologies already holding a share of the market, being thus less disruptive at the operational level.

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[49] While (1) might be considered *prima facie* the optimal solution in most scenarios, in practice it is often impossible to have all stakeholders converge towards a (practical) consensus due to their specific interests (e.g., commercial considerations, security, and privacy; inertia should not be underestimated given the costs inherent in change), and the necessary prerequisites for top-down standard imposition may not be met (or even not meetable in practice). Even if these prerequisites were met, it is also unclear whether the benefits of achieving interoperability would outweigh the drawbacks of imposing a single standard across the board, without considering the requirements and preferences of the involved stakeholders. This is particularly true when it comes to knowledge representation, as the level of precision in the representation, and the overall partitioning of the logical space (the domain), are heavily influenced by the domain of application, as well as by the specific use cases.

On the other hand, (2) usually poses technical challenges; it requires innovative and often complex solutions (and thus the investment of resources), and the degree of interoperability that can be reached is often inferior – problematically, this holds true independently of which kind of interoperability, and specific scenario, is considered: e.g., information can be lost in translations, computational times can increase if data has to be converted from one format to another, and energy exchanges can be slightly less efficient. As such, (2) is often related to issues having to do with scalability and sustainability. It is thus especially important to consider which approach should (or, minimally, can) be employed case by case, independently evaluating feasibility, pros and cons, endorsing a plastic and pragmatic position.

Secondly, and in a sense, encompassing the first principle, **OntoCommons is pluralistic in its consideration of all stakeholders' viewpoints and desiderata, and needs.** It offers customizable solutions within a scalable, layered framework with predefined levels of commitment and engagement; likewise, the system is inherently open to expansion and revision, and the tools allow for the direct engagement of the users. The project promotes pluralism, structured stratification, or the adoption/imposition of standards based on the situation.

Ultimately, the project aims to provide **solutions that are not only theoretically sound but also practically effective**, with the focus being on the latter. It's worth noting that approach (2) has been relatively underrepresented in the literature concerning various aspects of interoperability, although recent trends suggest a shifting landscape (see D2.10); as such OntoCommons is fully deserving of being labelled a "project rooted in pluralism".

6.2 Knowledge Representation Frameworks

(Relational) **Databases, Knowledge Graphs and** (Light-weight and Foundational) **Ontologies** all offer structured and systematic ways to **model, store, and manage data**. Although their roles can be seen as complementary (albeit interconnected), and there are some relevant idiosyncrasies among the technologies, it is not inappropriate to order them progressively based on the functionalities they offer, focusing on semantic aspects (loosely understood).

According to the DoA, **OntoCommons heavily emphasizes ontologies as the preferred knowledge representation frameworks. However**, it is worth noting that **many stakeholders rely solely on simple databases** to manage their data.[50]

To accommodate both of these perspectives, OntoCommons proposes a **vertically layered approach.** It provides stakeholders with an **interoperable network of ontologies** (the OCES) **and support for mapping** their databases and knowledge graphs into these frameworks. Specifically:

- **Schema alignment is facilitated by** one of the tools provided by the Consortium, known as **Bridge Concepts** (more on this infra). This tool is designed to be accessible to domain experts and data scientists who may not be specifically ontology experts. With the vast number of ontologies in the ecosystem and the addition of bridge concepts, finding a mapping is arguably much easier for stakeholders compared to standard scenarios.
- **Recommendations** are provided **for all procedures related to data format transformation**, along with a definite list of **requirements and best practices to ensure data reusability** by all the stakeholders contributing to the EcoSystem (e.g., related to annotations). The Mappings

[50] This choice can be influenced by various factors, including monetary considerations or the technology's accessibility. In some cases, using more complex technologies can be impractical, especially in simple scenarios or when dealing with big data, due to practical constraints. On the other hand, semantic enrichment significantly reduces the risks of errors, increases data interpretability and reusability (contributing to the valorisation of the data-capital) and is pivotal to achieve interoperability beyond local solutions. Depending on the quality of the mapping, querying functionalities can also be greatly improved.

themselves are designed to be trackable, integrated, and FAIR (more on this infra). This results in a semi-automatic workflow with easy-to-follow steps.

- **Semantic enrichment** is ensured by the mappings themselves, carried out in the most expressive language. Taking into account the pluralistic approach of OntoCommons, and the richness of the EcoSystem, this allows for informative characterizations, and increased customizability.

In practice, stakeholders can potentially continue to use databases and/or knowledge graphs while enjoying the advantages outlined above through alignment with the OCES.

On the other side, one of the advantages of choosing ontologies for knowledge management the relative easiness of reverting to knowledge graphs and databases from ontologies once the alignment has been established: while, as in the case of translations to less expressive formal languages, there is often no univocal algorithmic procedure, operating by subtraction is usually much simpler than doing so by addition. Again, a balance of pros and cons needs to be made case by case.

6.3 Logical expressivity

OntoCommons makes use of different formal languages, characterized by different levels of expressivity. Specifically, the project focuses on (ordered by decreasing logical expressivity):

- FOL/Common logic (ISO/IEC 24707);
- OWL 2 DL ("Description Logic") + SWRL (see https://www.w3.org/submissions/SWRL/);
- OWL 2 DL (in line with ISO 15926);
- RDFS ("Resource Description Framework Schema") (https://www.w3.org/TR/rdf12-schema/).

This choice was heavily influenced by considerations pertaining to their diffusion, overall stability, and the existence of supporting tools.

- **First Order Logic (FOL)** [Smullyan, 1995] is the *de facto* standard in academia, and one of the most renown formal languages. Not only is it accessible to the vast majority of the scholars with a background in mathematical logic, but it has been extensively studied and its properties are arguably well understood. Higher order logics, logics with modal operators and non-binary logics, fixed-point logics, all introduce useful tools, but are less accessible, and can be partially recaptured in FOL.
- **OWL 2 (DL)** is the most commonly used formal language when it comes to ontologies. It has been developed with ontology-use in mind by W3C, and offers a good trade-off between computational times and expressivity, staying within the realm of the decidable.
- **RDFS** is a key model for structured data exchange. While the semantic capabilities are extremely limited, it can be considered the standard when it comes to approaches based on triples, and relative query languages such as SPARQL.

As in the previous case, the pluralistic approach is a deliberate attempt to accommodate different needs and exploit the specific strength of each solution to improve the overall framework in a systematic and integral way. In this context, the central challenge lies in addressing the **trade-off**

between expressivity and computational costs, which can be considered one of the most pressing issues and limit of semantic technologies (see D2.10 and specifically §11 on the search for alternative solutions; compare with D2.7).

More pressingly, **decidability** can be considered a minimal precondition **for effective machine-usage**; yet, as it is well-known FOL is only semi-decidable (thus it can possibly result in non-terminating procedures), although there are useful decidable fragments, as well as decidable theories. It should be noted that there have also been some attempts to exploit cut-off techniques for non-terminating processes; however, such approaches seem inadequate in industrial contexts where precision and speed are required.

Taking these points into account, **OntoCommons requires FOL versions of TLOs** (and heavily recommends them for MLOs)**, and OWL 2 DL versions of each ontology part of the OCES, while the OWL framework itself relies on OWL 2 DL with added horn rules (SWRL).**

Since the TRO occupies a core role in the OCES, sub-optimal alignments (or mistakes) could heavily compromise the practical functionalities of the framework (exchanging data), the specific role of the TRO (e.g., error-checking, reasoning and facilitating further alignments), as well as the OCES's role as a conceptual and ontological resource (acting as a reference point for the creation of new ontologies and the comparison of different ontological choices among other things). As such, **it was decided to establish manual alignments** (the details will be offered this infra) among the ontologies, focusing **on their FOL versions, and then transposing the results in weaker formal languages** (Compare with D2.7 and D2.9 on this point).

For practical usage, the FOL alignments have to be "translated" into semantic web languages, for which there exist a number of supporting tools. The process is not automatic or algorithmic, and involves making a choice between different possible alternatives. The decision to opt for **OWL 2 DL + SWRL**, allowing horn rules, enables a higher retention rate from FOL with respect to OWL 2 DL, and has minimal effects on computational times (although more tests are required once the OCES is employed in practice). In fact, without compromising computability, the RL extension retains some of the advantages provided by expressive formal systems. Significantly, due to the close relationship between the two systems, transitioning from one to the other is straightforward. It is thus worth pointing out that the SWRL mappings can be utilized for on-demand data exchange or local applications, if not in standard use.

The OWL 2 DL versions of ontologies are those actually included in the framework, for all the practical purposes: given this is a widely used language and many tools are available for it, we find it is not a too stringent requirement for inclusion of other domain ontologies in OCES.

Implementations in less expressive languages are accepted for specialized applications which require it. In such cases, RDF is heavily recommended given its widespread use, as well as the established connections between the former and OWL. Notably, such implementations might heavily compromise the effective exploitation of the OCES, given the overall importance of reasoning. OntoCommons thus requires stakeholders to maintain a more expressive implementation in parallel, given the various benefits outlined above.

Overall, summarizing:

- This pluralistic approach allows most stakeholders to **focus solely on the implementations of the ontologies they are most familiar with**, without the need for expending resources or gathering competences, while **benefitting for a more solid framework.**
- The layered approach opens the door to stakeholders interested in exploiting only limited functionalities of the framework,
- and the **added requirements for the participation to the framework are minimal**, in line with OntoCommons' inclusive and open stance.

6.4 OntoCommons EcoSystem's Structure

In the literature on ontology interoperability, TLOs are often cited as potential tools to facilitate alignments and ensure consistency between lower-level ontologies, as well as to check for potential errors and improve reasoning capabilities. However, when such solutions are considered, it is often taken for granted that *only one* TLO should act as the core. Likewise, ontology hubs revolving around a single TLO (or MLO) are fairly common at the present time (e.g., IOF, cf. discussion in Sec 3.4). Over time, only a few projects have considered frameworks that include a plurality of linked TLOs for practical usage, with Wonder Web being a notable example.[51]

As already mentioned, in line with its pluralistic approach, OntoCommons follows in the steps of the Wonder Web Project in revolving around a plurality of TLOs (BFO, DOLCE, EMMO), each expression of a different worldview and, arguably, each one more effective in specific scenarios. Again, we underline that, at least for projects addressing a very wide scope, this kind of approach is heavily recommended.

[51] While alignments among TLOs are not uncommon, they often lack practical exploitations. This can be attributed to the (perceived) complexity of TLOs, the challenges in creating alignments among them, the gap between TLOs and applications (and thus investments), and the fact that pluralistic frameworks can only be effectively exploited in large, inclusive networks, and this easily brings in computational (scale) and IP issues (data control).

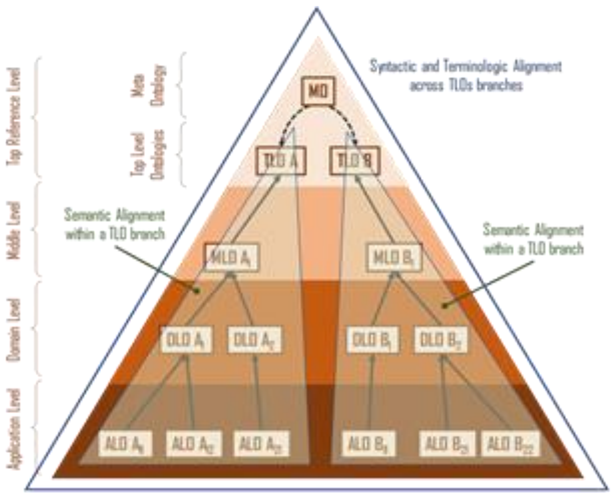

Figure 1 - OntoCommons Ecosystem structure

OntoCommons provides a single apical ontology known as the OntoCommons **Top Reference Ontology (TRO)**, encompassing the three TLOs as well as the "meta-ontology", i.e., pairwise alignments among those ontologies. The TRO's structure is meticulously designed to fulfil the following objectives:

- To provide **minimal connections** to the framework for a large number of ontologies grounded on the TLOs included in the TRO;
- To offer a pluralistic perspective in the selection of a representational framework for lower-level ontology development;
- To **enable comparison and interoperability**, serving as a common foundation (and the control test) for data sharing among lower-level ontologies, especially if based on TLOs part of the TRO.

OntoCommons is addressing two ways of interoperability:

Intra-ontology interoperability : The capability to enable data sharing between a single semantic representation of data from TLO to ALO coming from *a monistic ontology/domain approach* (one-to-one exclusive relation between ontology and domain of interest). This type of interoperability will be addressed by OntoCommons within a TLO ontology branch whose lower ontology levels share a common semantic framework.

Cross-ontology interoperability the capability to enable data sharing between different semantic representations of data from different TLOs branches coming from a *pluralistic ontology/domain approach*.

Below the TRO (cf. Figure 1), the OntoCommons EcoSystem (OCES) is populated with MLOs and DLOs from different communities. As a best practice, OntoCommons recommends that each lower-level ontology should be based on a given TLO, or on the TRO itself. In fact, this makes ontologies' content more accessible, and the connection is already capable of grounding minimal data interoperability with other ontologies part of the OCES. That said, also standalone ontologies are allowed in the framework, in which case they are aligned to the TRO either by means of standard harmonization techniques, or *via* "*bridge concepts*" (cf. Sec. 6.4.2).

Bridge concepts are also required to establish direct links between lower-level ontologies: in fact, while alignment to the TRO facilitates semantic comparison and checking for fundamental errors, the network's efficiency is heavily dependent on the **informativeness and precision of the alignments**, and this necessarily takes places at a lower abstraction level.

For more details on the EcoSystem Structure, we point the reader to OntoCommons D2.7, D2.9.

6.4.1 TRO alignments: Methodology

In the context of ontology alignment, OntoCommons aims to address various types of heterogeneity, such as terminological, syntactical, semantic, and semiotic heterogeneity, focusing (in general) on the latter. We recall that semiotic (or pragmatic) heterogeneity "is concerned with how entities are interpreted by people" [Euzenat & Shvaiko, 2013].

In the context of ontology alignment, the ideal goal is to create connections which allow the seamless transition from a representational system to the other[52]: obviously, as there are inherent limitations due to the ontologies' different domains of applications/perspectives/commitments, this can be considered a rule of thumb.

Within this context, one can say that *semantic interoperability* is established via semantic connections between classes and relations, which can also take the form of complex axioms rather than simple taxonomical relations of inclusions. *Syntactic interoperability* is guaranteed by the imposition of a specific formal language. Terminological heterogeneity is not resolved via the imposition of specific labels, but rather mediated by semantic relations (which clarify the labels, allowing the individuation of both synonyms and "false friends").

The focus on possible future usage poses challenges in itself, since different stakeholders are likely to make use of the framework for different purposes, and thus the connections require **different degrees of precision**. The problem is addressed in OntoCommons in a threefold way:

- the **alignments between TLOs** part of the TRO **are made as precisely as possible**, since they ground the entire framework;
- **direct alignments between specific ontologies and a given TLO** are **as precise as the lower-level ontology requires**;
- the **precision of mediated alignments can be adjusted** (made more precise or less precise) by operating on the bridge concepts. Based on needs, more/less precise bridge concepts can be introduced in the framework, thus establishing a layered and customizable environment.

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[52] Let S be a generic scenario being modelled, O′ and O′′ two ontologies and M′ a set of mappings from O′ to O′′, and R′ and R′′ the ways in which S would be modelled in O′ and O′′ respectively; a perfect mapping is such that for any generic scenario S, R′ + M′ fully recovers R′′.

Since the TRO aims to serve as a conceptual and ontological resource for various purposes, preserving the original richness and ontological commitments of TLOs and mappings is crucial. Due to the unique nature of TLOs and their complex mappings, carrying on a manual alignment based on FOL versions is essential for effectively building the TRO and preserving the richness of ontological commitments. Then, as already mentioned, these TRO alignments (in FOL) are transposed in OWL 2 DL + SWRL[53] for actual usage. For more details on the principles that have been adopted as **methodological guidelines for the alignment of ontologies that are part of the TRO**, please see OntoCommons D2.7. And for the concrete **recommended steps** needed **to perform an alignment of ontologies in FOL**, please see OntoCommons D2.9.

To close up this section, we would like to mention that, while the OntoCommons project heavily focuses on manual alignments, semi-automatic approaches making use of the TRO alignments to apply controls are being investigated in collaboration with the **Material Science and Engineering (MSE) Benchmark activity**[54], also connected to the Ontology Alignment Evaluation Initiative (OAEI). While caution is paramount with use of (semi-)automatic tools for building alignments, finding indirect ways to make use of the analysis provided by semi-automatic tools can be an interesting and fruitful line of research.

6.4.2 Bridge Concepts

Bridge concepts are one of the core entities provided by the Consortium to establish the OCES. Here a brief description is provided, focusing on matters related to interoperability; we point the reader to D2.5 (slightly outdated), D3.6, D3.7 and D2.9 for more details[55].

In a nutshell, a **bridge concept is a stand-alone entity to support semantic vertical and horizontal alignment between ontologies.** The associated **template contains four main parts** (Concept info, Knowledge domain resources, Vertical and horizontal alignments to existing ontologies), **to be filled by both domain experts and ontologists**, in collaboration with each other.

Going into more details, bridge-Concepts are designed to address OCES-specific challenges related to **scalability and pluralism**, as well as to tackle well-known issues related to interoperability and **usability** in the context of semantic web technologies. They do so by playing two fundamental roles:

1. **supporting ontology alignments among pluralities of ontologies**;
2. **providing a user-friendly interface** for stakeholders and domain experts.

In their first role, Bridge-Concepts function as standalone ontology entities, built and characterized independently of any ontology (i.e., ontology-neutral). They **serve as hubs in hubs-and-spoke**

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[53] This step could, in principle, be performed by semi-automatic or automatic tools. However, in the context of OntoCommons TRO, a manual alignment was executed to ensure the quality of the results.
[54] See repository https://github.com/EngyNasr/MSE-Benchmark/tree/main , also containing data for the MSE track at OAEI 2022 and 2023.
[55] For a template and examples, see also the repository:
https://github.com/OntoCommons/OntologyFramework/blob/main/bridge-concept-template.md

structures, **enabling strong semantic alignments among multiple ontologies**, essentially acting as data pipelines, or minimal ontology content patterns. Bridge-Concepts are also linked to all Top-Level Ontologies (TLOs) through strong semantic alignments upon creation, making TLO's benefits accessible to all stakeholders without the need for direct ontological support.

The hub-and-spoke structure substantially decreases the number of required alignments (from exponential linear with respect to the number of involved ontologies). Adding onto that, bridge concepts are engineered to support data exchanges at core junctions in the network, further reducing the number of required links for meaningful and informative alignments. Together, these two characteristics go ways toward solving issues related to scalability.

Notably, these tools **establish networks of connections** rather than creating super-ontologies or super-standards. This approach prevents interoperability issues at the meta-level, allowing for the growth of an interconnected network without shaky foundations or conflicts.

To establish alignments among ontologies, Bridge-Concepts connect with specific classes from a target via a semantic relation, such as class equivalence or sub-class relations (or possibly taking the form of complex axiomatic relations). These connections facilitate data sharing by effectively "moving" individuals from one ontology to another through the transitivity of taxonomical relations. **Bridge-Concepts play a crucial role in achieving semantic alignments among ontologies, particularly at lower levels where specializations and complementarity are essential.**

In their second role, Bridge-Concepts act as practical dictionaries customized for ontology implementation, ensuring accessibility for both stakeholders and domain experts and providing points of reference via connections to golden standards.

To better understand the role of bridge concepts, let us introduce a **distinction between formal and informal characterizations of ontology entities:**

- **Formal Characterizations:** These characterizations are *deeply ingrained in the ontology's structure. They pertain to the hierarchical organization of classes and relationships* (and the ontology's axiomatization in general), ultimately coming down to mathematical/structural aspects of the ontology.
- **Informal Characterizations:** In contrast, informal characterizations are more flexible and *relate to the annotations, intended use, and practical understanding of the ontology.* Informal characterizations include natural language labels, descriptions, comments, and contextual interpretations. These elements are not typically part of the ontology's formal logical structure. Informal characterizations provide clarity for human users and domain experts and often make the ontology more accessible and usable.

Bridge-Concepts operate primarily at the informal level. Since they are designed as standalone entities, they are intended to bridge the gap between ontologies with differing formal characterizations of concepts covering the same individuals. Bridge concepts aim to connect various formal characterizations to maximize benefits while minimizing drawbacks, contributing to the harmonization of diverse ontologies.[56]

Finally, given how crucial scalability is, the **analysis of candidate-bridge-concept terms** plays a crucial role their successful use later on. That is, in order to decide where to build a bridge (concept), it is recommended to make use of graph/network theoretical statistical approaches, as well as of ontologists' expertise for this task, taking into account the characteristics of the specific scenario encountered. The TRO is then also crucial in the aligning phase, providing a way to ground the overall network, and to evaluate the fruitfulness of the relevant alignments.

OntoCommons suggests the adoption of **bridge concepts as a tool for vast projects requiring connections among a plurality of ontologies.** Scalability and controllability will be pivotal for any other approach attempting to establish a comparable network of ontologies. While there might some room for good results with automatic and semi-automatic tools if the alignments among TLOs are considered, it is worth reminding that alignments are an investment, and precision is especially important in the NMBP domain.

6.5 Recommendations on Technical Principles, Tools & Platforms

Presenting all the ideas related to interoperability put forward in the course of the project is clearly beyond the scope of this document. More information concerning the technical principles can be found in OntoCommons D2.9 and the **LOTS4OCES methodology**. Some of the core points related to the recommended tools, and the relative workflows, have been touched on in § 5.3. See also OntoCommons D4.6 and D4.7.

Reaching a consensus on best practices concerning documentation is especially important when it comes to interoperability, given the **importance of the human factor in dealing with, and resolving, heterogeneity.** As a rule of thumb, when it comes to the recommended technical principles, OntoCommons opts for a unificatory approach, following trends in usage. In fact, in similar scenarios, a pluralistic stance undermines and overcomplicates the landscape.

[56] In general, it is worth adding that bridge concepts are rooted in assumptions extrapolated from anti-representationalist views of language, and strongly connected to conceptual engineering: in short, it is assumed that the concepts employed in everyday life are fuzzy by default, and specifically lack determinate semantics. Putting it roughly, communication is seen as rooted in bargaining acts, rather than on reference and universally shared semantics. Bridge concepts are ultimately an attempt to transpose this assumption in a machine-readable environment, replicating some degree of bargaining and imprecision within the limits of pragmatic tolerance, which are determined by specific use-case scenarios.

As a conclusive reminder, OntoCommons suggests the use of the **OntoPortal** initiative[57], specifically the **IndustryPortal Platform**[58]. The latter is maintained by members of the OntoCommons Consortium and, as a result, implements many tools (for example, it allows to store SSSOM mappings between ontologies, it points to the SousLeSens[59] suite of open-source tools, that allow to align and map ontologies). Alternatively, **Ocean Web** [60] can be employed to create, edit and align ontologies, although its functionalities are currently limited. General purpose repositories for cross-domain ontologies, as LOV (cf. Sec. 5.2), are also recommended.

57 https://ontoportal.org/
58 http://industryportal.enit.fr/
59 https://souslesens.enit.fr/vocables/
60 https://webprotege.stanford.edu/

7. Conclusions

This document concludes the OntoCommons activities on the Review of Domain Interoperability. We have addressed the topic of interoperability from different points of view (including the terminology used to describe it, the common requirements and the technical components proposed to address them) and gathered pointers to relevant literature, initiatives, recommendations, metrics and tools. Then, we have analyzed them, to identify both common points and differences, along various dimensions. To provide guidance to the reader to identify further references, we have also provided a list of tagged references, including many systematic reviews (e.g., one specializing on the quantification of interoperability or another on device interoperability).From the sheer amount of publications and initiatives addressing it, clearly "interoperability" has been a key concern, at least in the last two decades. We find that the term is used with slightly different meanings by different sources, and a plethora of facets and concerns have been analyzed in the literature. Various solutions and recommendations have been proposed, and we have given an overview of those. Also, we have presented a set of concrete scenarios, based on OntoCommons demonstrators. Beside the literature and the project own expertise, input has been gathered from the wider community, also thanks to a survey run during OntoCommons second Global Workshop.

Ontologies are often presented as a technical component to ensure interoperability regarding different requirements (including data-data, data-human, data-software, data-organization, and so on) but ontologies themselves suffer from interoperability. Ontocommons OCES tried to address this issue through a set of ontologies, approaches, methodologies, principles and tools.

As a matter of fact, interoperability is not "solved" yet in all cases, and, as technology advances, we expect that certain types of interoperability issues might be solved, however other will appear, in a continuous cycle: we do therefore recommend that the many ongoing efforts with overlapping purposes keep communicating with each other and ideally join forces.

The international Semantic and FAIR Knowledge Graph Alliance (KGA asbl) is launched by OntoCommons stakeholders in order to host OCES and federate efforts on ontology based/driven interoperability efforts by being a hub of collaboration with other thematic organisations and initiatives to accompany a successful data driven innovation.

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8. References

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[62] Also available at https://ec.europa.eu/research/participants/documents/downloadPublic?documentIds=080166e5c8dd288d&appId=PPGMS Note: This is EMMC-CSA D2.4, corresponding to T2.3.

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8.2 References to projects/initiatives

AMI2030, Advanced Materials 2030 Initiative, https://www.ami2030.eu/

CEN, European Committee for Standardization (Comité Européen de Normalisation), https://www.cencenelec.eu/about-cen/

CENELEC, European Committee for Electrotechnical Standardization *(Comité Européen de Normalisation Électrotechnique)*, https://www.cencenelec.eu/about-cenelec/

DDI, Data Documentation Initiative, https://ddialliance.org/

DSC, Data Sharing Coalition, https://datasharingcoalition.eu/

DSSC, Data Spaces Support Centre, https://dssc.eu/

ELIXIR, https://elixir-europe.org/

EMMC ABSL, European Materials Modelling Council ABSL, https://emmc.eu/

EMMC-CSA, European Materials Modelling Council CSA, https://cordis.europa.eu/project/id/723867

EOSC, European Open Science Cloud, https://eosc-portal.eu/about/eosc

ETSI, European Telecommunications Standards Institute, https://www.etsi.org/

FAIR-DO (FDO), FAIR Digital Objects (Forum), https://fairdo.org/

IDSA, International Data Spaces Association, https://internationaldataspaces.org/

IE, Interoperable Europe, https://joinup.ec.europa.eu/interoperable-europe

IEEE, Institute of Electrical and Electronics Engineers, https://www.ieee.org/

Interop (NoE), Interoperability research for networked enterprises applications and software (Network of Excellence), https://cordis.europa.eu/project/id/508011

INTEROP-VLab, International Virtual Laboratory for Enterprise Interoperability, http://interop-vlab.eu

IOF, Industrial Ontologies Foundry, https://www.industrialontologies.org/

OAEI, Ontology Alignment Evaluation Initiative, https://oaei.ontologymatching.org/

OAGi, Open Applications Group (Inc), https://oagi.org/

OAI, Open Archives Initiative, http://www.openarchives.org/

OPEN-DEI, OPEN-DEI: Aligning Reference Architectures, Open Platforms and Large-Scale Pilots in Digitising European Industry, https://www.opendei.eu/

RDA, Research Data Alliance, https://www.rd-alliance.org/

SOA4All, Service Oriented Architectures for All, https://cordis.europa.eu/project/id/215219

SDMX, Statistical Data and Metadata eXchange, https://sdmx.org/?page_id=2561

W3C, World Wide Web Consortium, https://www.w3.org/

A. Appendix: List of tagged references

In this Appendix we provide a list of tagged documents[63], which are a subset of the references given in Sec. 8.1.

Tag ID	Property	Values
T1	Reference type	journal publication, technical report, project result/outcome, formal text[64], other
T2A	Reference primary content	recommendation/principles, method, tool, review/comparison, use-case, formal principles/definitions, metric
T2B	Reference content	recommendation/principles, method, tool, review/comparison, use-case, formal principles/definitions, metric
T3	Interoperability of what type of entities?	Data, software, humans, ontologies, things, organizations
T4	Has definition of interoperability	Yes, No [If Yes: Defined, Reused]
T5	Has glossary (including entry for interoperability)	Yes, No
T6	Has classification of interoperability types	Yes, No [If Yes: Defined, Reused]
T7	Heterogeneity type addressed	Syntactic, Terminological, Conceptual, Semiotic
T8	Logical expressivity level of the solution	Low, High[65]

Table 12 – Properties and values for reference tagging

[63] For examples in the literature about references tagging, see e.g. [Schneider et al., 2022] and [Wieringa et al., 2006].

[64] Formal text includes: ISO standard, legislation, specification

[65] Meant as: high = FOL and beyond, low = RDFS, OWL-DL

Ref. ID	T1: Reference type	T2A: Reference PRIMARY content	T2B: Reference content	T3: Interoperability of what type of entities?	T4: Has definition of interoperability	T5: Has glossary (including entry for interoper-ability)	T6: Has classification of interoper-ability types	T7: Heterogen-eity type addressed	T8: Logical express-ivity level of the solution	(Optional) for reviews: # of Articles/approaches/ resources reviewed
[Amjad et al., 2021]	journal publication	review/comparison	review/comparison, tool	data, software, things	Yes (reused)	No	Yes (reused)	N/A	N/A	34 works and 19 tools
[Andročec et al., 2018]	journal publication	review/comparison		things	yes	no	yes (reused)	conceptual	N/A	105 (primary studies)
[Asuncion & van Sinderen, 2010]	journal publication	review/comparison	review/comparison	software, data	Yes (reused)	No	Yes (reused)	N/A	N/A	44 papers (with unique definitions)
[Berners-Lee, 2006]	other (webpage)	method	metric/method	data	no	no	no	no	N/A	
[Baumann et al., 2021]	technical report	methods	use-case	data	Yes	No	No	conceptual	N/A	
[Chávez-Feria et al., 2021]	journal publication	method	method	data	no	no	no	no		
[Cimmino et al., 2020]	journal publication	method, tool	method	data	no	no	no	no	N/A	
[Corcho 2021]	project result	recommendation/principles	method	all	Yes (reused)	No	Yes (reused)	All	N/A	
[Data act 2022]	formal text	principles		all	Yes (defined)	Yes (set of "definitions"	Yes (reused) [A bit hidden, cites ISO 2017 "interoperability facets"]	N/A	N/A	
[DSM 2023]	project result, other (website)	metric	recommendations	data	no	yes (however, no entry for	no	syntactic, terminological,	N/A	

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						interopera bility)		conceptual (indirectly)		
[DSSC SK 2022]	technical report	recommendation	recommendation, use-case(s) (pointers to)	data	Yes (reused)	Yes	Yes (reused)	N/A	N/A	
[EIF 2017]	technical report	recommendation/p rinciples		data, organizations, software	yes (Defined)	no	yes (defined)	syntactic, conceptual	N/A	
[EMMC-CSA 2019]	project result (deliverable)	principles	method, tool	software	Yes (defined)	No	Yes (defined)	All	High	
[ETSI 2019]	technical report	recommendations/ principles	review	data, things	no	yes (however, no entry for interopera bility)	no	conceptual	N/A	18 IoT-centric approaches/resources/pr ojects
[Euzenat, 2001]	journal publication	formal principles/definitio ns	review/compariso n	ontologies	Yes (defined)	yes	yes(defined)	all (focus on terminologic al, conceptual)	high	3 approaches
[Euzenat & Shvaiko, 2013]	other (book)	formal principles/definitio ns	review/compariso n	ontologies	Yes (defined - heterogeneity)	yes	Yes (defined - heterogeneit y)	all (focus on terminologic al, conceptual)	high	9 general matching approaches; 96 specific systems
[Fraga et al., 2020]	journal publication	review/comparison	review/compariso n	data, things, software, organizations						54 (primary studies)
[Garijo & Poveda-Villalón, 2020]	journal publication	guidelines/method	Method, use-case	ontologies	No		No	no	N/A	
[Guizzardi, 2020]	journal publication	principles	definitions, method	data, ontologies, humans	yes (defined)	no	no	conceptual, syntactic	medium	
[Gupta et al., 2022]	journal publication	metric	principles	data, ontologies	yes (defined)	no	yes (levels -- based on	conceptual, syntactic	N/A	

							types; defined, but taking inspiration from some references)			
[Gürdür et al., 2016]	journal publication	method	tool	data, software	yes	no	yes	terminological, conceptual	N/A	
[Gürdür & Asplund, 2018]	journal publication	review/comparison		data, things	yes (reused)	no	yes (own set, from existing ones)	conceptual	N/A	
[Hagelien 2021]	journal publication	method, tool	method	data	Yes	yes	no	Semantic interoperability	low	
[Hou et al., 2021]	journal publication	method	method, use-case	data	no	no	no	no		
[IEC 2019]	technical report (white paper)	recommendation	recommendations, use-case	All	Yes (defined)	Yes	Yes (sort of defined)	Conceptual, Terminological, semiotic	N/A	
[IEEE, 1990]	formal text	definitions		data	Yes (defined)	yes	no	N/A	N/A	
[IEEE, 1991]	formal text	definitions		data	Yes (defined)	yes	no	N/A	N/A	
[Janowicz et al., 2014]	journal publication	recommendation/principles	metric	ontologies	no	no	no	N/A	N/A	
[Janssen et al., 2014]	journal publication	metric	recommendations	data, systems	yes (both defined and reused)	yes (kind of)	yes (defined)	syntactic, conceptual, semiotic	N/A	
[da Silva Serapião Leal et al., 2019]	journal publication	review/comparison	review/comparison, metric	organizations	Yes (reused)	No	Yes (reused)	N/A	N/A	72 papers and 22 INAS approaches
[Matenzoglu 2022]	journal publication	method	method, tool, use-case	data	No	No	No	Terminological, Conceptual	low	

[Nagel & Lycklama, 2021]	project result (white paper)	recommendations/ principles		data	yes (defined)	yes (yes)	yes (defined)	N/A	N/A	
[Noura et al., 2018]	journal publication	metric	principles, review	things, software, data, ontologies	yes (kind of - descriptions) (defined)	yes (kind of)	yes (defined)	syntactic, conceptual, terminological	N/A	15 IoT interoperability platforms
[Ouksel & Sheth, 1999]	journal publication	metric	review	data	yes	yes (kind of)	yes (defined)	syntactic, conceptual, but the actual focus is on semiotic, though it is implicit	low	3 initiatives, 5 approaches to semantic interoperability, 2 approaches to representing information correlation, 9 papers in the issue the paper is an introduction to
[Panetto, 2007]	journal publication	review/comparison	use-case	Organisations, Software, data	Yes, Reuse	No	Yes, Reused	all	N/A	
[Parent 2000]	other (book chapter)	method	metric	data	no	no	no	conceptual, syntactic (implicitly)	N/A	
[RDA 2020]	technical report	recommendation/principles	metric (See "indicators")	data	no	yes (no)	No	N/A	N/A	
[Rezaei 2014]	journal paper	review/comparison	recommendation/ principles, metric	software, data, things, humans, organizations	yes (reused)	no	yes (reused)	syntactic	N/A	
[Szejka 2018]	journal publication	review/comparison		data	no	no	no	conceptual	N/A	14 references (selected, primary studies)
[Vatant 2012]	other (blog entry)	metric	recommendations	data	no	no	no	terminological, conceptual (indirectly)	N/A	

Table 13 – List of tagged references

B. Appendix: List of specific components

In this section we list few specific languages and software tools addressing some of the requirements listed in Sec. 5. They were mentioned in the scenarios, discussions or in the analyzed literature. Please note the table includes components at **various levels of maturity** (from research results to well-developed and widely used tools) and is **by no means exhaustive.** For a thorough landscape analysis of tool in ontology engineering, we point the reader to OntoCommons D4.3 "Report on Landscape Analysis of Ontology Engineering Tools". Here we mention additional components / assets, with a special focus on interoperability. So, for example, for CASPAR, GraphDB, LinkML, RDFlib, SimPhoNY, OTTR templates, we point the reader to OntoCommons D4.3.

Tool / asset short name or acronym	Type [software, semantic artefact (ontology, vocabulary, ...), format, language]	Tool/asset extended name	URL to web page / home page	Brief description
DCAT	Semantic artefact	Data Catalog Vocabulary	[URL][66]	"DCAT is an RDF vocabulary designed to facilitate interoperability between data catalogs published on the Web."
DLite	Software		[URL][67]	A lightweight data-centric framework for semantic interoperability
DQV	Semantic artefact	Data Quality Vocabulary	[URL][68]	"This document provides a framework in which the quality of a dataset can be described, whether by the dataset publisher or by a broader community of users."
ebXML	(Standard) Language	Electronic Business Extensible Markup Language (ebXML)	[URL][69]	"a methodology for developing a common set of semantic building blocks that represent general

66 https://www.w3.org/TR/vocab-dcat-2/
67 https://sintef.github.io/dlite/
68 https://www.w3.org/TR/vocab-dqv/
69 https://www.iso.org/standard/61433.html

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				types of business data, and provides for the creation of new business vocabularies and restructuring of existing business vocabularies.
EDOAL	Language, format, software	Expressive and Declarative Ontology Alignment Language	[URL][70]	"The Expressive and Declarative Ontology Alignment Language (EDOAL) allows for representing correspondences between the entities of different ontologies."
EMMOntoPy	Software		[URL][71]	Library for representing and working with ontologies in Python.
LOOM	Software	Lexical OWL Ontology Matcher	[URL][72]	"Lexical OWL Ontology Matcher (LOOM) is a freely available tool for ontology alignment. LOOM takes two ontologies represented in OWL and produces pairs of related concepts from the ontologies."
OTEAPI	Software	Open Translation Environment (OTE) API Core	[URL][73]	Framework for accessing data resources, mapping data models, describing the data to ontologies and perform data transformations
RML	Language	RDF Mapping Language	[URL][74]	"A mapping language defined to express customized mapping rules from heterogeneous data structures and serializations to the RDF data model." Superset of R2RML.
R2RML	Language	RDB to RDF Mapping Language	[URL][75]	"A language for expressing customized mappings from relational databases to RDF datasets."

[70] https://moex.gitlabpages.inria.fr/alignapi/edoal.html
[71] https://emmo-repo.github.io/EMMOntoPy/
[72] https://www.bioontology.org/wiki/LOOM
[73] https://pypi.org/project/oteapi-core/
[74] https://rml.io/specs/rml/
[75] https://www.w3.org/TR/r2rml/

SHACL	Language	Shapes Constraint Language	[URL][76]	A language for validating RDF graphs against a set of conditions.
Tripper	Software		[URL][77]	Triplestore wrapper for Python providing a simple and consistent interface to a range of triplestore backends
WASA	Language	Web API Annotation with Schema.org Actions	[URL][78]	"A specification for schema.org actions for annotating Web APIs."

Table 14 – List of example specific components to address interoperability

[76] https://www.w3.org/TR/shacl/
[77] https://pypi.org/project/tripper/
[78] http://wasa.cc/#/

C. Appendix: Selected input from OC events

In this Appendix we provide the full list of questions asked in the 15th June 2023 Mentimeter presentation (within OntoCommons 2nd Global Workshop in Oslo) and the answers to selected ones.

In the next table (Table 15) we report the questions asked, for which all results are available on the event website

(https://www.ontocommons.eu/sites/default/files/2023-09/OntoCommons%20Olso%20HW%20RoDI%20Session_With_Results-compressed.pdf).

#	Question	Possible answers
1	In which role are you here today?	• Ontologist • Database expert • Application developer • End user • Business developer • Other
2	Where does your institute/company sit on this map?	Pin to be located on a square, with axes: "Company size", "Percentage of public funding"
3	What are the main application domains of your company/institution?	(Up to three open answers)
4	How is materials & manufacturing data at your institution today?	• Open data • Linked data • FAIR data • Semantically enriched (i.e., rich metadata) • Human readable and human friendly • Machine readable • Data stewardship is in place
5	In your institute/company, semantic technologies …	• are heavily used • start to be used • are not used at all yet
6	What type(s) of heterogeneity do you mainly address? (Via use cases or solutions)	• Syntactic (different form) • Terminological (different names for the same entities) • Conceptual or semantic (different modeling of same domain)

		• Semiotic or pragmatic (different interpretations by different people) • All of the previous
7	What kind(s) of systems do you make more interoperable?	• Datasets • Databases • Software • Things • Humans • Communities • Ontologies • Other
8	How important are these "dimensions" when assessing interoperability solutions (i.e., methods and tools)?	• Logical expressivity • Precision of agreement • Computational complexity • Ease of integration with legacy tools/workflows • Use of standards
9	What OTHER "dimensions" are important when assessing interoperability solutions?	(Open answer)
10	What technical components (i.e., building blocks) are most crucial for interoperability?	• Crosswalks • Data models and formats • Data exchange APIs • Data provenance and traceability • Format converters • Mappings • Ontologies • Standards (including languages)
11	What OTHER technical components are also crucial for interoperability?	(Open answer)
12	What metrics or tools do you use to assess/quantify data interoperability and maturity?	(Open answer)
13	What interoperability principles/recommendations would you point out? (E.g., literature, initiatives, ...)	(Open answer)
14	How to facilitate cross-domain interoperability?	(Open answer)

15	What is your opinion on these statements about ontologies and standards (ISO-like)?	• We should ontologize standards • We should standardize ontologies • Standards and ontologies are different solutions, no need/benefit in merging these approaches
16	What role can large language models have for interoperability today?	• AI can replace ontologists • AI can help to acquire knowledge • AI can help to create lists of terms • AI can help in creating taxonomies • AI can help in identifying relationships between terms
17	How to best combine large language models with semantics?	(Open answer)
18	Is there any interoperability major aspect we missed?	(Open answer)

Table 15 – Questions asked in the 15th June 2023 Mentimeter session, OntoCommons 2nd Global Workshop

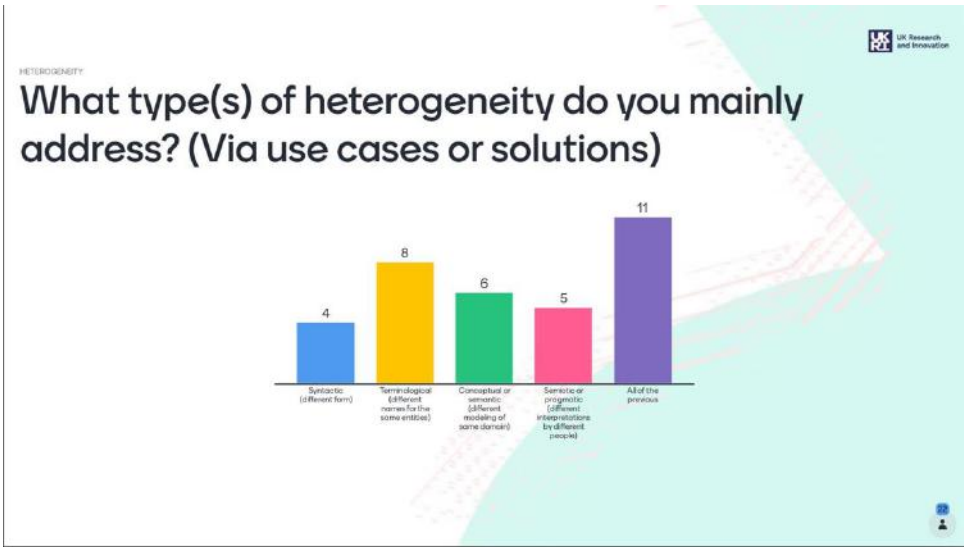

Figure 2 - Answers to Mentimeter question 6 - MQ6

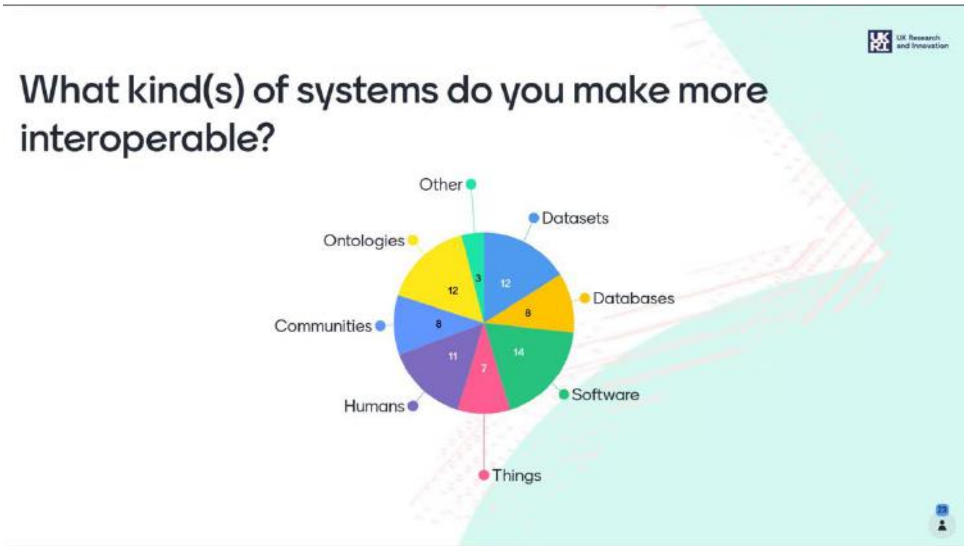

Figure 3 - Answers to Mentimeter question 7 - MQ7

Answers to Mentimeter Q9: "What OTHER "dimensions" are important when assessing interoperability solutions?"	
#	**Answer text**
1	automatic tools
2	Availability of good tooling
3	Availability of multiple trained experts in using the approach
4	Conformance to a single top-level ontology which already has widespread adoption in multiple domains
5	cost and time especially associated with change, scalability, adaptability
6	Ease of uptake. Measure how many make use of the interoperability solution after a certain maturity has been reached. And how many can make use of it without extensive help from the developers.
7	Ease of use
8	Easy extendibility to new domains
9	Generality, scalability
10	Guidance for application developers
11	High quality documentation
12	How fast can the humans collaborating finish the solution?
13	How intuitive the available tooling is.
14	it is important that interoperability standards are FINAL and not changing all the time in the background
15	Maintainability
16	Make it EASY!
17	Mutual understanding
18	parsimony
19	precision

20	Simplicity
21	simplicity
22	simplicity
23	Solid, respected, powerful governance, based on severe punishment of nonsense
24	Solid respected powerful governance
25	Tool
26	Tools and skills
27	User base; High-quality documentation; Active community
28	user friendliness in tooling

Table 16 – Answers to Mentimeter question 9 - MQ9

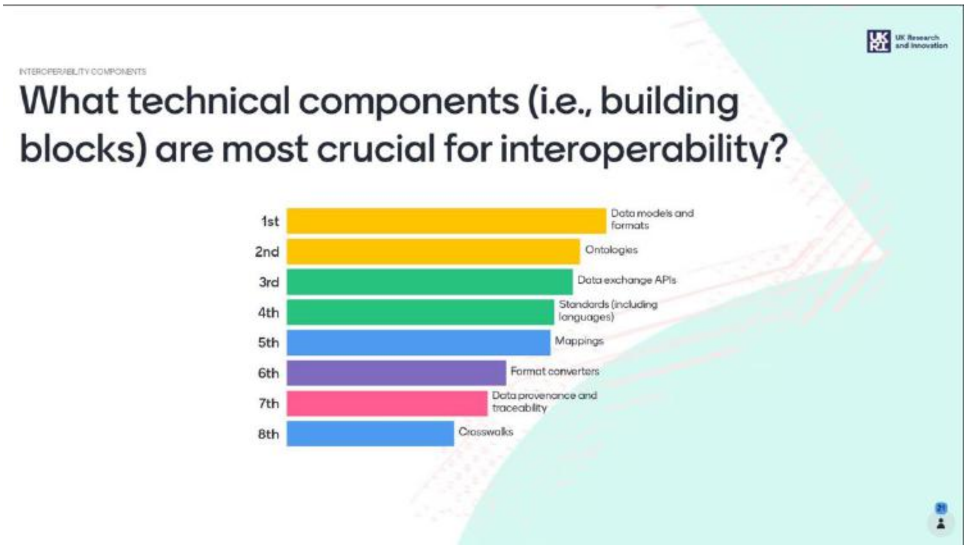

Figure 4 - Answers to Mentimeter question 10 - MQ10

Answers to Mentimeter Q11: "What OTHER technical components are also crucial for interoperability?"	
#	**Answer text**
1	Commitment of participants
2	Commonly shared methodologies
3	Community accepted terminologies and taxonomies
4	Good documentation
5	Many. It is a complex issue.
6	meaningful data must be present
7	Simplicity
8	smart manufacturing readiness assessment, digitalization maturity model/assessment
9	Solutions that validate whether your provided data has been made interoperable or not.

10	structured data availability
11	taxonomies of the field
12	Tools
13	User friendly integration tool
14	Well defined architectures of concerned systems
15	Well developed GUIs for ontology extension, data model construction, mapping to ontologies.
16	willingness

Table 17 – Answers to Mentimeter question 11 - MQ11

Answers to Mentimeter Q12: "What metrics or tools do you use to assess/quantify data interoperability and maturity?"	
#	**Answer text**
1	adding new systems
2	BFO
3	end-user satisfaction
4	End-user's satisfaction
5	Fair metrics , FOOPS
6	Fair metrics, empirical results
7	IOF
8	Level of semantic annotations
9	None
10	none
11	not measuring this yet
12	Not measuring this yet
13	Number of users
14	Number of years of use
15	oops and foops
16	standardization
17	User satisfaction
18	We don't do such assessments.
19	Whether output is meaningful/usable

Table 18 – Answers to Mentimeter question 12 - MQ12

Answers to Mentimeter Q14: "How to facilitate cross-domain interoperability?"	
#	**Answer text**
1	Adopting standards
2	Adopting top ontologies
3	Being part of eco-systems
4	Bring stakeholders together
5	Building communities

6	Common standards
7	Communication
8	Cooperative / co-creation communities
9	cross domain like cross industry is very difficult. I think that this would be more need base, i.e., only the parts that need to be interoperable need to be brought together and mapped.
10	cross-domain interoperability is created when there are cross-domain projects with concrete work to be done
11	Data documentation
12	Develop system-thinking
13	document your work
14	Ecosystems/networks of ontologies.
15	Flexibility - standardise on the interfaces
16	Good ontologies
17	Ontological alignment
18	Rigorous systems that can help find out which parts of various ontologies are compatible
19	Shared top level ontology and modelling patterns
20	Show the (commercial) benefits of adopting a cross-domain ontology (or any ontology for that matter...)
21	Standardize applicability of ontologies
22	Top level ontology
23	Use existing ontologies
24	Use foundational ontology
25	Use structured vocabularies and ontologies
26	Using common ontology

Table 19 – Answers to Mentimeter question 14 - MQ14

D. Appendix: List of interoperability types

As mentioned in Sec 3.2, below we list all the prefixes for interoperability that we identified:

- Behavioural - see [ISO 19941:2017], [IEC 2019], [Nagel & Lycklama, 2021]
- Cloud – see [Koussouris et al., 2011]
- Conceptual – see [Euzenat & Shvaiko, 2013] [Gupta et al., 2022]
- Constructive – see [Gürdür & Asplund, 2018]
- Cultural – see [Koussouris et al., 2011]
- Data – see [Koussouris et al., 2011] [ISO 19941:2017] [Gürdür & Asplund, 2018] [Andročec et al., 2018] [IEC 2019] [Nagel & Lycklama, 2021]
- Dyacronic - see [Panetto, 2007]
- Ecosystems – see [Koussouris et al., 2011]
- Electronic Identity – see [Koussouris et al., 2011]
- Encoding - see [Euzenat, 2001]
- Enterprise – see [Asuncion & van Sinderen, 2010] [Gürdür & Asplund, 2018]
- Functional – see [Gürdür & Asplund, 2018]
- Human – see [EMMC-CSA 2019]
- Information – see [Gürdür & Asplund, 2018]
- Knowledge – see [Koussouris et al., 2011]
- Legal - see [EIF 2017] [DSSC SK 2022]
- Lexical - see [Euzenat, 2001]
- Network – see [Koussouris et al., 2011] [Andročec et al., 2018] [Noura et al., 2018]
- Numerical – see [EMMC-CSA 2019]
- Object – see [Koussouris et al., 2011]
- Operational – see [Gürdür & Asplund, 2018]
- Organizational - see [EIF 2017] [DSSC SK 2022]
- Platform – see [Panetto, 2007] [Noura et al., 2018]
- Policy - see [ISO 19941:2017], [IEC 2019], [Nagel & Lycklama, 2021]
- Pragmatic – see [Asuncion & van Sinderen, 2010] [Euzenat & Shvaiko, 2013] [Janssen et al., 2014] [Gupta et al., 2022]
- Process – see [Asuncion & van Sinderen, 2010] [Koussouris et al., 2011] [Gürdür & Asplund, 2018]
- Programmatic – see [Gürdür & Asplund, 2018]
- Rules - [Koussouris et al., 2011]
- Semantic – see [Ouksel & Sheth, 1999] [Euzenat, 2001] [Panetto, 2007] [Asuncion & van Sinderen, 2010] [Euzenat & Shvaiko, 2013] [Janssen et al., 2014] [EIF 2017] [ISO 19941:2017] [Noura et al., 2018] [EMMC-CSA 2019] [IEC 2019] [Nagel & Lycklama, 2021] [DSSC SK 2022] [Gupta et al., 2022]
- Semiotic - see [Euzenat, 2001] [Euzenat & Shvaiko, 2013]

- Service – see [Koussouris et al., 2011] [Andročec et al., 2018]
- Social – see [Koussouris et al., 2011]
- Software – see [Panetto, 2007] [Koussouris et al., 2011]
- Structure - see [Ouksel & Sheth, 1999]
- Synchronic – see [Panetto, 2007]
- Syntactic – see [Euzenat, 2001] [Asuncion & van Sinderen, 2010] [Euzenat & Shvaiko, 2013] [Janssen et al., 2014] [ISO 19941:2017] [Noura et al., 2018] [IEC 2019] [Gupta et al., 2022]
- System – see [Ouksel & Sheth, 1999] [Gürdür & Asplund, 2018] [Noura et al., 2018]
- Technical – see [Janssen et al., 2014] [EIF 2017] [Gürdür & Asplund, 2018] [DSSC SK 2022] [Gupta et al., 2022]
- Terminological – see [Euzenat & Shvaiko, 2013]
- Transport – see [ISO 19941:2017] [IEC 2019].

Caveat: Scope and purpose need to be taken in account when comparing the various flavours. The list only aims to show the variety of concerns and points of view that can arise. See also the comments /caveats already made about this list in Sec. 3.2.

E. Appendix: List of interoperability-related terms

Below we list a few terms that are closely related to interoperability:

- Alignment
- Compatibility
- Heterogeneity
- Integration
- Mappings
- Semantic conflict