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Review article

An analysis of interoperability in materials and manufacturing: Definitions, classifications, requirements, and recommendations

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ABSTRACT

In this paper, we analyze the interoperability landscape for materials and manufacturing in a broad sense and with a particular focus in the context of data. To set the stage and give an overview of the various facets of this topic, we collect and compare existing definitions and classifications of interoperability (its types, layers, levels) and summarize recommendations from various entities and communities. After this, we carry out an analysis on a set of interoperability scenarios, propose a broad structure of requirements for interoperability, and list some key components that can be used to meet these requirements, with a particular emphasis on the role of semantic technologies and knowledge representation. Finally, we highlight future challenges and suggest directions for best practices. Throughout the paper, we emphasize common points and differences in the landscape. Through this process, relevant dimensions are identified, and various tables are provided with useful syntheses and structured categorizations that can serve as a base for future theoretical work, as well as immediate practical guidance (e.g., for requirements gathering, literature navigation).

1. Introduction

In our rapidly transforming and globally interconnected society, where digitalization, data-driven tools and the Web have pervaded more and more aspects of our lives, *interoperability* is usually seen as a resource-saving characteristic (in terms of time and money), if not a necessity. The earliest uses of the term in the relevant technical sense date to the late 1960s and early 1970s, primarily in the military and computing sectors [1]. Over time, interoperability has become a staple in literature on digitalization and the Web, where it consolidated its status as a desirable, pivotal feature. On occasion, non-interoperable

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systems have been deliberately designed as a defense or protection mechanism (for instance, different rail gauges historically acted as barriers to invasion, and vendors often create proprietary formats or systems that can only be used with or within their own products). Such practices, however, are typically portrayed negatively. As with many terms carrying a positive connotation, “interoperability” has since been adopted by different authors and communities, with its meaning adapted to diverse contexts and stretched to accommodate specific perspectives and approaches. However, as a first approximation, most will agree that interoperability has to do with the capacity of two (or more) entities to usefully function together. Therefore, when one says that an artifact is “interoperable”, they implicitly mean it is “interoperable *with*” something else (often, with a certain reference framework). Indeed, each and every aspect concerning communicative exchanges, as well as cooperation and coordination based on interactions, has been investigated under the wide umbrella of “interoperability”, from message encoding and decoding to mechanisms ensuring that nodes in a network do not act on outdated information.

Naturally, such a broad notion invites specifications from scholars and practitioners dealing with a plurality of aspects. Typical distinctions that are encountered in the literature include syntactic *vs* semantic interoperability, and separation of concerns. The objects of interoperability might be data, software, databases (and data spaces), semantic artifacts, web-based platforms, devices, or even ourselves (i.e., researchers from different backgrounds). Likewise, a variety of *metrics* of interoperability have been proposed (e.g., within FAIRness evaluation tools, available for both data and ontologies), often focusing on specific aspects or use cases. While these measurements in themselves will vary a lot across tools, they can indicate what the directions for improvement are.

Interoperability is a requirement for many use cases and application scenarios, from the conversion of text documents between formats, to more serious applications, such as recognizing qualifications across countries and integrating data for (global) digital product passports (DPPs). DPPs are a topical interoperability example from the materials and manufacturing field, with wide industrial and societal implications [2]. They exemplify the interoperability challenges faced by the sector. A DPP integrates data from a diverse range of fields and sources, including the materials, their compositions, a range of properties, safety data, life cycle data, etc. However, at present the validity, proper meaning and hence interoperability of datasets is often not assured. At the same time, the DPPs themselves must be integrated into a range of systems, such as Enterprise Resource Planning Systems, hence interoperability of the software systems is required [3]. Today, achieving interoperability in a field as broad and complex as materials and manufacturing remains somewhat elusive, despite there being a wide range of relevant publications and recommendations, in particular the FAIR principles [4] that were published more than a decade ago. Achieving interoperability with respect to a specific aspect, and even more so across the board, is far from trivial: there are *barriers* to be overcome and various *solutions* have been proposed.

In this paper, we offer a broad overview of the topic with two main aims: first, to provide a snapshot of the diverse and often fragmented ways in which interoperability is actually understood across the materials and manufacturing domain, highlighting the facets that emerge as most prominent and that one may wish to consider; and second, to collect and distill a set of recommendations emerging both from the OntoCommons initiative (see details below) and from proactive engagement with the wider community and its core stakeholders. In doing so, we also identify a set of key concepts, classifications, requirements, technical components, relevant initiatives, and references, providing readers with the means to contextualize them within a broader perspective.

The literature on interoperability is vast and many reviews have been compiled previously (e.g., [5–15]). Most of these choose specific aspects to focus on, such as interoperability evaluations [5–8], a single interoperability type [9,10], or given applications, as the Internet of Things (IoT) [11,12] or product-related processes [13,14]. Exceptions giving relatively broad overviews are [5,15], where the first one contains extensive catalogs of definitions and types, and the second one draws connections to methods from adjacent disciplines. Here we adopt a broad perspective that brings together the diverse facets of interoperability considered salient across the materials and manufacturing ecosystem, including not only academic contributors but also practitioners, industrial actors, and other core stakeholders. Particular attention is devoted to aspects that are crucial for interpreting and understanding current debates, such as terminology. Given the attention to both theory and practice, our results can serve as a base for future theoretical work and also as immediate practical guidance. This work builds on a previous report [16] from the OntoCommons Horizon 2020 project, that has been substantially updated and extended here. OntoCommons was a Horizon 2020 Coordination and Support Action to foster the use of ontology-based data documentation in the materials and manufacturing fields, and its outcomes span various dimensions, including foundational theoretical results, industrial use cases, and landscape analyses (of tools, domain ontologies, etc.). Its effort in community building notably brought about the formation of the Knowledge Graph Alliance (KGA, cf. Section 3.4).

Fig. 1 illustrates a logical progression of our work. The methodology (Section 2) summarizes how we collected and organized input from a diverse set of sources, including scientific publications, technical reports, surveys, project outcomes and discussions emerging from community activities. This forms the basis for the state-of-the-art (Section 3), where we start with the terminology and examine definitions of interoperability (both in general (Section 3.1) and specifically for the semantic facet (Section 3.3)), as well as interoperability classifications from the literature (Section 3.2). Alongside these conceptual elements, we then move on to list relevant initiatives and organizations active in the materials and manufacturing domains (Section 3.4), and summarize a set of high-level recommendations emerging from previous works (Section 3.5). Next, the topic of interoperability assessment is briefly discussed in Section 3.6. The gathered conceptual elements are then applied to the analysis of a set of actual interoperability use cases (Section 4), from which recurring patterns and shared needs are identified. Building on these insights, we propose in Section 5 a structure of interoperability requirements in a broad sense, as well as various means of addressing them (Section 5.1). Since we focus on knowledge representation and ontologies as one major means to address interoperability, Section 6 gives an overview of solutions to represent and store data and knowledge. Finally, we highlight future challenges in Section 7 and conclude in Section 8.

To help the reader in navigating the literature, in Appendix A we give a list of tagged references and in Appendix B we provide a list of interoperability types and references addressing them. A brief glossary is also given in Appendix E.

2. Methodology

The work leading toward [16], on which the present paper builds upon, was structured into three interconnected working groups (WGs): WG1: “Terminology and classifications of interoperability”, WG2: “Technical components to support interoperability” and WG3: “Interoperability scenarios”. The main results from these WGs are presented in Sections 3 (3.1, 3.2 and 3.3), 5, and 4, respectively. WG1 provided initial sets of terms as inputs to WG2 and WG3 (which was used for tagging their resources), and WG3 provided input for the requirements in WG2.

Overall, the sources examined for this work included: documents (publications, formal texts and reports), input from project partners and participants at the OntoCommons events (in their presentations, or via

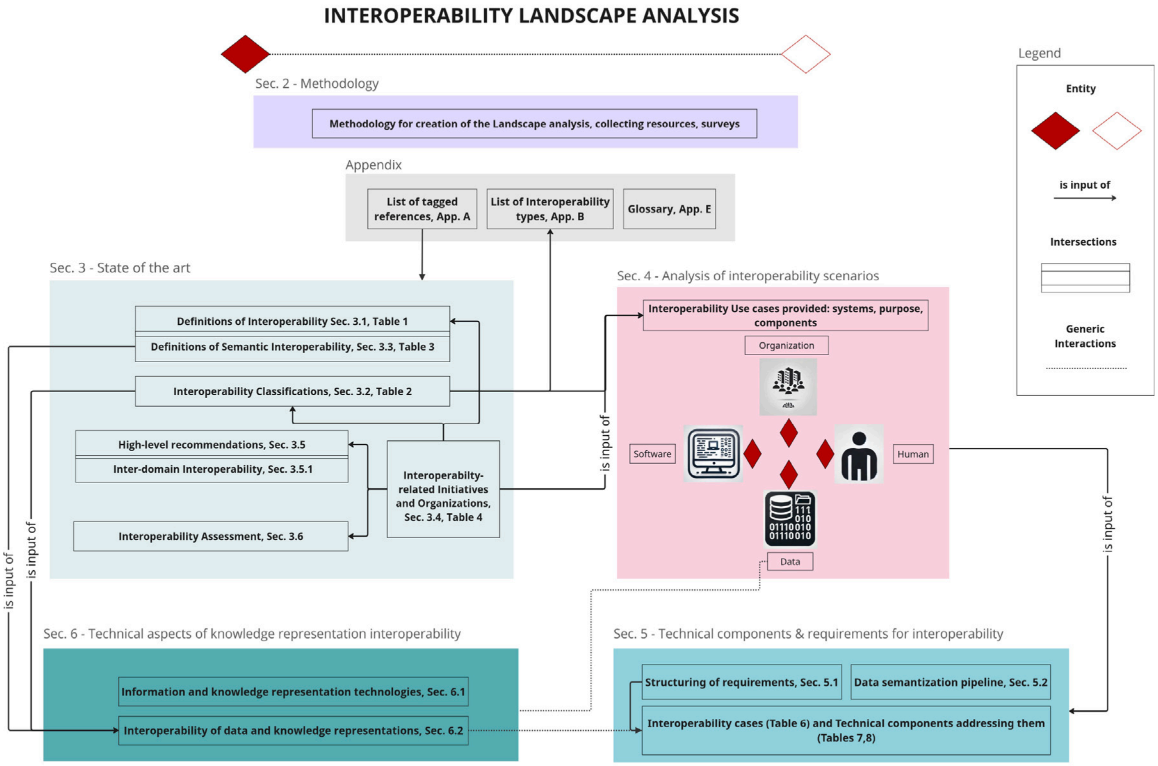

Fig. 1. Graphical overview of the central sections of the paper and connections between them. Each colored box represents a section (with subsections within), and solid arrows between boxes indicate that a (sub)section informs ("is input of") another, whereas dotted lines indicate a more generic interaction. Diamonds indicate entity (types): the four highlighted ones emerge from Section 4 and are used for the analysis in Section 5.

interactive sessions[2]), and project use cases. By design, some elements of the resulting landscape are more systematic, whilst others are more qualitative. The documents used for the terminological analysis and the associated set of tagged references were found through a combination of three complementary routes:

1. a systematic search on the Web of Science catalog for entries having "interoperab*" in the title. For the present manuscript, the search was run on 1 July 2024, and gave 7664 results from all database areas[3]; of these results, 156 were of the type "review", and of these, 29 had "systematic" in the title. To narrow down this set, we focused on these review papers and selected ones relevant for the scope of OntoCommons based on the resource's title and abstract.
2. questionnaires submitted in the course of the OntoCommons project and related events, both to partners and external participants,[4] integrated with resources pointed out informally by the latter;
3. where appropriate, secondary resources cited in the documents obtained through routes (1) and (2) (e.g., when tracing back the original source of a given definition or classification).

Routes (1) and (3) jointly ensure adequate coverage of the academic literature, with route (1) providing a systematic entry point and route (3) enabling us to trace influential secondary sources and original definitions/classifications. Route (2), together with contributions identified through route (3), complements this perspective by surfacing additional recent publications and non-scholarly resources considered salient by practitioners in the target domain. Taken together, these routes arguably offer a balanced and comprehensive overview, covering aspects related to how interoperability is understood, negotiated and approached in practice. Notably, the various initiatives and organizations listed in 3.4 were primarily identified *via* the second route. The overview presented in Section 3.5 collects the highlights from various documents and discussions, but does not attempt to cover all references exhaustively.

Each resource obtained through routes (1) to (3) was examined by two of the authors, who were responsible for tagging them and extracting definitions and classifications of interoperability. In case of discrepancies, the values were discussed until a consensus was reached. Also, a sample was cross-checked by different authors at the end of the process to ensure uniformity of evaluation. The tags were defined through an iterative procedure, in which the initial classification scheme was adjusted by adding, merging, and splitting categories in the classification process. In the tagging process, we identified (non-exclusive) priority criteria, such as: (a) focusing on materials and manufacturing; (b) focusing on the interoperability of *data*; (c) exploiting ontologies or other semantic technologies; (d) prioritizing the outputs of European initiatives; (e) highlighting methods appropriate to the domain level, both intra-domain and inter-domain; (f) prioritizing recent/active efforts; (g) prioritizing use cases from the OntoCommons

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[2] For example, at the OntoCommons 2nd Global Workshop in June 2023, 28 people participated in the interactive session on interoperability, with this breakdown of profiles: Ontologist (54%), End user (21%), Other (14%), Application developer (7%), Business developer (4%), Database expert (0%). Respondents belonged to institutes/companies of different sizes and with various amounts of public funding. Data based on answers to the question "In which role are you here today?" and "Where does your institute/company sit on this map?". Cf. Appendix C of [16] (page 66) for a full list of questions and a pointer to the results.

[3] The top four WoS research areas were: Computer Science (4422), Engineering (2619), Telecommunications (1005), and Medical Informatics (535).

[4] See Appendix C of [16] for more details.

project. These criteria served as a basis to refine our analysis for the purpose of this work.

Finally, the other main routes used to identify resources for the overall interoperability landscape (but not part of the terminological analysis and references tagging) included:

4. the requirements matrix, which served as guidance to identify further resources related to the technical components (cf. Section 5.1);
5. knowledge representation levels (cf. Section 6).

The methodology for the analysis of interoperability scenarios involving OntoCommons demonstrators is detailed in Section 4. Compared to [16], the results have been thoroughly updated and improved, with an added analysis of definitions of semantic interoperability (cf. Section 3.3) and a discussion of challenges (cf. Section 7). The overview of knowledge representation and related interoperability solutions has been generalized here, and made independent from the OntoCommons approach (cf. Section 6). Some other parts on OntoCommons deliverables and project specifics have been removed for brevity; we point the reader to [16] for more.

2.1. Scope and limitations

In brief, we mainly focus on interoperability at the information and knowledge level (as opposed to physical interoperability, cf. Section 3.1) in the context of materials and manufacturing.

In more detail, our methodological choices and the development of this work entail trade-offs that must be acknowledged in order to clarify the scope, generalizability, and relevance of our results. First, the inclusion of a plurality of heterogeneous sources – an opportunity afforded by the project's vantage point – precludes conducting a proper systematic review and partially limits reproducibility. Likewise, it impedes the application of sharp inclusion or comparison criteria.

Second, given the project's focus and aims, a degree of bias toward European activities and data/ontology-oriented approaches is to be expected. Similarly, the interactions considered here stem from a specific, well-defined set of use cases, partners, and demonstrators directly or indirectly associated with the project. Nonetheless, it should be noted that OntoCommons engaged a large and diverse group of actors across the materials and manufacturing field, including major industrial stakeholders, ontology communities belonging to different hubs, and standardization bodies both within *and beyond* Europe — with advisory roles held by non-EU participants. This breadth of participation, together with the project's duration, the variety of use cases examined (cf. Section 4) and the absence of evidence for strong synchronic geographical divergences in technological, academic, or industrial practices, provides strong grounds to regard the reported results as indicative of general tendencies in the field.

Concerning generality and representativity beyond materials and manufacturing, we note that often interoperability problems are found to be common across domains. Some concepts around interoperability can, in principle, be defined and discussed at a very general level (e.g., abstract definitions), whereas others necessarily require instantiation and contextualization to be meaningful (e.g., implementations, priorities, metrics, KPIs). That said, even the former often carry an implicit application perspective (cf. discussions in Section 3). With this caveat, we expect that the domain-agnostic parts of our findings will capture concerns that are relevant for other domains as well.

Finally, throughout the paper we occasionally report simple descriptive statistics, such as the proportion of entities exhibiting a given property (cf. Sections 3 and 4): we stress that such quantifications are provided solely for ease of presentation and to highlight broad trends; given the limited sample size and the rapidly evolving landscape, they are not intended for predictive purposes.

3. State of the art

3.1. Overview of existing definitions of interoperability

In this section, we collect distinct definitions of interoperability that we have identified from our literature analysis. They are given in Table 1, and ordered by year published.

Note that here we have restricted the list to interoperability itself, without further specifiers (e.g., not "syntactic interoperability"),[5] however, the following two sections will address interoperability types and the specific facet of semantic interoperability. While the list in Table 1 cannot be complete (the literature is vast, and secondary sources such as reviews have not been expanded to include all of their individual primary sources), we are confident that it covers the major authoritative definitions and gives a reasonable overview of others that have been proposed.

Most of the collected definitions agree that interoperability is an "ability" or a "capability" (with only two outliers defining it as a "process" [29] or a "paradigm" [21]). The *subjects* involved in the definitions include "(ICT) systems", "functional units", "devices", "applications", (computerised) "products", "datasets", "manufacturing software", (data processing) "services", "data spaces" and "organizations". The variety of terms exemplifies a tendency to produce definitions which are in fact context and problem/goal specific, rather than fully general. As regards *counting* of the subjects, we see that they are "two or more", and plural forms are used. Also, we note that in multiple cases it is pointed out that the subjects are "different"/"of different types" [10,19,28,29], and in one case, that they are "from non-cooperating resources" [4].[6] We underline here that "different" can relate to type or tokens, but also more importantly hint at separation, i.e., at the fact the two entities retain some independence from each other. Focusing on the *predicates*, we find that "exchange" and "communicate" are prominent, but are mostly accompanied or terminated by an action, like "use", "work", "interact", or "execute". Indeed, the first aspect is often explicitly characterized as being ancillary to the second one. The *objects* involved in the core of the definitions are "information", "data", "knowledge", and "programs". We note in passing that the focus on action and on the plural nature of the subjects are in line with the etymology of "interoperability" (cf. EMMC's definition in Table 1 [27]).

Various adverbs or adverbial clauses are used to underline a deep collaboration: "(work) together effectively", "in a useful and meaningful (manner)", "(process) collaboratively or cooperatively", "(work) in conjunction", and, "without restriction". Other specifications refer to or imply a lack of ad-hoc exchange protocols: ["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"]. Finally, a number of references underline the desired *smoothness* of interoperability: with minimal or without "effort", and "seamless".

Focusing on the subset of definitions that belong to formal texts from standardization or legislation bodies (Ref. [17] by IEEE, [20,23,24] by ISO, and [30] from European law), we notice that ISO 19941 [24] and the Data Act [30] essentially expand on the IEEE definition [17] ("exchange and use" as core, with "systems" as subjects),

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[5] Strictly speaking, the list does not contain *quality specifiers*; however, some of the entries explicitly contain an *entity specifier* (namely: manufacturing software interoperability [20], data level interoperability [22], and data space interoperability [32]).

[6] Incidentally, this implies that what some authors see as *trivially* interoperable, others do not consider interoperable at all. For a logically sound definition of interoperability, we recommend taking care of the trivial limiting cases (e.g., is a system interoperable with itself, are systems of the same type interoperable). As well as reflexivity, symmetry is also a point that needs clarification (e.g., if interoperability is restricted to entities of the same nature or not, and if it is a symmetric property).

Table 1
List of interoperability definitions (ordered by year). For a detailed analysis of the common points and differences between the definitions, see Section 3.1. Note: for readability both here and in similar tables, we use an additional identifier for references alongside the bibliographic citation number, namely "[< First Author > < Publication Year >]".

Source ID	Definition of interoperability
[IEEE 1990] [17]	"Ability of systems to exchange information and use the information that has been exchanged".
[EIF-eu 2004] [18]	"Interoperability means the ability of information and communication technology (ICT) systems and of the business processes they support to exchange data and to enable the sharing of information and knowledge".
[Panetto 2007] [19]	"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] [20]	"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".
[Naudet 2010] [21]	"An interoperability problem appears when two or more incompatible systems are put in relation. Interoperability *per se* is the paradigm where an interoperability problem occurs".
[Janssen 2014] [22]	"At the data level [...] interoperability is the ability of two or more datasets to be linked, combined, and processed".
[ISO 2382:2015] [23]	"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] [4]	"Ability of data or tools from non-cooperating resources to integrate or work together with minimal effort".
[ISO 19941:2017] [24]	"Ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged".
[EIF-eu 2017] [25]	"[For the purpose of the EIF,] interoperability is the ability of organisations to interact toward mutually beneficial goals, involving the sharing of 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] [26]	"Capability of two or more functional units to process data collaboratively or cooperatively".
[EMMC-CSA 2019] [27]	"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".
[Nagel 2021] [28]	"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".
[Gupta 2022] [29]	"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".
[Data Act 2023] [30]	"'Interoperability' means the ability of two or more data spaces or communication networks, systems, connected products, applications, data processing services or components to exchange and use data in order to perform their functions".
[Diraco 2023] [31]	"Interoperability [...] refers to the ability of different systems or components to work together in a coordinated manner, exchanging and utilizing information seamlessly".
[Ali 2024] [10]	"Interoperability [...] refers to the fundamental ability of different computerised products or systems to connect and exchange information without restriction, either in terms of implementation or access".
[DSSC 2024] [32][a]	"Data space interoperability: The ability of participants to seamlessly exchange and use data within a data space or between two or more data spaces".

[a] For recent versions of the DSSC Starter Kit, as v1.5 [33], the glossary is on a website [32].

to which they add the counting specification ("two or more"). On the other side, ISO 16100-1 [20] and ISO 2382 [23] explicitly address the modality of communication/exchange. We note that, while probably implying it, none of the definitions in this subset mentions explicitly the correctness of the exchange (cf. discussion on this point in Section 3.3).

In analyzing the definitions presented in the table, it is evident that the concept of interoperability encompasses both physical systems or assets and purely informational entities, with a stronger emphasis on the latter. While the overarching objective remains similar, the nature of interoperability concerns differs significantly between the two. For instance, the compatibility of various USB port types, the customization of screwdrivers for different screw head designs, and the ability of radios to communicate in compatible frequencies and signaling are all fundamentally determined by the construction and geometric configuration of these systems (physical interoperability). In contrast, interoperability in the realm of information is largely governed by aspects such as syntax, structure, and semantics. In the following sections, we will primarily focus on the interoperability of information objects. Of course, such information objects might be and typically are associated with physical ones: this includes models that describe system architecture and behavior, manufacturing protocols and production plans, as well as device, product, or asset specifications. Ensuring interoperability among these information entities is essential for enabling both human and software systems to accurately reference and interact with physical systems based on a shared understanding of reality.

Negative definitions can also help in better clarifying a concept. To narrow down what interoperability *is not*, we point to the discussions in [21,34,35] where it is contrasted with "integration" (general *vs* ad hoc, loose *vs* tight coupling), in [27] where it is contrasted with "compatibility" (semantic *vs* syntactic, common framework *vs* one-to-one connections), in [24] where it is separated from "portability" (the latter begin characterized by the ease of the process), and finally in [36], where it appears as one of the possible "compatibility levels".[7]

We close this section by mentioning two examples that we found of *ontologies of interoperability*, where formal axiomatizations are given both in general [21] and for software [37]. Beside being terminological assets, these can be considered as technical components as well.

Gaps, key differences between definitions and notes on their consequences

We have analyzed the collected definitions along multiple dimensions: subjects (including their counts), predicates, objects, depth of collaboration, lack of ad hoc protocols, smoothness and correctness.

A general issue we identify is the informal nature of definitions. With few exceptions,[8] the definitions are not accompanied by complete

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[7] The compatibility levels in [36] are: Coexistence, Interconnectability, Interworkability, Interoperability, Interchangeability.

[8] By asking whether sources are self-contained with respect to terminology, that is, whether they define all key terms that appear in their definition of interoperability, we find the following: ISO 2382:2015 [23] is completely self-contained; other sources address the necessary lexicon partially [17,20,21,26,30,32]. Of these, assets from IEC/ISO/IEEE are often complemented by definitions in their respective references or by other resources given by these organizations (as the IEC electropedia https://www.electropedia.org/).

vocabularies/glossaries where each key term they contain is clarified: as a consequence, there is often room for different interpretations and robust comparisons are necessarily hindered.

By focusing on the core concepts and relations, we find that several abstract but consequential issues are not explicitly addressed by most of the analyzed definitions: (1) symmetry in the nature of the subjects (i.e., is it restricted to subjects of the same nature, as software-software, or not?); (2) its directionality/symmetry at the relational level (e.g., is the interaction directional or not? does "X interoperates with Y", entail that "Y interoperates with X"?); (3) usefulness/correctness of the result (e.g., if X and Y by interoperating give: (i) some result, (ii) a meaningful/useful result, (iii) *the* correct result).

Different valid stances can be taken for each point. While these concerns might seem abstract, they do have practical implications: (1) relates to scope and generality, applicability of the definition; (2) relates to the (or lack of, or bi-) directionality of the relation; and (3) relates to the success criteria and is a base for interoperability assessment.

The only exceptions in Table 1 that are explicit about any of these points are: ISO 19941-2017 [24] on the second point ("mutually use"); [19] ("in a useful and meaningful manner") and [29] ("accurately", "correct") for the third point. For the others, from the wording of the definitions, we can assume that in most cases symmetry is assumed to be in place for both (1) and (2), there is lack of directionality, and for (3) it is implicitly assumed that the result is at least meaningful, if not correct.

In Appendix E, as part of the provided glossary, we give an operational definition of "interoperability" for the purposes of this paper, explicitly touching on these three gray areas. A point in which we divert from the main trends just summarized is that we explicitly allow the interoperating subjects to be of different nature (e.g., human and software).

3.2. Overview of existing classifications of interoperability

In general, interoperability means that different "entities" can usefully function together, in different "ways". Depending on what these entities are and how they interact, one can identify different types (or levels, layers, aspects, categories, facets, flavors) of interoperability. Table 2 lists interoperability classifications found in the literature, ordered by the year published and tagged with respect to relevant dimensions.

Various common scenarios are found depending on the *relation between the various facets within a given classification*: they can be all mutually disjoint or might overlap; they can be ordered or not; and especially for ordered ones, some facets might be necessary for later ones to be realized. We can name these dimensions as *disjointness*, *ordering* and *necessity* (a prerequisite-like character) of the facets.[9] Also, in some references, the focus is on the *variation of the subject* (e.g., [11]), in others the focus is instead on the *quality* of interoperability (e.g., [39]), and then some others combine the two. Finally, the fact that a certain term is used by multiple authors does not necessarily imply that they all agree on its meaning.[10] With these three caveats in mind, we record in Appendix B all the prefixes for interoperability found in Table 2, plus an additional one from the literature (cognitive), yielding a total of 65 types.

We note that two references appearing in Table 2 do not provide "interoperability classifications" strictly speaking, but rather describe related classifications which we nevertheless find it useful to include here. In fact, Ref. [40] gives types of interoperability "concerns", "barriers" and "approaches", while [42] gives "heterogeneity" types.

In the last column of Table 2 we tag each classification based on whether the facets entail a subject variation (Sv) or a quality variation (Qv), as well as their disjointness (D) and hierarchical (H) nature. We see that quality variation is the most common, followed by mixed ones (simultaneous quality and subject variation), and half of the overall entries display a hierarchical ordering of the facets. We note that hierarchies are mainly present for the quality variation case, and most of these classifications comprise "syntactic" and "semantic" facets; an exception is represented by the EIF-eu (Refs. [18,25]), that has "technical" and "semantic" facets instead. Focusing on the "syntactic" and "technical" facets, while from the previous observation they might seem to be interchangeable, we find that in a few cases they are simultaneously present, i.e., next to each other, namely in Refs. [22,29,33]). In all these (hierarchical) classifications, technical interoperability appears at a lower level than the syntactic one. Of the subjects, those appearing in at least three classifications are: "data", by far the most common, followed by "business", "service", "system", "policy" and "process". Similarly for the qualities, in order of frequency, they are: "semantic", "syntactic", "technical", "pragmatic", followed by "behavioural", "conceptual", "organizational" (cf. Appendix B).

Focusing on the two classifications that belong to formal texts from standardization bodies (namely, Ref. [40], which is re-used by ISO 11354-1 [44], and ISO 19941 [24]), we notice that there is no common facet (except, partially, "data"). Of course some common underlying ideas are there, but, while it is possible to attempt a mapping between the two,[11] such a mapping would be a very loose one.

Among the various types of interoperability identified in Appendix B, particular emphasis is placed on those concerned with how information is represented through language, both natural and formal. These include, among others, data, conceptual, semantic, and syntactic interoperability. The prominence of this focus can be attributed to the fundamental role of language in facilitating information exchange, as well as enabling computational processes to meet the demands of practical applications. Since in this way, interoperability is realized when the information content is used in practice, it is natural that to syntactic and semantic interoperability, pragmatic interoperability is sometimes added as a pillar of equal importance [9,46] – with the differentiation of "semiotic" into syntax, semantics, and pragmatics going back to Morris [45]. This idea, however, has struggled to take off effectively, mainly because pragmatics as a field of linguistics is itself less standardized and unified than syntax and semantics.[12]

In contrast, interoperability between complex systems (ranging from individuals to collective entities such as businesses, communities, societies, and governments) encompasses additional dimensions, including software, applications, technical, organizational, cultural, behavioral, policy, and process interoperability. Although these higher-order interoperability concerns arise from intricate socio-cultural and evolutionary influences on collective perspectives, they remain ultimately dependent on the interoperability of information at the linguistic level. The way in which information is structured – through diverse formats,

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[9] As an example of necessity, from Euzenat in [39] "each level cannot be achieved if the previous ones have not been completed". The types given by Panetto in Fig. 1 of [19] are pairwise alternatives, and this can be seen a partial example of disjointness (e.g., synchronic/diachronic and vertical/horizontal dimensions are definitely orthogonal to each other).

[10] For example: "semantic" and "conceptual" are synonyms in [42], whereas they are distinct facets in [29].

[11] For example, the "cloud, transport and syntactic" interoperability terms in ISO 19941 could relate to the "technological" barrier in ISO 11354, "semantic" to "conceptual", and "policy" to "organizational". The "behavioural" facet in ISO 19941, that focuses on the correctness of the exchange, could be seen as overlapping with the "process" concern of ISO 11354.

[12] To describe syntax, most can agree on using a variant of Chomskyan generative grammar, such as Backus–Naur form; the different ways of specifying semantics can be represented in propositional logic. Pragmatics, however, is split into the directions established by Grice and Searle, and more importantly, there is no obvious first choice for how to write up something about pragmatics that would be common knowledge and practice among computational scientists and engineers.

Table 2

List of interoperability classifications (ordered by year). We tag each entry based on: whether the facets within each classification entail *subject variation* (Sv) and/or *quality variation* (Qv); *disjointness* of the facets (D) and their *hierarchical* (H) ordering are also pointed out. When the ordering is increasing (decreasing), e.g., in complexity or abstraction, we use H^+ (H^-). For more details and highlights of common points and differences, see Section 3.2.

Source ID	Classification of interoperability	Tags
[Ouksel 1999] [38]	"Levels of interoperability – system, syntax, structure, and semantic".	Qv, H^+
[Euzenat 2001] [39]	"Levels of interoperability": "encoding", "lexical", "syntactic", "semantic", "semiotic".	Qv, H^+
[Chen 2003] [34]	Layers: "Business", "Knowledge", "Application", "Data", "Communication" (cf. Fig. 4 of reference).[a]	Sv, H^-
[EIF-eu 2004] [18]	"Three aspects of interoperability": "organisational", "semantic", "technical".	Qv, H^-
[Ford 2007] [5]	"Most (if not all) types of interoperability can be classified as either technical or non-technical".[b]	Qv, D
[Panetto 2007] [19]	"Horizontal interoperability", "Vertical interoperability", "Synchronic interoperability", "Diachronic interoperability", "Model-driven interoperability", "Semantic-driven interoperability" (cf. Fig. 1 of reference).	Qv, D (pairwise)
[Guédria 2009] [40]	"Interoperability concerns": "data, service, process, business"; "Interoperability barriers": "conceptual, technological, and organizational"; "Interoperability approaches": "integrated, unified, and federated".[c]	Sv (conc.), Qv (barr. & Appr.)
[Asuncion 2010] [9]	"Three layers: syntactic, semantic, and pragmatic".[d]	Qv, H^+
[Koussouris 2011] [41]	"Enterprise 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".	Sv, H^+ (by groups)[e]
[Euzenat 2013](*) [42]	"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]" (cf. also Appendix E).	Qv, H^+
[Janssen 2014] [22]	"interoperability [, which is commonly seen as occurring at four levels]: "Technical interoperability", "syntactic interoperability", "semantic interoperability", "pragmatic interoperability".	Qv, H^+
[EIF-eu 2017] [25]	"Four layers of interoperability: legal, organisational, semantic and technical".	Qv, H^-
[ISO 19941:2017] [24]	Interoperability terms: "cloud interoperability", "transport interoperability" (intended as communication infrastructure), "syntactic interoperability", "semantic data interoperability", "behavioural interoperability", "policy interoperability".	Sv, Qv
[Gürdür 2018] [7]	Interoperability types: "System interoperability", "Technical interoperability", "Enterprise interoperability", "Functional interoperability", "Programmatic interoperability", "Operational interoperability", "Process interoperability", "Information interoperability", "Data interoperability", "Constructive interoperability".	Sv, Qv
[Andročec 2018] [11]	Interoperability level: "Data", "service", "network", "application" (see Fig. 4 of reference).	Sv
[Noura 2018] [43]	"[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".	Sv, Qv, H^+
[EMMC-CSA 2019] [27]	Five levels of semantic interoperability, ordered by abstraction, are identified: "scientific community level", "(materials) user case level", "materials characterization level", "materials modelling level" and "numerical level".	Sv, H^-
[IEC 2019] [26]	Aspects: "Syntactic", "Semantic data", "Transport" (intended as communication), "Behavioural" and "Policy" (see Fig. 1-3 of reference).	Sv, Qv
[Nagel 2021] [28]	"[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".	Qv
[Gupta 2022] [29]	Levels: ["No Interoperability",] "Technical Interoperability", "Syntactic Interoperability", "Semantic Interoperability", "Pragmatic Interoperability", "Dynamic Interoperability", "Conceptual Interoperability".	Qv, H^+
[Diraco 2023] [31]	"Four levels of interoperability emerge from the analysis of the recent literature: (1) device and protocol interoperability, (2) data format interoperability, (3) semantic interoperability, and (4) interoperability in machine learning algorithms".	Sv, Qv
[García 2024] [33]	"In the context of data spaces [. . .] three distinct levels: data interoperability, intra-data space interoperability, and cross-data space interoperability." With aspects: technical, syntactic, semantic, organisational, legal, and business. (Note: the last three only apply to data spaces, not to data).	Sv, Qv, H^+ (two sets)

[a] Part of the IDEAS interoperability framework. The requirements from the IDEAS project expert group were [34]: "inter-enterprise coordination, business process integration, semantic application integration, syntactical application integration, and physical integration".

[b] Also, in the appendix of [5], 64 interoperability types from the literature are listed.

[c] This is part of the Enterprise Interoperability Framework. We call it EIF-ent (to avoid confusion with the European Interoperability Framework, which we abbreviate EIF-eu). This classification is also part of ISO 11354-1 [44].

[d] Naming syntax, semantics, and pragmatics as main branches of the formal theory of language is well established today; this was introduced by Morris [45], together with the term *pragmatics*.

[e] The facets belong to four levels of granularity: core elements (elements 1 to 6), some combination of those (7–10), cloud (11) and ecosystems (12) [41].

grammatical rules, and specialized vocabularies – underpins systemic interoperability at scale.

We can generally say that, in hierarchical classifications from the literature, the lower levels are, if not necessary, at least important for the following ones to build on. Also, typically, the lower ones are easier to achieve than the higher ones. Nevertheless, priorities and detailed requirements are scenario- and capability-dependent and cannot be stated in general: e.g., if one aims to address interoperability at the semantic level, they might ignore syntactic issues, as long as they can handle them and the message content is correctly passed.

Gaps, key differences between classifications and their consequences

The entries in Table 2 show multiple overlaps, at least at the level of labels. Almost all the sources accompany each given facet with an explanation or elucidation, sometimes in the form of examples. However such elucidations are of variable depth, clarity and rigor. Therefore, robust comparisons, mappings or integrations of classifications across sources are hindered.

An important information that should be given more explicitly is the relation between the facets belonging to a classification. In certain situations (e.g., in implementations) it would also be valuable to document the tolerance to errors at the (lower) interoperability levels upon which a given level depends. This tolerance to errors is a dimension that relates to the correctness aspect discussed in Section 3.1.

A fundamental distinction that is useful in our view, but not always adopted by the authors of classifications in Table 2, is that one between subject (what interoperates) and quality (how do they interoperate) variation: we will exploit it in the structuring proposed in Section 5. Disentangling these two dimensions can help to clarify and simplify the landscape.

3.3. *Overview of existing definitions of semantic interoperability*

Given the ubiquitousness and conceptual relevance of this specific type of interoperability, and also its close connection with the technologies we mostly focus on in this manuscript, we list in Table 3 a set of definitions of *semantic interoperability*, ordered by their year of publication. Most of the definitions were found using Table 2 in the previous section as a guidance to locate references.

Let us proceed with an analysis of the definitions. In line with what we found in Table 1, semantic interoperability is thought of as an "ability", "capability" or "faculty". Most of the definitions (except [22]) have *"meaning"* (of "data", "syntactic elements", "information", "concepts", "messages", "representations") at their core. While a thorough theoretical discussion on semantics (involving philosophy, linguistics, etc.) is beyond the scope of this paper, it is important to mention here that *meaning* and *semantics* themselves are far from univocally or unambiguously defined and understood. According to some theories, the meaning of a term is fully determined by its referent in the world, or associated with certain states of the world ("real-world semantics"); for others, it is determined by its relation with other linguistic or mathematical elements ("model/information semantics").[13] This distinction is clearly visible, e.g., when comparing the first two entries in Table 3. While discrepancies among theories of meaning might be operationally less radical than one might assume, it would be optimistic to presuppose they have no consequences. Indeed, for some authors the distinction between semantic and semiotic/pragmatic interoperability rests on the putative gap between alternative theories of meaning, and their specific relationships with cooperation and coordination (compare with [9,39]).

Context is often not enough to clarify the authors' ancillary assumptions, and some scholars appear to oscillate among different understandings. These "hidden variables" contribute to obfuscating the discussion, and make any comparison on this point vastly reliant on interpretation. Even the definitions not citing "meaning" directly are hinged on related terms: "interpretation" and "understanding" (of information and data respectively); thus, even these definitions can be interpreted in vastly different ways. In general, both "understanding" (of data, meaning, information), and "interpretation" (of content, knowledge, information) are often part of the definitions as well — with "content", "knowledge" and "information" themselves being understood differently by different authors and in different contexts.

Performing an analysis in terms of subject–predicate–object similar to what was done in Section 3.1, we find what follows. The *subjects* are "communicating parties", "applications", "assets (e.g. agents, machines, systems)", and "systems" (collaborating, participating, computer). If not strictly subjects, we find other entities "across", "over" or "between" which the interoperation takes place are "languages", "humans", "information sources" and "devices". We underline that for Guizzardi [47] humans are the actual ultimate subjects of interoperability. In Table 3, we find that humans/users are also explicitly mentioned by [29,38]. Subject specifications tend to reflect the authors' diverse focus and domains of specialization. Different subjects can be plausibly related with varying requirements, approaches, and associated metrics.

In three cases, the *counting* is explicitly addressed and the subjects are said to be "two" or "two and more". Diversity is underlined as well, as in "diverse"/"different" (systems), "heterogeneous" (information sources, environment), "regardless of the vendor", or as different in terms of the original "purpose" ("any other application [...] not initially developed for this purpose" [18]). The *predicates* are "understand" and "interpret", as well as "exchange" and "share". The *objects* are "meaning" (of data, data elements, data model, syntactic elements, information, message), "knowledge" (piece of), "information", "data" (elements), "expression", and "relations between elements".

In some cases, an emphasis is put on the *depth* of the understanding/interpretation ("at a higher level", "within a context", "context-sensitive", "relationships between [data elements]", "propositional meaning"), and in many cases on its *correctness* ("correct"/"correctly", "same"/"in the same way", "preserved", "real", "effective", "precise", "without any [...] meaning and intent loss"). We note in passing that in the definition of interoperability in general (cf. Section 3.1), there is a focus on the interaction being useful and meaningful. However, its accuracy and correctness is only explicitly mentioned in one case, i.e., in the work by [29]. Finally, we note that while in most cases content and format are seen as two disjoint aspects (e.g., [27]), in the European Interoperability Framework from the EC [25], which we will refer to as EIF-eu, semantic interoperability by definition includes syntactic aspects as well.

Gaps, key differences between definitions of semantic interoperability and their consequences

For semantic interoperability definitions, we find a similar situation as discussed above in 3.1 for the more general definitions. Analogously, we have analyzed the collected definitions along multiple dimensions: subjects (including their counts), predicates, objects, depth of collaboration, and correctness. We note that in many references there is commendable attention to the lexicon,[14] however only ISO 19941 [24] is accompanied by a complete glossary (indirectly, *via* the overall ISO dictionary) of all key terms appearing in the definition.

A key difference between definitions is whether *real-world* or *model/information* semantics is being considered, but only a few sources are explicit about this, namely: [9,38] use real-world semantics, whereas [39] uses model/information semantics. For some others, given the relevance of real-world entities and the respective properties throughout the sources, we might infer they adopt the real-world semantics framework (e.g., [26,47]). On this debate, Guarino and Guizzardi argue that knowledge systems must ultimately engage with real-world semantics: mapping the terms *ham*, *bacon*, and *sausages* to abstract sets in a model-theoretic structure may yield a formal interpretation, but it does not explain why pigs would become alarmed when the farmer repeatedly utters those words [49].

Finally, symmetry of the interoperating subjects is not discussed. The only exception in Table 3 touching on the directionality of interoperation is [26] ("understand each other's data"). In most cases there is a clear emphasis on the correctness of the exchange, see discussion above.

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[13] For instance, in logical theories, non-logical symbols are said to be given a "meaning" by their *interpretation*, where interpretation is a function from non-logical symbols (i.e., connectives are excluded) to another mathematical artifact (e.g., a set-theoretical structure, given standard model-theoretical semantics for predicate logic).

[14] E.g., in [26] there is a whole section on what "understanding" means, both for humans and machines, while [39] formally defines core concepts as "language", "representation", "interpretation".

Table 3
List of semantic interoperability definitions (ordered by year). For a detailed analysis of the common points and differences between the definitions, see Section 3.3.

Source ID	Definition of semantic interoperability
[Ouksel 1999] [38]	“Semantic interoperability will [...] support high-level [...] context-sensitive information requests over heterogeneous information resources, hiding system, syntax, and structural heterogeneity”. We “focus on [...] semantics related to mapping of objects in the model or computational world onto the real world, or the issues that involve human interpretation, or meaning and use of data or information”
[Euzenat 2001] [39]	“Semantic interoperability is the faculty of interpreting knowledge imported from other languages at the semantic level, i.e. to ascribe to each imported piece of knowledge the correct interpretation or set of models.” “When trying to assess the understanding of an expression coming from a system by another one, there are several possible levels of interoperability: [...] semantic: being able to construct the propositional meaning of the representation”
[EIF-eu 2004] [18]	“This aspect of interoperability is concerned with ensuring that the precise meaning of exchanged information is understandable by any other application that was not initially developed for this purpose. Semantic interoperability enables systems to combine received information with other information resources and to process it in a meaningful manner.”
[Asuncion 2010] [9]	“[To ensure semantic interoperability,] the meaning of the syntactic elements should be understood by collaborating systems; i.e.; they share the same meaning of the data in relation to the entity or phenomena it represents in the real world.”
[Janssen 2014] [22]	“Semantic interoperability ensures that information is interpreted in the same way. [...]”
[EIF-eu 2017] [25]	“In the EIF, semantic interoperability covers both semantic and syntactic aspects: - The semantic aspect refers to the meaning of data elements and the relationship between them. It includes developing vocabularies and schemata to describe data exchanges, and ensures that data elements are understood in the same way by all communicating parties; - The syntactic aspect refers to describing the exact format of the information to be exchanged in terms of grammar and format.”
[ISO 19941:2017] [24]	“Semantic data interoperability: interoperability[a] so that the meaning of the data model within the context of a subject area is understood by the participating systems”
[Szejka 2017] [14]	“Semantic interoperability [...] is the only [interoperability type] that ensures the effective information sharing in a collaborative and heterogeneous environment.” “[...] without any information and knowledge meaning and intent loss during this process.”
[Noura 2018] [43]	“Semantic level interoperability deals with the technologies needed for enabling the meaning of information to be shared by communicating parties.”
[EMMC-CSA 2019] [27]	“Interoperability operates at semantic level, focusing on the meaning of the data, independently on their specific format” and “meaning of the data (i.e., what they represent, semantic interoperability)”
[IEC 2019] [26]	(From the text) “Semantic interoperability can be defined as the ability of two or more assets (e.g. agents, machines, systems) to exchange and understand each other’s data correctly” (glossary) “semantic: meaning of concepts, often expressed through classes and their properties as data structures”
[Guizzardi 2020] [47]	“I defend here that, with the possible exception of a scenario in which by “machine” we mean strong artificial intelligence (AI), semantic interoperability is always about interoperation with meaning preservation between humans, even in the cases in which these are mediated by machines and information structures”.[b]
[Hagelien 2021] [48]	“Semantic interoperability is the exchange of information with a shared meaning between two computer systems.”
[Gupta 2022] [29]	“Semantic Interoperability: [...] Interpretation of content and understanding the meaning of message which can be used to generate useful results for users involved is the main objective that this level focuses on. [...]”
[Diraco 2023] [31]	“Semantic Interoperability: The capability of diverse systems to not only exchange information but also understand it at a higher level [...]”. It “ensures that the real meaning of shared data is preserved across systems, applications, and devices, regardless of the vendor.”

[a] Term 3.1.1 in [24], cf. Table 1.

[b] In [47], Guizzardi also includes a more formal definition: “two systems A and B semantically interoperate if the coded relations connecting the information structures of A and B: (i) preserve the semantics of the referents represented in those structures; (ii) reflect the real-world meta-properties of the represented relations; and (iii) yield a resulting information structure that constraints the possible states of the resulting system to the intended ones, i.e., to those that represent intended state of affairs according to the conceptualizations underlying A and B.”

Summary of gaps, key divergences in the terminology and notes on their consequences

The definitions and classifications surveyed above, notwithstanding their commons points, exhibit considerable surface-level variations revealing a marked fragmentation in how interoperability is understood and framed in the materials and manufacturing domain. As anticipated, this fragmentation can be partly explained by the broadly positive valence of the label and by the diversity of goals, contexts, and practical applications in which it is cited.

At a closer look, patent divergences in definitions and classifications are only the tip of the iceberg. A general issue is that most definitions are brief, informal, and are not accompanied by self-contained vocabularies or glossaries clarifying key terms; they also rely on notions whose interpretation is far from standard across the community.

Also, although many definitions and classifications are tailored to particular scenarios or stakeholder needs, they are frequently presented as completely general or without explicit statements of scope and context. Scholars and practitioners alike tend to put emphasis on challenges aligned with their own expertise or experience. This tendency is especially relevant when data (rather than physical systems) are concerned, where the problem space and the KPIs/metrics of success are arguably harder to delimit. Notably, this is not merely a semantic concern, as there are downstream consequences for the approaches taken into consideration, and the overall adequateness of solutions/final products.

Taken together, the combination of fragmentation and terminological opacity hampers communication and expectation-setting, with cascading effects on coordination and trust. A unifying framework covering all aspects/facets is still missing. As a step toward that, we do advocate for increased terminological rigor and clarity, and coordination between efforts wherever possible.

3.4. Pointers to initiatives and organizations

In Table 4, we list major initiatives, organizations and projects that are primarily relevant to interoperability in the context of materials and manufacturing. For each we give, beside the acronym and full name, a geographical range and domain of activity, and the self-assessed (from websites and documentation) entity type. For “active”, we mean that the initiative or organization continues to produce results or organize events in the given year. Some of these have a long-standing track record, some are more recent, and others, now inactive, are cited for their historical relevance.

Table 4
List of initiatives/organizations relevant to interoperability in materials and manufacturing (alphabetical order). See also the main text, Section 3.4.

Acronym	Full name	Geogr. range	Domain	Type	Active in 2025
CEN [50]	European Committee for Standardization	Eu[a]	Multi-sector (standardization)	"Association", "European Standardization Organization" (one of the three)	Yes
CENELEC [51]	European Committee for Electrotechnical Standardization	Eu	Electrotechnical	"Association", "European Standardization Organization" (one of the three)	Yes
DDI Alliance [52]	Data Documentation Initiative Alliance	World	Social sciences & human activities	"International collaboration"	Yes
DigiPass [53]	Harmonization of advanced materials ecosystems serving strategic innovation markets to pave the way to a Digital Materials & Product Passport	Eu	Digital product passport, advanced materials	(HE) project	Yes
CoE-DSC [54]	Centre of Excellence — Data Sharing and Cloud	Eu	Cross sector	"Open and inclusive initiative"	Yes
DSSC [55]	Data Spaces Support Centre	Eu	Generic/cross sector	(DEP) project	Yes
ELIXIR [56]	–	Eu	Life sciences	"Infrastructure" and "intergovernamental organisation"	Yes
EMMC ABSL [57]	European Materials Modelling Council ABSL	Eu	Materials modeling	"Non-profit Association"	Yes
EMMC-CSA [58]	European Materials Modelling Council CSA	Eu	Materials modeling	(H2020) project	No
EOSC (Association) [59]	European Open Science Cloud (Association)	Eu	Science	"Association"	Yes
ETSI [60]	European Telecommunications Standards Institute	World (name is a relic)	ICT	"European Standardization Organization" (one of the three)	Yes
FAIR-DO (FDO) [61]	FAIR Digital Objects (Forum)	World	Generic/cross-sector	"Neutral, bottom-up and inclusive international network"	Yes
IAM-I[b]	Innovative Advanced Materials Initiative	Eu	Materials	"International non-profit association"	Yes
IDSA [62]	International Data Spaces Association	Eu/World	Generic/cross-sector	"Non-profit" "association"	Yes
IE [63][c]	Interoperable Europe	Eu	Public sector	EC initiative	Yes
IEEE [64]	Institute of Electrical and Electronics Engineers	US/World	Engineering and technology	"Technical professional organization", "not-for-profit organization"	Yes
Interop (NoE) [65]	Interoperability research for networked enterprises applications and software (Network of Excellence)	Eu	Enterprises	(FP6) Project	No
INTEROP-VLab [66]	International Virtual Laboratory for Enterprise Interoperability	Eu	Enterprises	"Non-profit International Association"	Yes
IOF [67]	Industrial Ontologies Foundry	World	Industry	"Organizational unit" (of OAGi)	Yes
ISO [68]	International Organization for Standardization	World	Multi sector (standardization)	"Independent, non-governmental international organization"	Yes
KGA [69]	International Semantic and FAIR Knowledge Graph Alliance	World	"Industry & cross-sector"	"non-profit organization"	Yes
OAEI [70]	Ontology Alignment Evaluation Initiative	World	Generic (alignment)	"Initiative"	Yes
OAGi [71]	Open Applications Group (Inc)	US-Based/World	Enterprises	"Non-profit standards organization"	Yes
OAI [72]	Open Archives Initiative	World	Generic (Pre-prints)	"Initiative"	No
OMG (SDO) [73]	Object Management Group (Standards Development Organization)	World	Computers (Software, middleware, system modeling)	"International, open membership, not-for-profit technology standards consortium"	Yes
OntoCommons [74,75]	Ontology-driven data documentation for Industry Commons	Eu/World	Materials science and manufacturing	(H2020) project	No
OPEN-DEI [76]	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 [77]	Research Data Alliance	World	Generic/cross-sector	"Global initiative", "global community"[d]	Yes
SDMX (Initiative) [78]	Statistical Data and Metadata eXchange (Initiative)	World	Statistics	"Global initiative"	Yes

(*continued on next page*)

Table 4 (*continued*).

Acronym	Full name	Geogr. range	Domain	Type	Active in 2025
SOA4All [79]	Service Oriented Architectures for All	Eu	Generic (Web services)	(FP7) project	No
WorldFAIR [80]	Global cooperation on FAIR data policy and practice	Eu	Disciplinary and cross-disciplinary	(HE) project	No
W3C [81]	World Wide Web Consortium	World	Cross sector (Web)	"International public-interest non-profit organization"	Yes

[a] The abbreviation "Eu" stands here for Europe in the geographic sense.

[b] IAM-I replaces AMI2030, the Advanced Materials 2030 Initiative, now inactive.

[c] Previous programmes were called IDABC (Interoperable Delivery of European eGovernment Services to public Administrations, Business and Citizens) and ISA (Interoperability Solutions for European Public Administrations).

[d] Two related legal entities: the RDA Foundation, which is a "non-profit charitable organisation", and the RDA AISBL, "a non-profit organisation", supports the RDA community in Europe).

Concerning recent activities, we will mention the Knowledge Graph Alliance (KGA), which is a non-profit association to continue OntoCommons' work, and DigiPass CSA (HORIZON-CL4-2023-RESILIENCE-01-39), which began in 2024 and focuses on product digital passports. An initiative to start from 2026 is MaterialsCommons (HORIZON-CL4-INDUSTRY-2025-01-MATERIAL), whose aim is to set up a federated digital infrastructure for research and innovation on advanced materials in Europe. In particular, in relation to organization-to-organization interoperability, we highlight the Enterprise Interoperability Framework (EIF or FEI, which we will refer to as EIF-ent so as not to confuse it with the aforementioned EIF-eu). This was proposed by David Chen and collaborators in the scope of INTEROP (for a historical perspective, see [34,35,82]) and is an ISO standard (ISO 11354-1 [44,83]).

Although the public sector is not the main focus of this paper, we also include Interoperable Europe (IE), whose predecessors were IDABC (Interoperable Delivery of European eGovernment Services to public Administrations, Business and Citizens) and ISA (Interoperability Solutions for European Public Administrations), as this line of programmes notably produced the New European Interoperability Framework [25] (EIF-eu). Other interoperability frameworks have been proposed, for example by the EOSC [84] and by WorldFair [85], with the latter focusing on cross-domain use.

Activities around "data spaces" and similar digital infrastructures targeted to either industrial communities or scientific ones (e.g., IDSA and DSSC, EOSC) are an important source of recommendations, at least at the European level, and are therefore included.

3.5. Overview of existing high-level recommendations: common points and differences

In this section, we give an overarching view of the recommendations obtained from the analysis of the literature and also of the discussions at OntoCommons events. There is a common set of "ingredients" (recommendations, design principles) on which most initiatives and authors will agree, but there are also some "branching points" where opinions can differ and typically a decision is then necessary. We conclude the section with a discussion of the inter-domain problem.

Common recommendations (RE) for interoperability include:

RE1. Creation and adoption of *standards* (for terminologies, formats, etc.)
RE2. *Openness* of standards and protocols. Avoidance of vendor lock-in
RE3. Use of *controlled vocabularies* (human and/or machine readable; including ontologies, ontologies networks/ecosystems, modeling patterns)
RE4. *Community* building (collaboration, communication, co-creation; cross-enterprise and ideally at a global level)
RE5. Data *provenance* tracking
RE6. Data *structuring*
RE7. Data *linking*
RE8. Establish, share and adopt solid *methodologies* for the development of semantic artifacts
RE9. Provide *documentation* and guidance for semantic artifacts — Document, curate, share and maintain them
RE10. Establish a solid *governance* of semantic artifacts
RE11. *Value demonstration* of semantic artifacts. Show (commercial) benefits of adoption

In the above, while some recommendations are very general (RE1–RE4), some focus on data (RE5–RE7) and others on semantic artifacts (RE8–RE11). Common design principles (DP) for semantic artifacts include:

DP1. Composability
DP2. Concreteness (e.g., use-case driven, need-driven development)
DP3. Explicitness (of used knowledge) (Related: Transparency)
DP4. Extendibility, adaptability, scalability
DP5. Human readability and machine readability
DP6. Maintainability (Related: Sustainability)
DP7. Measurability (Example: possibility to assess compliance/interoperability)
DP8. Modularity. Hierarchical structure (e.g., by abstraction levels)
DP9. Parsimony (i.e., as complex as needed, as simple as possible. Related: Occam's razor.)
DP10. Reuse
DP11. Rigor
DP12. Separation of concerns
DP13. Stability
DP14. Usability (Related: Ease of uptake, user-centricity)

Of these, many are generally applicable to software artifacts as well, however we point out "Explicitness" and "Rigor" as being especially core to knowledge representation. Typical "branching points" (BP) that we identified, in general and for data and knowledge representation, include[15]:

BP1. Centralized *vs* decentralized governance
BP2. Monolithic *vs* modular approach
BP3. Single *vs* pluralistic approach/model [Related: Standardization *vs* bridging]
BP4. Logical expressivity level (low *vs* high) [Related: Precision needs, e.g., of mappings, reasoning needs]
BP5. Automation level (manual *vs* automatic) [E.g., when generating mappings between models]
BP6. Open-world *vs* closed-world assumption in data modeling

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[15] DP8 is a commonly accepted principle, however the degree of modularity can vary (cf. BP2 below); similarly for DP11 (cf. BP4).

While a specific implementation or interoperability solution can include choices that sit in between the extremes in each dimension (e.g., combining different expressivity levels for different tasks, or using manual and automatic processes at different stages of development), these are points for which explicit design decisions need to be made as they will have strong implications and effects down the development line. Of course, such methodological and technical design decisions are informed by environmental constraints and by the requirements of the case at hand. In the rest of this section, we discuss the aforementioned branching points, and give examples of different takes regarding them.

The governance and pluralism[16] dimensions are often entangled together. Also, it is clear that 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. Section 3.4) in their Leiden declaration: they "Support distributed solutions where useful to achieve robustness and scalability, but recognise the need for centralised approaches where necessary".

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 the first type is the IOF (cf. Section 3.4), where BFO is the common top-level ontology for the rest of the models, while an example of the second type is OntoCommons, with three top-level ontologies[17] (BFO [87,88], DOLCE [89,90] and EMMO [91]) that are aligned to the Top Reference Ontology (cf. [92]). For a historical reference on pluralism in this context, see also the WonderWeb project [93], where a library of foundational ontologies was planned. This branching point can be framed within the broader context of means to address heterogeneity, with the core options being standardization and bridging: in the first approach, heterogeneity is eliminated altogether through the imposition of a universal standard/protocol, and in the second one, it is regimented via procedures to adapt one of the involved elements to make it compatible with others. Again, the boundaries between the two approaches are much less defined than they might initially seem: for instance, bridging frameworks/tools can themselves become a standard, or rely on standards at a different level.[18] Within any given field, it is typical that infrastructural technologies (as found, e.g., in exchange protocols), which appear in the early development stages of such a field, are established as standards, serving as a foundation for bridging approaches at higher levels.

When it comes to expressivity levels (cf. Section 6), simpler models can facilitate integration with existing workflows (see [94], for example, where a model for mappings is proposed), while more complex languages enable richer statements and deeper inferences (see a related discussion in [26] on the 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. Therefore, there could be arguments to choose the simplest language with enough complexity to address the tasks at hand, but a future-proofed solution would be to select a more powerful one. To make an informed decision on this aspect, it is important to be aware of existing options, their capabilities and limits, how they relate to each other (e.g., what languages are a subset of others), and the availability of associated software tools. Another key factor to take into account are one's needs in terms of automatic reasoning: for example, reasoning is a core part in decision support systems and whenever explanations are required.

In the semantic web, the "Open-world assumption" is a fundamental one, whereas databases typically function within the "Closed-world assumption". When bringing together different disciplines and practitioners, it is important to have in mind these opposite views in order to be able to integrate them and avoid fundamental pitfalls [95].

In general, guidance in the design and 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, as required in the automotive and pharmaceutical sectors, the needs in terms of the precision of mappings will be different from, say, those in the entertainment sector.

Before moving to the inter-domain problem, we underline that while in this section we summarize high-level recommendations, throughout the rest of the paper we give other (more) actionable advice, in various forms, and embedded within different discussions, see in particular Section 3.6, Sections 5–7, Appendix C, and Appendix D.

3.5.1. *Inter-domain (or cross-domain) interoperability*

Finally, we survey different approaches for dealing with the inter-domain (or cross-domain) interoperability challenge. By inter-domain, we mean that there are at least two domains[19] of discourse, that are typically based on different, domain-specific conceptualizations. They may or may not have some sub-domains in common, but there is at least a clearly defined (theoretical or practical) objective for making a connection between them. Ambiguities, misinterpretations and clashes are likely to arise when drawing connections, hence well-defined solutions for inter-domain interoperability are required. We identified two main types of approaches:

ID.I *Implicit* inter-domain approaches

  ID.I.1 Adhering to common methodologies and principles
  ID.I.2 Using the same minimal set of domain-agnostic standards
  ID.I.3 Using a common mid- or top-level ontology. Also using domain-agnostic ontology design patterns

ID.E *Explicit* inter-domain approaches

  ID.E.1 Developing conceptualizations across the domains
  ID.E.2 Developing a multi-perspective framework, by construction addressing multiple domains

The implicit approaches are based on the identification of common principles lying *outside* the domains, and they avoid going into the domain concepts. As an example of such an approach, the IDSA suggests using "common design principles" and "consistent practices" across data spaces for different domains as well as implementing "the same minimal set of functional, legal, technical, operational agreements and standards" (see [28], text and Figure 3, and the IDSA Reference Architecture cited therein). Similarly the CDIF [85] is "based on profiles of common, domain-neutral metadata standards". Typical domain-agnostic standards are those for generic datasets (e.g., DCAT) or at a higher granularity level (e.g., DDI-CDI specification [96], which goes down to the datum level). Examples of top-level ontologies were already mentioned in the previous section, and for an overview of ontology design patterns, see [97]. An example of a mid-level set of ontologies used in the materials and industrial domain is IOF-core,[20] which utilizes BFO for the top-level.

In the second category of approaches, the domains are instead entered explicitly, to some extent. This approach can be challenging

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[16] Pluralism refers here to accommodating multiple views, possibly, but not necessarily, coming from different groups/communities.

[17] See also ISO 21838-1 [86] on the requirements for a top-level ontology. The subsequent parts of the standard contain examples of top-level ontologies.

[18] Compare with [35], where the authors identify three approaches, considering meta-level standardization as a separate one.

[19] The level of abstraction at which "domains" are defined is debatable, but for the present discussion this is not relevant. It suffices to say that a domain concerns a limited field of knowledge, as opposed to addressing the whole of it.

[20] IOF-core ontologies https://github.com/iofoundry/ontology/tree/master/core.

without a common foundation (see above), especially in terms of axioms consistency. In general, [26] recommends developing “common cross-domain semantic and ontological foundations”. A solution put forward by the OntoCommons project for ID.E.1 is that of “bridge-concepts” and associated templates [98,99], which act as gateways between domains and make the shared conceptualization as explicit as possible. More fundamentally, it is possible to represent different views on the data explicitly (cf. ID.E.2): an example of this is provided by the EMMO [91], which rests on a general foundational theory (mereocausality).[21]

Finally, we note that some of the approaches above enable disambiguation and harmonization between pre-existing domain artifacts/assets (e.g., ontologies), whereas others are to be used at earlier stages of the artifact/asset development.

Overall, while in principle an explicit approach would seem to be the most obvious choice, we have found in multiple cases that the suggested solution to the inter-domain challenge is given in domain-agnostic terms, dropping some of the benefits of semantic technologies.

3.6. *Pointers to existing interoperability assessments (models and metrics), and related assessments*

Multiple models and metrics to assess interoperability have been proposed in the literature: they concern the interoperability of various entities (datasets, software, organizations) and can be designed to assess one,[22] two, or more entities. Relevant keywords in this context are: interoperability evaluation, assessment, metric, FAIRness, and also digital maturity. Here we highlight some references, whereas for further reading we point the reader to entries in Table A.10 with a “metric” tag for their content, and in particular the reviews [6,8,38,40,43], where multiple approaches are compared.

At the qualitative level, and for historical reasons, we recall the “five-stars” approaches of linked data [100] and of linked data vocabulary use [101,102]. The goal of such ratings, more than technical, is to encourage technology adoption, and to indicate some directions for incremental improvements.

In the FAIR principles [4], four facets are separated, and three guiding principles are identified for “I-interoperability” (cf. 7.3 and discussion therein). Multiple sets of FAIRness “codes” or metrics implementing these principles have been proposed for data/datasets (see for instance those provided by the RDA [103], FAIRsFAIR [104] and FAIRplus [105]) and a number of dedicated tools for FAIRness evaluation also exist (e.g., F-UJI [106] for datasets and FOOPS! [107] for ontologies and vocabularies; both tools are available online as web services).

For a proposed method to measure semantic interoperability between two overlapping domain ontologies, see [108]. At the organization level, interoperability within and between enterprises is considered: we highlight a number of reviews [8,40] as well as the ISO standard 11354-2:2015 [83].

Finally, on a somewhat different but related line, [109] proposes to visualize interoperability (in tool chains, via node-link diagrams).

Most methods provide as an output a quantification (typically numerical) of interoperability. Needless to say, a number of design, technological and implementation decisions are necessary to produce these quantified results, especially when some automation is involved, so their outcomes have to be considered in this light.

4. Analysis of a set of interoperability scenarios

We have analyzed interoperability scenarios from 17 use cases. The use cases[23] were provided by the OntoCommons project that aimed to foster standardized data documentation in NMBP[24] domains. As such, the use cases represent a variety of domains in this scope, and involved large corporations, SMEs and also research institutions. The use cases being analyzed were selected in two phases, the first as part of the OntoCommons project consortium from its inception and covering a wide range of industrial areas in the NMBP domains. In the second phase a campaign was launched to acquire additional demonstrators to improve the variety of industrial stakeholders in order to increase requirement collection quality and results impact. The campaign was open to every stakeholder in the NMBP domain, and after collecting the applications, a set of selection criteria [111] was applied promoting diversity both in terms of challenges and the variety of geographical locations. The final set represented a wide range spanning seven different domains (Manufacturing, Material Development, Biotechnology, Lifecycle Assessment, Materials Processing, Materials Characterization and Materials Modelling). These use cases included both SMEs and large enterprises from diverse industrial sectors of materials and manufacturing (aerospace, electronics, chemical, metal, equipment manufacturing, and retail), originating from many different countries over three continents, and covered many different ontological and semantic challenges in a broader sense. The analysis has been conducted over the course of several months based on surveys filled out by the various use-case partners, and it focuses on four main dimensions. 1. *Interoperability challenge*: a high-level view of the tasks that require interoperability between different systems and actors; 2. *System types*: types of systems and actors that need to be interoperable (e.g., humans, communities, data, databases, software, IoT devices); 3. *Purpose*: the reason why interoperability is needed (we will cover four potential purposes from [26], namely understanding, finding, operating, and updating); 4. *Technical components*: the technological artifacts used to achieve interoperability.

Although limited to NMBP domains, this analysis provides a good indication of the commitment of both big and small companies to the adoption of semantic technologies for tackling interoperability challenges. In the following subsection, we present a condensed summary of results for each dimension, and further details can be found in [16].[25] The quantification given in the following is only used as a presentation instrument, and does not aim to provide any statistical basis for predictive analysis. Please see also note at the end of Section 2 on this.

4.1. *Interoperability challenge*

There are many types of interoperability challenges that can be addressed and on many levels. For instance on a technological level, interoperability facilitates timely, efficient, and effective completion of applications, in addition to finding new, smarter, and more adaptive services [112], or on a personal level, it facilitates the communication of all agents involved in a certain network. Based on the survey carried out, we found the following use case reports in relation to interoperability, ordered by frequency of appearance. 8 use cases reported data interoperability issues between different departments of a company and

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[21] The EMMO 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. For example, a book can be broken down into pages (physicalistic-reductionistic), but also into chapters and sentences (symbolic-reductionistic).

[22] When a single entity is considered, either interoperability within it or with a given reference framework is actually assessed.

[23] The use cases are an interoperability-oriented subset of 22 use cases (demonstrators) from OntoCommons. See https://ontocommons.eu/ontocommons-demonstrators and [110]. In this paper, two more use cases are included in addition to those already in [16], namely numbers 19 and 20.

[24] NMBP: Nanotechnologies, Advanced Materials, Biotechnology and Advanced Manufacturing and Processing. This is an acronym used in Horizon programmes.

[25] See Tables 4, 5, 6 in Ref. [16], each analyzing a set of use cases. In particular, the entries therein for questions Q1, Q2, Q5 and Q6 are the base for the condensed summaries given in Section 4.

in relation to the data formats used. 7 use cases reported interoperability between applications that use data described with ontologies (e.g., during data exchange) or applications that are used for ontology development. 2 use cases report mismatches (heterogeneity) both at the semantic and syntactic levels. 3 use cases reported interoperability of ontologies in different domains (including automatic mapping). 2 use cases reported interoperability between different manufacturing processes and stakeholders.

4.2. System types

As identified in the interoperability challenges above, there are many types of systems where there are interoperability needs. Most of the use cases reported work on interoperability between human actors and IT systems. In particular, starting from the most frequent ones, we found that in 13 cases, the issues related to *data/databases*. For 8 cases, the issues were between the *human operators*. This is not surprising since stakeholders in a supply chain (on individual, department or company level) have different backgrounds (such as country, spoken language, experiences, studies) and different goals for their work and sometimes lack the same "language". For 7 cases, the issues were due to *software or APIs* developed in different languages or simply in different versions of a given language. For 5 cases, it was related to the *ontologies* that they used in their companies, for instance, where a company used different ontologies to model different aspects of their business but they did not have a common upper ontology or defined mapping mechanisms.

4.3. Purpose

Following [26] and the definitions given therein, we consider four different purposes whereby systems and actors need interoperability to complete their goals, namely: *understand, find, update and operate.*[26]

Next we summarize the answers in each of these categories. 13 use cases reported that they need interoperability to facilitate understanding between different actors, particularly in cross-domain scenarios. 12 use cases chose "finding" as a purpose for interoperability. This is not surprising, as many of the use cases involved some level of data integration from heterogeneous sources. The main purpose of such integration is to enable uniform querying across data sources, which is tightly coupled with the finding purpose. 12 use cases reported that updates across heterogeneous sources was a purpose for them. We observe that "updating" typically appears together with "finding" as a purpose. This is not unexpected, as finding typically is required in order to update data objects. Finally, 14 use cases reported that operating on heterogeneous data was for them a purpose for achieving interoperability. This is particularly the case in manufacturing scenarios such as aircraft manufacturing, where simulations are involved. There were also many use cases that powered various intelligent pipelines involving machine learning and reasoning, which reported operating on data as a purpose.

4.4. Technical components

Due to the nature of the OntoCommons project from which we collected the use cases, interoperability challenges were mostly addressed with semantic technologies. Ontologies are used in the core of these technologies. All use cases used ontologies with different levels of expressivity to enable a unified data representation or alignment of heterogeneous data models. Ontology development was supported by tools like Protégé and in-house visualization and editing tools. Moreover, technologies like ontology templates were used. At the data level, knowledge graph technology was used to integrate heterogeneous data. Triplestores were the storage solution of choice for the use cases. The knowledge graphs typically used RDF as a data model, however, there was also one use case that used property graphs (for these and other technical components mentioned, cf. also Sections 5 and 6).

Table 5
DHOS matrix structure for interoperability requirements: Who interoperates with whom?

	Data	Human	Organization	Software
Data (d)	$d \leftrightarrow d$	$d \leftrightarrow h$	$d \leftrightarrow o$	$d \leftrightarrow s$
Human (h)	–	$h \leftrightarrow h$	$h \leftrightarrow o$	$h \leftrightarrow s$
Organization (o)	–	–	$o \leftrightarrow o$	$o \leftrightarrow s$
Software (s)	–	–	–	$s \leftrightarrow s$

5. Technical components and requirements for interoperability

In this section, we propose a systematic structuring of interoperability requirements and analyze what technical components address such requirements (Section 5.1), focusing on the role ontologies can play in this. This allows us to abstract and logically organize the specific components and requirements from the use cases into a broader picture, identify further ones and to see how a variety of activity fields can be framed in terms of interoperability. In Section 5.2, we touch on the data lifecycle and semantization pipeline.

5.1. Data, humans, organizations, and software (DHOS)

Interoperability requirements can be structured as a matrix, in terms of *who* (x) is to interoperate *with whom* (y), and in *what way* (z). We selected a small set of relevant system types[27] and interoperability levels (cf. Glossary, Appendix E), and then considered all possible combinations of $x \leftrightarrow y$ interoperability at the level z, yielding a space

$$\{\text{data}, \text{human}, \text{organization}, \text{software}\}^2 \times \{\text{syntactic}, \text{semantic}, \text{pragmatic}\}, \tag{1}$$

with symmetry in the first two arguments,[28] cf. Table 5. Taking into account said symmetry, this results in up to 30 cases, where the question considered is *how ontologies and technical components can support* the respective sort of interoperability. Therein, the three interoperability levels are syntax, semantics, and pragmatics. In an analogy with the DIKW pyramid [113], for some purposes this might also be extended to four levels: syntactic, semantic, epistemic, and pragmatic. Concerning the ordering of entities in Eq. (1), and similarly in the tables contained in this section: the system types (subject variation) are simply ordered alphabetically, whereas the interoperability levels (quality variation) are ordered hierarchically, by increasing complexity, with each one building on the previous one.

We underline that in our approach the interoperating entities can be of different nature. Data, humans, organizations, and software (DHOS) are for the present purpose defined as follows:

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[26] Ref. [26] defines these purposes: "Understand something: This involves matching data to a model as best one can, often using other information to interpret the data in the context in which it is found/ used. [...] Find something: Querying and matching is used to locate something, on the basis of specific given information and often requires traversing models to identify a match. [...] Update something: Data is provided using matching and assignment, which then updates values in a repository for subsequent use. [...] Operate on something: Using data and matching to perform operations on items". For example scenarios, see ibidim.

[27] See also the values for T3 (type of entities), in Table A.9. Here, we do not include "things" (physical devices), as the focus of this paper is on information and knowledge, more than physical interoperability; also we do not include "ontologies" as a separate case (e.g., this would lead to cases such as ontology-ontology interoperability), but rather consider how ontologies can affect all the other cases. Nevertheless, ontologies are of course covered under the general category "data".

[28] As there is no directionality in the "interoperability" relation, cf. Appendix E.

Table 6
Catalog of interoperability cases and typical scenarios. The 10 cases in the first column are as in Table 5. See also Section 5.1 for the DHOS notation and more details on the reasoning behind this structure.

System type	Interoperability level	Requirements that may occur in typical use-case scenarios
$d \leftrightarrow d$	Syntactic	Convert data formats
	Semantic	Integrate data from different sources, or using different data models
	Pragmatic	Integrate access rights, IP rights, and contextual information on data
$d \leftrightarrow h$	Syntactic	Read/write data
	Semantic	Understand, annotate, find, compare, and document data
	Pragmatic	Modify data in agreement with a protocol; contextual aspects
$d \leftrightarrow o$	Syntactic	Data conversion; comply with in-house data formats and schemas
	Semantic	Landscaping and conceptual engineering; organizational terminology and cross-organizational alignment
	Pragmatic	Data and metadata quality and curation standards, data management, data certification, and compliance with legal requirements
$d \leftrightarrow s$	Syntactic	Read/write data
	Semantic	Understand, annotate, find, compare, and document data
	Pragmatic	Ingest, retrieve, extract data
$h \leftrightarrow h$	Semantic	Shared understanding
	Pragmatic	Communication, collaboration
$h \leftrightarrow o$	Semantic	Categorization/taxonomic organization of roles
	Pragmatic	Specification of roles
$h \leftrightarrow s$	Syntactic	Mapping high-level to low-level programming languages
	Semantic	Mapping human languages and human activities to a formal representation and vice versa
	Pragmatic	Software usability, user experience, natural language processing, human–computer interaction, bespoke ways of interacting with toolkits, monitoring
$o \leftrightarrow o$	Semantic	Defining business goals, modeling business processes, etc. [19]
$o \leftrightarrow s$	Syntactic	Annotate source code and binary files on institutional long-term storage and reproducibility-oriented data preservation systems
	Semantic	Specify features and requirements
	Pragmatic	Multilinguality, licensing, IPR, access management, SaaS, cybersecurity
$s \leftrightarrow s$	Syntactic	File I/O, format/syntax of packages or streams used to exchange data
	Semantic	Exchange of information
	Pragmatic	Information management in knowledge-based architectures

Data: "Representation of facts, concepts, or instructions in a manner suitable for communication, interpretation, or processing by humans or by automatic means" [17, p. 23].

Humans, here, meaning: Those who directly and individually engage with digital artifacts, e.g., as users, administrators, or programmers.

Organizations: "Processes of ordering of action and of relations in reference to given social ends" [114, p. 10].

Software: "Computer programs, procedures, and possibly associated documentation and data pertaining to the operation of a computer system" [17, p. 66].

Following this structure and for each of the 30 cases, we list typical scenarios and requirements in Table 6, and then the corresponding technical components in Table 7. This analysis is generic, not targeting any particular infrastructure or research and development project; it was compiled based on the authors' experience from requirements analyses and the discussions within OntoCommons, and can serve as a catalog that developers can go through when compiling a requirements register for their own project; similarly, it can be used to formulate target metrics, such as key performance indicators, in research proposals. No *general* prioritization is proposed here for each of the potential systems requirements that are listed, as this would need to be assessed for each development project specifically. As a more concrete illustration of such a structure, examples of specific requirements, metrics and KPIs for an actual project are given in Appendix C.

Taking for example the first case, data-data interoperability, format conversion acts at the syntactic level, whereas integration of different data models takes place at the semantic level and data contextual information at the pragmatic level (cf. Table 6). Accordingly, in Table 7 we see that format converters are technical components at the syntactic level, with mappings at the semantic level, or at the pragmatic level if they include contextual information. We proceed analogously for the other cases. While some entries are straightforward and would be commonly mentioned in the context of interoperability, we found this structuring allowed us to identify other typical scenarios and components as part of the same bigger picture: e.g., the human-software pragmatic level, which includes the recognition of human activities and software usability. The benefit of this broader view is that more fields of activity and research might benefit from each other.

To ground the entries in Table 6 to assessments and concrete implementations, we take, as an example, the FAIRsFAIR F-UJI tool codes [106] and see how the two sets compare. The F-UJI codes correspond to FAIR quality assessment metrics for data (cf. Section 3.6), inspired by the GO-FAIR structuring of FAIR concerns. With this, e.g., the "$d \leftrightarrow d$, pragmatic" case maps at least to codes FsF-F2-01M and FsF-R1.1-01M. The case "$h \leftrightarrow h$, semantic", maps at least to F-UJI codes FsF-I1-01M and FsF-R1.3-01M. Many codes will be affected by the most abstract entries. The F-UJI implementations of the code metrics have several data processing aspects of the assessment related to many FAIR codes. For example, the absence or quality of Persistent Identifiers (PIDs) in a dataset will impact its FAIRness score on many FAIR codes and in turn many entries in the DHOS interoperability matrix.

Guided by the analysis from Tables 6 and 7, we finally list the types of components/assets that are particularly relevant for the scope of the present paper in Table 8. By construction, this list is at a high level, as listing all individual tools would be beyond the scope of this work. For a comprehensive landscape of concrete ontology engineering tools, we direct the reader to [117]. After this broad overview, we look into requirements from the data lifecycle perspective, then Section 6 will focus on knowledge storage and representation.

5.2. Data lifecycle and semantization pipeline

In this section, we give a different perspective for the requirements and technical components, namely, in terms of the data life cycle and the data semantization pipeline. Following the Materials 2030 Roadmap [135] (cf., therein, Fig. 2: "Four priority topics to achieve the data life-cycle of advanced materials"), one can identify four macro activities and their corresponding phases in the life cycle of materials

Table 7
Technical components corresponding to the interoperability cases. See corresponding typical scenarios in Table 6 and the main text for more details on the DHOS structure, Section 5.1.

System type	Interoperability level	Technical components
$d \leftrightarrow d$	Syntactic	Format converters; data formats, including grammars e.g. in Backus–Naur form
	Semantic	Ontologies; ontology networks; mappings and crosswalks; data models/schemas
	Pragmatic	Web services and APIs; provenance tracking; protocols for data integration, e.g., harvesting; mappings that account for contextual aspects; mediation systems
$d \leftrightarrow h$	Syntactic	Human-readable formats
	Semantic	Taggers, data annotators; rich annotations and human-readable metadata
	Pragmatic	Conceptual engineering tools; data validators; protocols e.g. for data discovery
$d \leftrightarrow o$	Syntactic	Format converters; grammar definitions e.g. in Backus–Naur form
	Semantic	Tools for conceptual engineering and landscaping
	Pragmatic	Data management plans; ontologies matching legal requirements; certificates, systems providing certificates
$d \leftrightarrow s$	Syntactic	Data format
	Semantic	Machine-readable metadata; automated annotator
	Pragmatic	APIs for data exchange
$h \leftrightarrow h$	Semantic	Domain vocabularies/glossaries, industry standards, ontologies
	Pragmatic	Good practice specifications; the *pragmatic web*[a]
$h \leftrightarrow o$	Semantic	Front ends, dissemination material, recommender systems
	Pragmatic	Organizational guidelines, access regulations, security and authentication
$h \leftrightarrow s$	Syntactic	Compilers
	Semantic	Ontologies for what can be measured and understood about humans, ontologies of agency, intentionality, human emotion, signals e.g. from wearable devices
	Pragmatic	Metaportals; human activity recognition; user interfaces, manuals, documentation
$o \leftrightarrow o$	Semantic	Business process models; formal specifications and contracts
$o \leftrightarrow s$	Syntactic	Long-term storages, research data infrastructures; taxonomies and ontologies of programming languages, operating systems, and hardware architectures
	Semantic	Registers of available software; requirements analysis tools; taxonomies and ontologies of software features
	Pragmatic	Standards and recommendations on cybersecurity; roles related to software access rights, taxonomies and ontologies for software-related services and SaaS
$s \leftrightarrow s$	Syntactic	Wrappers, technical interfaces; tools for porting across programming languages
	Semantic	Process model topologies [115,116]
	Pragmatic	Web services and APIs

[a] Note: this is underdeveloped and threatens to be a bottleneck in societal and industrial digitalization.

and manufacturing data: 1. Generate new data; 2. Document data; 3. Manage dataspace, and 4. Use and exploit data.

Within the scope of this paper, “Document data” is the most relevant one, followed by “Manage dataspace”. Focusing on data documentation, clearly different levels of depth can be identified. For example, according to Friis et al. [136], one can break data documentation down into four types: 1. Cataloging documentation, e.g., describing how data can be found and accessed; 2. Structural documentation, e.g., describing how the data are structured and represented numerically; 3. Contextual documentation, e.g., making data reusable by providing context and provenance; 4. Semantic documentation, e.g., enhancing data semantically by mapping them to ontologies. We emphasize that, in realistic scenarios (e.g., in materials modeling), not all the data and their metadata will be represented semantically (for example, as RDF triples) – only part of the data will be represented, and exactly how much depends on the needs of the specific use case at hand as well as on computational limits. With this caveat in mind, we can ask what are the steps to turn existing “data” (in any form) into “linked data”, in the view of semantic web practitioners. For example, in Radulovic et al. [137] (therein, see also Fig. 2), the linked data generation process is organized into eight main steps or tasks.[29] This is followed by four steps for the linked data publication process (see also Fig. 3 in [137]).[30] In particular, steps G7, G8, P1, P2, P3, and P4 are relevant for the present document; for more details and examples, we point the reader to the respective sections in Radulovic et al. [137], where subtasks are identified, tools are pointed out, and a complete scenario is given.

Clearly, the references cited above have different scopes, with the Materials 2030 Roadmap [135] and Friis et al. [136] addressing materials modeling and manufacturing data in general, whereas Radulovic et al. [137] focus 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. However, the concrete steps, such as adding a semantic layer to an existing database, creating a new data and knowledge storage for an enterprise, etc., will depend on the scenario at hand. “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. Further references can be found in the cited sources, and concrete scenarios can be found in Section 4.

6. Technical aspects related to knowledge representation interoperability

In modern industry environments, particularly within the manufacturing and materials sectors, the evolution of digital infrastructure

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[29] Steps of the linked data generation process, according to Radulovic et al. [137]: G1. Select data source; G2. Obtain access to data source; G3. Analyze licensing of the data source; G4. Analyze data source; G5. Define resource naming strategy; G6. Develop ontology; G7. Transform data source (intended as: Transformation of data into RDF format); G8. Link with other datasets.

[30] Steps of the linked data publication process, according to Radulovic et al. [137]: P1. Ensure legal compliance; P2. Publish the dataset and the ontology on the web; P3. Publish metadata and online documentation; P4. Enable dataset discovery.

Table 8
Selected, particularly relevant components, cf. Table 7, alphabetically ordered. The components marked with [$\star$] are the interoperability-related building blocks of a dataspace, following e.g. García Robles et al. [33] as well as Nagel and Lycklama [28]. In the third column, a "$\star$" indicates any type (d, h, o, s). For this DHOS structure, Section 5.1.

Component	Elucidation	Interoperability cases	Ref.
Compilers		$s \leftrightarrow \star$	
Conceptual engineering tools or practices		$d \leftrightarrow h$	[118,119]
Crosswalks	Sequences of mappings	$d \leftrightarrow d$ (semantic)	[120]
Cybersecurity standards and recommendations		$o \leftrightarrow s$	
Data annotators/taggers	Data enrichment	$d \leftrightarrow h$	[121,122]
Data assessment tools	FAIR maturity assessment etc. (cf. Section 3.6)	–	[123,124]
Data-exchange APIs [$\star$]	Data sharing and publication	$d \leftrightarrow d$ and $s \leftrightarrow s$	[33,125] [28,126]
Data models and formats [$\star$]	Data documentation	$d \leftrightarrow d$ (syntactic, semantic)	[28,33]
Data provenance and traceability components [$\star$]	Data documentation and publication	$d \leftrightarrow d$	[28,33]
Data validators	E.g., validation of compliance with a format or schema, or content validation	$d \leftrightarrow \star$	[127]
Formal languages, serializations		$\star \leftrightarrow \star$ (syntactic)	
Human activity recognition Tools		$h \leftrightarrow s$	[128,129] [130]
Long-term storage		$\star \leftrightarrow \star$	
Mappings	Semantic correspondences	$\star \leftrightarrow \star$ (semantic)	[131,132]
Metadata/discovery protocols		$d \leftrightarrow h$	[28,33]
Metaportals	Single point of entry to system	$h \leftrightarrow s$	[133]
Natural language dictionaries, vocabularies, and glossaries	Including technical glossaries	$h \leftrightarrow h$	
Ontologies and taxonomies		$\star \leftrightarrow \star$	
Ontology networks	"A set of ontologies and a set of alignments between these ontologies" [42]	$\star \leftrightarrow \star$	[42]
Recommender systems		$h \leftrightarrow o$	
Registries and repositories of semantic artifacts	E.g. LOV	$\star \leftrightarrow \star$	[134]
Research data infrastructures and dataspaces		$\star \leftrightarrow \star$	[28,33]
Schema mediators	Related to mappings/interfaces	$d \leftrightarrow \star$ and $s \leftrightarrow \star$	[42]
Typesetting tools and text processors	LaTeX, LibreOffice, etc.	$h \leftrightarrow h$	
User interfaces		$h \leftrightarrow s$ (pragmatic)	

has resulted in the coexistence of multiple, heterogeneous information representation technologies. Most industrial systems operate within federated environments. The increasing volume and complexity of data, concerns over data sovereignty, access restrictions, and the different objectives of various stakeholders all contribute towards heightening the need for effective and tailored interoperability mechanisms. Before delving into these mechanisms, we survey key knowledge and information representation technologies that underpin modern information systems.

6.1. *Information and knowledge representation technologies*

The evolution of information representation technologies – from relational databases to NoSQL systems, graph databases, and ultimately ontological frameworks – reflects a broadening of both functional capacity and technical complexity. Each stage in this progression introduces enhanced expressivity for modeling increasingly complex data relationships and semantic constructs, but this comes with corresponding trade-offs in system complexity, performance, and usability.

A core distinction can be drawn between SQL (Structured Query Language) and NoSQL (not-only-SQL or non-SQL) data management systems [138], where SQL systems are based on predefined schemas and tabular structures, and are optimized for well-structured, relational data. These systems effectively support property attribution to individuals *via* field-record (slot-value) structures, but they are limited when it comes to representing complex or inherited properties. In contrast, NoSQL systems accommodate a range of flexible formats (e.g., document, key–value, columnar, and graph models) and support dynamic schemas, which makes them better suited to handle unstructured data and large-scale distributed systems. They are particularly advantageous for real-time big data processing due to their horizontal scalability and reduced reliance on the rigid Extract, Transform, Load (ETL) pipelines commonly required by relational databases.

Among NoSQL solutions, graph databases [139] – particularly those employing the Resource Description Framework (RDF) – represent a shift towards semantically enriched modeling. RDF enables representation through subject–predicate–object triples, with each element identified by Uniform Resource Identifiers (URIs). This triple structure naturally supports the attribution of properties, facilitates relation modeling between entities, and allows a single node to act both as a subject and object across different statements. RDF's ability to encode higher-order statements (*via* reification) and partially represent existential knowledge (*via* blank nodes) enhances its expressivity, although at the cost of conceptual and computational complexity. SPARQL, its associated query language, exploits this structure to perform complex graph-based queries. Before moving on, we note that, while RDF is at the core of the W3C stack of standards, a different non-RDF approach for graph databases is that of property graphs: these have lower expressivity overall, but allow to assign properties to edges as well, not only nodes. They are widely used in applications, however the solutions and languages here are less standardized and more vendor dependent. Comparing the two solutions in terms of performance and capabilities, labeled property graphs (LPG) have been shown to perform considerably better than RDF in terms of volume and density of the graph as well as speed of query in a number of comparative studies. However, the minimalism of LPG makes it unsuitable for data integration, query federation, and most importantly, support to logical inference and consistency check. That is where the verbosity of RDF pays off.

Moving further along the spectrum, technologies such as RDFS and OWL build upon RDF to support richer ontological modeling.[31] RDFS introduces mechanisms for class hierarchies, domain and range constraints, and minimal entailment. OWL (Web Ontology Language) adds several expressive profiles – RL, QL, EL, and DL – each offering trade-offs between inference power and computational tractability. OWL 2 DL, underpinned by the $\mathcal{SROIQ}$ description logic, provides high expressivity while retaining decidability, although it may be computationally infeasible in some industrial settings. Nevertheless, its use enhances model validation, reduces misconceptualization, and facilitates deeper semantic integration. For foundational ontologies, even more expressive formalisms like first-order logic (FOL) [140] or higher-order logic are sometimes required, accepting undecidability in exchange for analytical depth. We note that FOL is the *de facto* standard in academia.

On the other side, SHACL[32] can be used to impose shape constraints on the RDF graph. SHACL and OWL sit side-by-side in the W3C's semantic web stack, but are based on different views: while OWL employs logic-based satisfiability and inferencing under an open-world view, SHACL is a constraint language for validation under a closed-world view. With this difference, most 'class constraints' in OWL are expressible as 'shape constraints' in SHACL. This interchangeability has given rise to the debate over the effectiveness of adopting one as a sole means for data modeling over the other. Perhaps the more advisable pattern is to use OWL for the conceptual ontology (subsumption, equivalence, property characteristics), and SHACL for instantiation constraints (that specify what a valid record looks like for integration, ETL, and API contracts).

This progressive expansion of representational capacity offers significant advantages for semantic integration, automated reasoning, and multi-source interoperability. However, these benefits are accompanied by trade-offs in the learning curve, implementation complexity, deployment effort, and performance overhead. Technological choices must therefore balance expressivity with the practical constraints of usability and scalability in real-world industrial systems. Furthermore, the ongoing evolution of information representation technologies, including shifts in paradigms, necessitates the development of interoperability solutions that support both transitional and hybrid system architectures.

6.2. Interoperability of data and knowledge representations

When data and knowledge need to be transferred from legacy representation formats to a newer or upgraded system, or if seamless interaction across federated and heterogeneous environments is required, various technological solutions are available. In the following subsections, we detail challenges and solutions for data and knowledge representations at the syntactic, semantic and semiotic (contextual) interoperability levels.

6.2.1. Challenges and solutions for syntactic interoperability of data and knowledge representations

Syntactic interoperability ensures that data exchanged between systems can be correctly parsed and interpreted despite variations in encoding, serialization, or formats. Common challenges include character encoding inconsistencies (e.g., UTF-8 vs. ASCII), formatting differences in date, time, currency, and numbers, and mismatches in identifiers or classification codes. Multilingual scripts, varying serialization styles (e.g., RDF/XML vs. Turtle or JSON-LD), and issues of versioning and backward compatibility also frequently disrupt interoperability.

To address these challenges, widely adopted standards offer consistency. Character encoding standards such as UTF-8, ASCII, and ISO-8859-1 ensure reliable text representation. Serialization formats like RDF/XML, Turtle, JSON-LD, N-Triples, OWL/XML, Manchester, and Functional Syntax allow logical models to be expressed in interchangeable syntactic forms. Common data formats – XML and JSON for hierarchical structures, and modeling languages like ER diagrams, UML, BPMN, and SysML[33] – further support structured representation across tools.

Methodologies such as consistent naming conventions, multilingual tagging, and deterministic serialization rules reduce ambiguity and improve system compatibility. These are complemented by software tools that facilitate syntactic translation and alignment.

To handle syntactic differences, schema mapping techniques help translate XML or JSON schemas into standardized models like DCAT.[34] Middleware or wrapper services further support legacy system integration by exposing outdated formats *via* modern interfaces (e.g., RESTful JSON). Version negotiation mechanisms allow systems to handle diverse or evolving syntax standards dynamically.

6.2.2. Challenges and solutions for semantic interoperability of data and knowledge representations

Semantic interoperability ensures that systems not only exchange data but interpret it consistently. It addresses challenges such as inconsistent schema structures, terminology ambiguity (including synonymy and polysemy), a lack of canonical vocabularies, metadata misalignment, evolving schemas, and ontology inconsistencies.

One effective approach involves organizing formal languages hierarchically. Languages like RDF and OWL 2 are an illustration of this, with OWL extending RDF through enhanced semantic constraints, such as class hierarchies and logical axioms. Standardized mappings facilitate the upward transformation from RDF to OWL, maintaining semantics across systems. While the reverse transformation is possible, it requires simplifications and may lead to information loss. Most of commonly used constraints can be expressed in either OWL or SHACL,

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[31] See RDF (https://www.w3.org/RDF/), RDF Schema (https://www.w3.org/TR/rdf12-schema/) and the Web Ontology Language (https://www.w3.org/OWL/), as well as the references therein.

[32] Shapes Constraint Language (SHACL) (https://www.w3.org/TR/shacl/).

[33] Entity Relationship (ER) diagrams, Business Process Model and Notation (BPMN), Unified Modeling Language (UML) and System Modeling Language. BPMN, UML and SysML are developed and maintained by the OMG.

[34] DCAT (Data Catalog Vocabulary), see https://www.w3.org/TR/vocab-dcat-2/.

but SHACL carries a closed-world view, which enables data validation and is convenient for connections to databases or as part of data pipelines.

Declarative mapping tools support these transitions. D2RQ,[35] although not a W3C standard, is widely used to expose relational data as RDF without altering the source. R2RML,[36] a W3C recommendation, enables customizable mappings from SQL schemas to RDF, aligned with domain ontologies. RML[37] extends this capability to semi-structured formats such as XML, JSON, and CSV, making it suitable for diverse industrial data sources. These tools help integrate legacy systems into modern semantic frameworks without compromising infrastructure.

Schema alignment techniques are essential for harmonizing data models. Element-level approaches match ontology components based on labels, synonyms, or instances to resolve terminological inconsistencies. Structure-level techniques focus on class and property hierarchies to capture relational meaning. While both methods have limitations – such as overlooking contextual semantics or misinterpreting ambiguous structures – they remain foundational to semantic matching.

To enhance automation and scalability, recent methods combine alignment strategies with machine learning and external semantic resources. These hybrid approaches improve accuracy by leveraging statistical models and curated knowledge bases like WordNet or Wikidata. Additionally, logical validation is often included to ensure consistency. Despite showing promise, these methods remain constrained by computational cost and domain-specific training needs.

In the ontology alignment research community, the state-of-the-art can be summarized as “LLM-in-the-loop hybrid alignment”: Agent-OM, HybridOM, and “LLM as oracle” extensions of LogMap[38] are used for candidate generation, scoring, or oracle-style validation of uncertain mappings, mostly as enhancements on classical ontology matching systems [141]. These works show clear gains over pre-LLM baselines on the standard benchmarks, though their cost and complexity may be prohibitive. The LLMs4OL-Large Language Models for Ontology Learning challenge, an initiative launched by Babaei Giglou et al. in 2024 following their work [142], is a source of recent contributions on the topic.

Manual alignment remains critical in domains with limited documentation or high conceptual complexity. It allows experts to incorporate informal or domain-specific knowledge and apply formal techniques unsuitable for automation. However, it is labor-intensive, costly, and difficult to scale.[39]

6.2.3. Challenges and solutions for semiotic or contextual interoperability of data and knowledge

Semiotic interoperability deals with the highest and most complex level of interoperability: ensuring shared understanding not only of data and its structure, but also of its intended meaning within specific social, legal, organizational, or contextual settings. Unlike syntactic and semantic interoperability, which focus on format and meaning, semiotic interoperability must address differences in worldviews, domain-specific interpretations, and pragmatic constraints.

One of the central challenges at this level arises from differences in ontological and epistemological foundations. Different systems or organizations may rely on divergent assumptions about what entities exist and how knowledge about them is structured. For example, what constitutes a “product”, a “process”, or a “resource” may vary significantly across domains or even departments within the same organization. Solutions at this level must therefore account for deep conceptual alignment rather than mere terminological matching.

Domain-specific, sector-specific, and organizational vocabularies pose another key challenge. These vocabularies encode local or community-based understandings, often shaped by years of practice, regulation, or industrial standards. Achieving interoperability requires not only mapping these vocabularies onto a shared ontology but also preserving their contextual meaning. This includes application-specific semantics, which dictate how terms are interpreted based on functional roles or workflow-specific usage.

Further complexity arises from societal and cultural influences, where worldviews shape not only terminology but also the relevance and interpretation of data. For example, legal and regulatory frameworks differ significantly across jurisdictions, which can affect how compliance-related data is interpreted and shared. These legal variances demand flexible and jurisdiction-aware representations to ensure that data remains valid and actionable across boundaries.

Solutions to these challenges are diverse and typically layered. One class of solutions involves extensions of OWL and RDF, such as Fuzzy OWL [143], RDF-star (and the related SPARQL-star),[40] and RDF-Time [144], which add capabilities for representing vagueness, uncertainty, temporal aspects, and higher-order relationships. These extensions enhance the expressive power of existing formalisms to represent nuanced contextual or pragmatic constraints. For instance, RDF-star allows making statements about statements, enabling the representation of metadata such as provenance or legal qualification.

SKOS (Simple Knowledge Organization System) is widely used to manage controlled vocabularies and taxonomies. It supports the representation of concept schemes and their relationships (e.g., broader, narrower, related), and allows alignment between different conceptual structures. SKOS facilitates mapping between community-specific terminologies and broader, cross-domain ontologies, thereby addressing domain-specific and organizational vocabulary differences.

Federated knowledge graphs offer another powerful solution. These allow different organizations or systems to maintain separate yet interconnected knowledge bases. Through techniques such as ontology alignment, linking via shared identifiers (URIs), and distributed querying (e.g., via SPARQL endpoints), federated knowledge graphs support context-aware data sharing without requiring full semantic unification. They are particularly effective in addressing action-specific interpretation and organizational specificity, as they preserve local semantics while enabling cross-system integration.

Metadata standards and annotations also play a vital role. By embedding contextual metadata – such as provenance, temporal validity, licensing, and jurisdictional scope – into data models, systems can interpret the information appropriately in context. This supports legal compliance and enhances trust in data sharing.

Finally, FAIR-compliant frameworks (Findable, Accessible, Interoperable, Reusable) embed semiotic considerations into data design and governance. These frameworks emphasize rich metadata, community-driven standards, and explicit licensing, all of which contribute to

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[35] http://d2rq.org/.

[36] R2RML (RDB to RDF Mapping Language), see https://www.w3.org/TR/r2rml/.

[37] RML (RDF Mapping Language), see https://rml.io/specs/rml/.

[38] LogMap Ontology Matching tool, https://www.cs.ox.ac.uk/isg/tools/LogMap/.

[39] For OntoCommons recommendations on this, see [92]. The project developed a layered Ontology Commons EcoSystem (OCES), which supports multiple formal languages tailored to varying use cases. FOL is used for top-level ontologies where expressivity is critical; OWL 2 DL with SWRL provides a balance between reasoning and computational feasibility for domain-level models; and RDFS supports lightweight integration. OntoCommons promoted beginning with expressive models and projecting into simpler ones. Mappings within OCES enable semantic enrichment and data reuse across systems. Since reliable automatic translation from FOL to OWL is lacking, OntoCommons favored manual translation to preserve semantic intent. OWL 2 DL is the preferred language for inclusion, while RDF is acceptable for lightweight applications. Maintaining parallel implementations in expressive formalisms is encouraged to support reasoning and alignment fidelity.

[40] https://www.w3.org/2021/12/rdf-star.html.

ensuring that data is meaningful and usable across varying contexts and stakeholder groups.

In summary, semiotic interoperability requires a holistic approach that combines enhanced formal expressivity, vocabulary management, contextual metadata, and (typically) federated architectures. Tools and standards such as those mentioned above help address the multi-faceted challenges posed by diverse ontological commitments, legal constraints, and cultural worldviews. By adopting these solutions, systems can move beyond structural and semantic alignment to achieve truly context-aware data interoperability.

While developing a roadmap for priority actions is beyond the scope of this work, we give in Appendix D selected priorities from OntoCommons Roadmap and map them to the cases from the DHOS matrix in Section 5.

7. Future challenges and best practices

This section discusses some of the lessons learned and best practices for realizing interoperability, starting at the level of (i) a digital ecosystem, (ii) extending it to human interactions, and closes the first part with (iii) implementation considerations based on FAIR principles and beyond. It then discusses how (iv) emerging technologies and (v) AI agents bring opportunities but also new challenges into the landscape.

7.1. Knowledge centricity

An important recommendation when creating a digital ecosystem for a self-defined community is to start with the data and what it means, rather than a set of applications (cf. the Data-Centric Manifesto[41]). Applications typically have their own complexity and data models and can therefore be said to be data silos by design. Implementing and maintaining compatibility between applications and their different versions is tedious, expensive and error prone. The costs of maintenance and integration of new applications for such a system are high and will only increase with the number of applications. In contrast, ecosystems that start with the knowledge, focusing on the meaning of the data, and then go on to build their applications around such a semantic basis can integrate new applications almost for free.

7.2. Human centricity — combining human and digital interoperability

Industry 5.0 [145] complements Industry 4.0 by putting research and innovation at the core of the transition towards a more sustainable, human-centric and resilient industry. Human centricity as a design principle refers to designing systems, processes, and technologies with a primary focus on the needs, preferences, and behaviors of people. It prioritizes the user experience, ensuring that tools and systems are intuitive, accessible, and aligned with human capabilities, and involve combining human and digital interoperability, i.e., the integration of human expertise with digital technologies. This relate to the system types $d \leftrightarrow h$ and $h \leftrightarrow s$ in the list of interoperability cases and typical scenarios (Table 6) and the corresponding technical components addressing them (Table 7) in Section 5.

7.3. Implementation considerations for interoperability

The FAIR data principles [4] for making digital resources (re)usable by others, have since their publication in 2016 been broadly endorsed and adapted. With respect to interoperability, FAIR defines the following three guiding principles: “[Principle] I1: (Meta)data use a formal, accessible, shared, and broadly applicable language for knowledge representation.”; “[Principle] I2: (Meta)data use vocabularies that follow FAIR principles”; “[Principle] I3: (Meta)data include qualified references to other (meta)data” [4]. The rather open formulations of these guidelines allow different communities to interpret them differently and implement their own solutions. This is probably one of the key factors for the wide adoption of the FAIR principles, but has also resulted in incompatible implementations.

For instance, within the scope of a closed and homogeneous community, a community-defined exchange format, such as a table or generic JSON, may work well and be considered FAIR by the community if the format is uniquely named and consistently referred to. However, this misses the original intention of the FAIR principles and will most likely result in data exchange outside the community that will be disproportionately time consuming, if it is even possible at all (see Section 3.5.1 for cross-domain interoperability). To address such issues, Jacobsen et al. (2020) [146] introduced their *FAIR implementation considerations* to assist accelerated global participation and convergence towards accessible, robust, widespread and consistent FAIR implementations.

In a similar line, reflecting on the implementation of recommendations, but focusing on semantic interoperability, a dedicated task force from the EOSC Association has discussed how to concretize and implement the recommendations from the EOSC-IF [84], see Åkerström et al. [147].

Preserving FAIR data over time requires trustworthy digital repositories. To support this, the TRUST [148] guiding principles (standing for Transparency, Responsibility, User focus, Sustainability and Technology) were developed. These principles may also support interoperability, since knowing that a repository verifies integrity of data and metadata assures users that the data is more likely to be interoperable. These principles are well aligned with technologies like blockchain [149], see below.

7.4. Emerging technologies

Blockchain and digital twins are examples of key emerging technologies that, building on interoperability at lower levels, on one side address certain interoperability issues, and on the other bring in new challenges, reiterating a pattern we have already seen, and that is natural with evolving and complex technologies. Here we focus on these two examples, highlight their specificity and relate them to the general picture proposed in this paper. Not surprisingly, semantic technologies are pointed out as enabler in both these fields.

Blockchain creates trust based on decentralized user consensus, transparency and immutability through cryptographic hashing [149]. As such, it is a technology that addresses the security and trust aspects of data exchanges, and can be an enabler, for example, for tamper-proof digital product passports. However, interoperability issues at various levels emerge in the interaction between different blockchain platforms, and between blockchain and legacy systems. In particular, different blockchain platforms have developed different programming languages and execution environments to ensure that smart contracts can interact across multiple chains. Each blockchain having its own unique consensus mechanisms, cryptographic protocols, and smart contract languages, the absence of standardized protocols among blockchain platforms arises as a significant barrier [150]. While most of these requirements are either $d \leftrightarrow s$ or $d \leftrightarrow d$, other interoperability requirements are also $d \leftrightarrow o$. For example, technical interoperability issues also stem up from the governance structure and its capability to handle regulatory uncertainty arising from the variation of data privacy laws and regulatory compliance requirements [151]. Current chain-to-chain and chain-to-legacy interoperability relies on network-level protocols, transaction-level mechanisms, contract-level primitives, and gateway/oracle systems that bridge blockchains with traditional infrastructure. Future progress depends on unified cryptographic and trust models, virtualized and hardware-accelerated consensus, semantic and equipment-level interoperability [151], and standardized communication frameworks that integrate blockchains with legacy systems at scale. Key challenges remain in securing cross-chain operations,

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[41] https://datacentricmanifesto.org/principles/.

enabling full smart-contract portability [152], achieving semantic alignment with legacy architectures [151], and maintaining performance without sacrificing decentralization [153].

The field of digital twins (DTs) is also very active and quite mature. Vocabularies have been developed to define what a DT is and the related concepts, e.g. the ISO/IEC 20173:2023 [154]. If we consider the simpler function of a DT, namely "visualization", then a DT can be seen as a tool supporting $h \leftrightarrow h$ communication. On the other side, with complexity new levels come in, as the "cognitive interoperability" facet [10]. Dedicated initiatives have been created, as the Digital Twin Consortium (see [155] for their proposed DT interoperability framework) and the National Digital Twin Programme in UK. The analysis of DT interoperability levels in the literature shares similarity with ours. For example, Acharya et al. classify 77 DT interoperability challenges into six levels: technical (protocols/hardware), syntactic (data formats), semantic (shared meaning), pragmatic (use in context), dynamic (evolution over time), and organizational (cross-stakeholder processes) [156]. Other researchers mention incompatibility of syntax, representation of properties/behavior, communication mechanisms, and semantics in different DT standards (AAS, DTDL,[42] etc.), hidden assumptions, different spatial/temporal scales and abstraction level, and quality differences between models, semantic heterogeneity among data schema not supporting mixture of multiple sensor data and digital models, and lack of consensus on requirement and model specification among domains [157–159]. The application of ontologies and other semantic techniques is a popular choice for a systematic view [160]. In future, it is expected that the interoperability frameworks will converge into maturity levels, metrics and maybe certification schemes at each level [156].

7.5. AI and interoperability

The introduction of AI-based and AI-enhanced approaches in the knowledge representation pipeline, as well as the deployment of AI agents in knowledge systems, presents new challenges and opportunities for interoperability. Currently, machines primarily manipulate symbols, and execute procedures based on those symbols, with their meanings heavily reliant on semantic grounding provided by human agents [47]. With the rising relevance of non-human agents in knowledge acquisition and representation, it will be imperative to develop frameworks and techniques to integrate the data produced by humans and non-humans. Similarly, with the development of more sophisticated AI agents, procedural knowledge might also have to take different forms, to guarantee machine-to-machine (M2M) and human-to-machine interoperability in practical scenarios. In the short term, this might warrant an extension of the interoperability graph scenario proposed in 5.1 to include non-human agents. Including AI-based and AI-enhanced approaches in the knowledge representation pipeline has the potential to significantly impact scalability, with the automatic, or semi-automatic creation/enrichment of knowledge frameworks from datasets and natural language text, and association with persistent web resources or databases. However, the importance of semantic grounding for the effective alignment of different representations, and their interpretation, cannot be underestimated if these new technologies are to enhance interoperability across the board. As in other contexts, the amount and quality of data generated by AI might well result in a noisy data environment, negatively impacting the ecosystem.

A very active field of research is neuro-symbolic (or neural-symbolic) AI, where connectionist methods (e.g., deep learning) are combined with symbolic ones (e.g., semantic technologies described above). As these two families have complementary strengths, their combination is very promising (e.g., to support explainability of AI methods); however, usually information and knowledge are encoded in fundamentally different ways in the two (sub-symbolic *vs* symbolic) [161], raising a fundamental interoperability challenge.

8. Conclusions

In this work, which builds on and extends [16], we have collected and analyzed 18 definitions of interoperability, 22 classifications, 15 definitions of semantic interoperability, provided a list of 32 initiatives and tagged 44 references along relevant dimensions. Moreover, 65 types of interoperability were identified. As well as this terminological analysis, we have provided overviews of the topic from a number of different angles, including: recommendations, requirements, technical components, trends from a representative set of use cases. Interoperability is obviously a complex topic, as it entails multiple aspects as discussed in this work. We have identified major common points as well as key differences between the existing definitions and classifications, and provided multiple structures to summarize and rationalize the broad landscape, including, e.g., common and branching points found in the recommendations, approaches for cross-domain interoperability, and an organization of requirements in terms of interacting entities and interoperability levels. Then, we focused on knowledge representation and (data) storage, and summarized alternative options, together with details of their interoperability. We concluded by highlighting future challenges, in particular regarding computer–human interoperability and the role of AI. We offered a very broad perspective, as often many aspects of interoperability are relevant at the same time: a timely and prototypical example of this in the materials and manufacturing domain is represented by digital product passports.

It is a fact that interoperability has not yet been "solved" in all cases, and as technology advances we expect that while certain types of interoperability issues may be solved, others will appear in a continuous cycle. We therefore recommend that the many ongoing efforts with overlapping purposes keep communicating with each other and ideally join forces whenever possible and wherever suitable. Our analysis has highlighted an often fragmented and somewhat opaque landscape, which we have structured and simplified to some extent: a thorough and overarching theoretical framework would enable stronger comparisons and improve clarity. As a step in that direction to which each one can contribute, we recommend the introduction and promotion of logically sound definitions and clearer expressions when discussing interoperability (e.g., "interoperable with" rather than "interoperable", adding specifiers about the level of interoperability, referring to the definitions being adopted, etc.), and the use of such instruments as interoperability profiles. We highlight the importance of making explicit any background assumptions and the considered scope. The responsibility of a more rigorous use of language around interoperability falls on both those discussing the topic, proposing vocabularies or other assets defining it, and on those using them. Increased communication and especially increased rigor will increase both the quality and proper use of the assets, with downstream practical consequences, such as more efficient and precise communications on interoperability matters. Moreover, they will help in further clarifying the interoperability landscape, as the differences between the various models will be sharper and more robust connections will be possible.

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CRediT authorship contribution statement

Silvia Chiacchiera: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization.

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[42] Asset Administration Shell (AAS) and Digital Twin Definition Language (DTDL).

John Breslin: Writing – review & editing, Supervision. **Ana Teresa Correia:** Writing – original draft, Investigation, Formal analysis. **Jesper Friis:** Writing – review & editing, Writing – original draft. **Emanuele Ghedini:** Writing – review & editing, Supervision. **Gerhard Goldbeck:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Martin Thomas Horsch:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Mohamed Hedi Karray:** Writing – review & editing, Supervision, Funding acquisition. **Bjørn Tore Løvfall:** Writing – review & editing. **Jinzhi Lu:** Writing – review & editing. **Ilaria Maria Paponetti:** Writing – review & editing, Visualization, Investigation, Formal analysis. **María Poveda-Villalón:** Writing – review & editing, Resources. **Arkopaul Sarkar:** Writing – review & editing, Writing – original draft. **Umutcan Serles:** Writing – original draft, Investigation, Formal analysis. **Ilian T. Todorov:** Writing – review & editing, Project administration. **Noel Vizcaino:** Writing – review & editing, Data curation. **Lan Yang:** Writing – review & editing, Investigation. **Francesco Antonio Zaccarini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. List of tagged references

In Table A.10 we provide a list of (manually) tagged documents, which are a subset of the references given in the bibliography. This served as a basis for identifying the interoperability definitions (cf. Table 1) and classifications (cf. Table 2). The tag values are given in A.9. Our approach for reference tagging was inspired by similar works in the literature, see e.g., [170]. For re-usability, we provide an RDF version of the data in the Supplementary material, both in JSON-LD and TTL formats. This was created by mapping the tags to widely used standards, as SKOS and Schema.org. As described in Section 2, at least two authors tagged the references and uncertain values were discussed. We underline that some of the dimensions of tagging are inherently sharper than others, and as a consequence: the values given for each entry for T1, T4, T5, T6, T8 are very robust, whereas those for T2 A, T2B, T3, T7 are more tagger-dependent and should be seen in that light.

Appendix B. List of interoperability types

To show the variety of concerns and points of view that can arise, we list below 65 interoperability types that we have identified and point to the references that discuss them. This list was mostly obtained by expanding the classifications of interoperability given in Table 2, with an extra addition (Cognitive interoperability). As this aggregated list is heterogeneous by construction, the scope and purpose needed to be taken in account when comparing the various flavors.

We note that two references in the list do not give "interoperability" types strictly speaking, but rather described related facets which we found it useful to include here: in fact, Ref. [40] gives types of interoperability "concerns", "barriers" and "approaches"; [42] gives "heterogeneity" types (see Table 2 for details). Finally, we note that in a few instances we did separate a type into its components, in particular for "semantic data" from [24,26].

In alphabetical order, the interoperability types are: (ML) Algorithm [31], Application [11,34], Behavioural [24,26,28], Business [33,34,40], (Materials) Characterization [27], Cloud [24,41], Cognitive [10], Communication [34], (Scientific) Community [27], Conceptual [29,40,42], Constructive [7], Cultural [41], Data [7,11,24,26,33,34,40,41], Data format [31], Data-sharing [28], (Intra- and cross-) Data space [33], Device [31,43], (Cross-) Domain [43], Diachronic [19], Dynamic [29], Ecosystems [41], Electronic identity [41], Encoding [39], Enterprise [7], Federated [40], Functional [7], Horizontal [19], Information [7], Integrated [40], Knowledge [34,41], Legal [25,33], Lexical [39], Model-driven [19], (Materials) Modelling [27], Network(ing) [11,43], Non-technical [5], Numerical [27], Objects [41], Operational [7], Organizational [25,33,40], (Cross-) Platform [43], Policy [24,26,28], Pragmatic [9,22,29,42], Process [7,40,41], Programmatic [7], Protocol [31], Rules [41], Semantic [9,22,24–29,31,33,38,39,42,43], Semantic-driven [19], Semiotic [39,42], Service(s) [11,40,41], Social networks [41], Software (systems) [41], Structure [38], Synchronic [19], Syntactic [9,22,24,26,29,33,39,42,43], Syntax [38], System [7,38], Technical [5,7,22,25,29,33,33], Technological [40], Terminological [42], Transport [24,26], Unified [40], (Material) Use(r) case [27], Vertical [19].

Appendix C. Example of specific requirements and KPIs in the DHOS structure

The generic requirements catalog presented in Table 6 and Section 5 can be used in practice when designing a specific data infrastructure or

Table A.9
Properties and values for reference tagging.

Tag ID	Property	Values
T1	Reference type	Journal publication, technical report, project result, formal text,[a] other
T2A	Reference primary content	Recommendation/principles, method, tool, review/comparison, use-case, formal principles/definitions, metric
T2B	Reference secondary or other content	[same values as T2A]
T3	Interoperability of what type of entities?	Data, software, humans, ontologies, things,[b] organizations
T4	Has definition of interoperability	Yes, no (If yes: defined, reused)
T5	Has glossary (including entry for interoperability)	Yes, no, ∼ yes[c] (If yes: yes, no)
T6	Has classification of interoperability types	Yes, no (If yes: defined, reused)
T7	Heterogeneity type addressed	Syntactic, terminological, conceptual, semiotic
T8	(For reviews) # of Articles/approaches/resources reviewed	–

[a] Formal text includes: ISO standard, legislation, specification.

[b] Here and across the document, "thing" is intended as "physical device" (cf. Internet of Things, IoT).

[c] The "∼ yes" option refer to cases where a number of concepts is defined/characterized, but they do not appear as a list in a separate section.

Table A.10

List of tagged references (alphabetically ordered). Cf. Table A.9 for details on the analyzed properties and their allowed values. Note: for readability, we use an additional identifier for references alongside the bibliographic citation number, namely "[⟨First Author⟩ ⟨Publication Year⟩]".

Ref. ID	T1: Ref. type	T2A: Content I	T2B: Content II	T3: Entities	T4: Define	T5: Glossary	T6: Classify	T7: Hetereogenity	T8: # resources
[Ali 2024] [10]	Journal publication	Review/comparison	Definitions	Software	Yes (defined)	No	No	Conceptual, semiotic	90 papers
[Amjad 2021] [12]	Journal publication	Review/comparison	Tool	Data, software, things	Yes (reused)	No	Yes (reused)	n/a	34 works and 19 tools
[Andročec 2018] [11]	Journal publication	Review/comparison		Things	No	No	Yes (reused)	Conceptual	105 primary studies
[Asuncion 2010] [9]	Journal publication	Review/comparison		Software, data	Yes (reused)	No	Yes (reused)	n/a	44 papers (with unique definitions)
[Berners-Lee 2006] [100]	Other (webpage)	Method	Metric	Data	No	No	No	No	
[Baumann 2021] [162]	Technical report	Methods	Use-case	Data	Yes	No	No	Conceptual	
[Chávez-Feria 2021] [163]	Journal publication	Method	Tool	Data	No	No	No	No	
[Cimmino 2020] [164]	Journal publication	Tool	Method	Data	No	No	No	No	
[da Silva Serapião Leal 2019] [8]	Journal publication	Review/comparison	Metric	Organizations	Yes (reused)	No	Yes (reused)	n/a	72 papers and 22 INAS approaches
[Data act 2023] [30]	Formal text	Principles	Definitions	All	Yes (defined)	Yes (yes)	Yes (reused)[a]	n/a	
[Diraco 2023] [31]	Journal publication	Review/comparison		Data, software, humans, things	Yes (defined)	No	Yes (defined)	All	>100 papers (8 in interoperability), 26 public datasets
[DSM 2023] [105]	Project result, other (website)	Metric	Recommendation	Data	No	Yes (no)	No	Syntactic, terminological, conceptual	
[García 2024] [33]	Technical report	Recommendation	Use-case(s) (pointers to)	Data	Yes (reused)	Yes	Yes (reused)	n/a	
[EIF-eu 2017] [25]	Technical report	Recommendation/principles		Data, organizations, software	Yes (defined)	No	Yes (defined)	Syntactic, conceptual	
[EMMC-CSA 2019] [27]	Project result (deliverable)	Principles	Method, tool	Software	Yes (defined)	No	Yes (defined)	All	
[EOSC-IF 2021] [84]	Project result	Recommendation/principles	Method	All	Yes (reused)	No	Yes (reused)	All	
[ETSI 2019] [165]	Technical report	Recommendation/principles	Review	Data, things	No	Yes (no)	No	Conceptual	18 IoT-centric approaches/resources /projects

(*continued on next page*)

Table A.10 (*continued*).

Ref. ID	T1: Ref. type	T2A: Content I	T2B: Content II	T3: Entities	T4: Define	T5: Glossary	T6: Classify	T7: Hetereogenity	T8: # resources
[Euzenat 2001] [39]	Journal publication	Formal principles/definitions	Review/comparison	Ontologies	Yes (defined)	Yes	Yes (defined)	All (focus on terminological, conceptual)	3 approaches
[Euzenat 2013] [42]	Other (book)	Formal principles/definitions	Review/comparison	Ontologies	Yes* (defined - heterogeneity)	Yes	Yes* (defined - heterogeneity)	All (focus on terminological, conceptual)	9 general matching approaches; 96 specific systems
[Ford 2007] [5]	Technical report	Review/comparison	Metric, definitions	Data, software, humans, things, organizations	Yes (reused)	No	Yes (defined - plus collated list of reused types)	n/a	14 measurement models. Also: 34 definitions and 64 types
[Fraga 2020] [13]	Journal publication	Review/comparison		Data, things, software, organizations	Yes (reused)	No	Yes (reused)	Terminological, conceptual, semiotic	54 primary studies
[Garijo 2020] [166]	Journal publication	Recommendation/principles	Method, use-case	Ontologies	No	No	No	n/a	
[Guédria 2009] [40]	Journal publication	Metric	Review/comparison	Organizations, data	No	No	Yes* (reused - concerns, barriers, approaches)	Syntactic, terminological, conceptual	5 maturity models
[Guizzardi 2020] [47]	Journal publication	Principles	Definitions, method	Data, ontologies, humans	Yes (defined)	No	No	Conceptual, syntactic	
[Gupta 2022] [29]	Journal publication	Metric	Principles	Data, ontologies	Yes (defined)	No	Yes (defined)	Conceptual, syntactic	
[Gürdür 2016] [109]	Journal publication	Method	Tool, case study	Data, software	No	No	No	Terminological, conceptual	
[Gürdür 2018] [7]	Journal publication	Review/comparison	Metric	Data, things	Yes (reused)	No	Yes (own set, from existing ones)	Conceptual	48 papers, 26 INAS models
[Hagelien 2021] [48]	Journal publication	Method	Tool	Data	No	Yes	No	All	
[IEC 2019] [26]	Technical report (white paper)	Recommendation	Use-case	All	Yes (defined)	Yes	Yes (defined)	Conceptual, terminological, semiotic	
[IEEE 1990] [17]	Formal text	Definitions		Data	Yes (defined)	Yes	No	n/a	
[IEEE 1991] [167]	Formal text	Definitions		Data	Yes (defined)	Yes	No	n/a	
[Janowicz 2014] [102]	Journal publication	Recommendation/principles	Metric	Ontologies	No	No	No	n/a	
[Janssen 2014] [22]	Journal publication	Metric	Recommendation	Data, systems	Yes (both defined and reused)	~yes	Yes (defined)	Syntactic, conceptual, semiotic	

(*continued on next page*)

Table A.10 (*continued*).

Ref. ID	T1: Ref. type	T2A: Content I	T2B: Content II	T3: Entities	T4: Define	T5: Glossary	T6: Classify	T7: Hetereogenity	T8: # resources
[Matentzoglu 2022] [94]	Journal publication	Method	Tool, use-case	Data	No	No	No	Terminological, conceptual	
[Nagel 2021] [28]	Project result (white paper)	Recommendation/principles		Data	Yes (defined)	Yes (yes)	Yes (defined)	n/a	
[Noura 2018] [43]	Journal publication	Metric	Principles, review	Things, software, data, ontologies	Yes (reused)	~yes	Yes (defined)	Syntactic, conceptual, terminological	15 IoT interoperability platforms
[Ouksel 1999] [38]	Journal publication	Metric	Review	Data	No	~yes	Yes (defined)	Syntactic, conceptual, semiotic	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] [19]	Journal publication	Review/comparison	Use-case	Organizations, software, data	Yes (both defined and reused)	No	Yes (reused)	All	5 maturity models
[Parent 2000] [168]	Other (book chapter)	Method	Metric	Data	No	No	No	Conceptual, syntactic	
[RDA 2020] [103]	Technical report	Recommendation/principles	Metric (See “indicators”)	Data	No	Yes (no)	No	n/a	
[Rezaei 2014] [6]	Journal publication	Review/comparison	Recommendation/principles, metric	Software, data, things, humans, organizations	Yes (reused)	No	Yes (reused)	Syntactic	10 interoperability evaluation models
[Szejka 2017] [14]	Journal publication	Review/comparison		Data	No	No	No	Conceptual	14 references (selected, primary studies)
[Vatant 2012] [101]	Other (blog entry)	Metric	Recommendation	Data	No	No	No	Terminological, conceptual	
[Weichhart 2021] [169]	Journal publication	Method		Organizations, things, data	Yes (reused)	No	No	Conceptual, semiotic, syntactic	

[a] It cites ISO 19941:2017 [24] “interoperability facets”.

Table D.11
Classification of recommendations from OntoCommons roadmap [171]. Abbreviations: TLO — top-level ontology, MLO — mid-level ontology, DLO — domain level ontology, OCES — OntoCommons Ecosystem, VRE — Virtual research environment.

#	Recommended action	Level	Type
1	Alignment of TLO/MLO/DLO ontology layers	Semantic	$d \leftrightarrow d$
2	Creation of FAIR and reusable DLOs	Semantic	$d \leftrightarrow d$
3	Adoption of standardized units and metrology	Semantic	$d \leftrightarrow d$
4	Development of data marketplaces	Semantic	$d \leftrightarrow d$
5	Establishment of shared semantic annotation principles	Semantic	$d \leftrightarrow d$
6	Deployment of ontology-aware modeling toolchains	Semantic	$d \leftrightarrow s$
7	Use of semantic reasoning and validation engines	Semantic	$d \leftrightarrow s$
8	Provision of OCES semantic knowledge-graph services	Semantic	$d \leftrightarrow s$
9	Coordination across ontology-governance communities	Semantic	$o \leftrightarrow o$
10	Harmonization of semantics used across standardization bodies	Semantic	$o \leftrightarrow o$
11	Establishment of industry-wide ontology registries	Semantic	$o \leftrightarrow o$
12	Structured ontology-literacy programmes	Semantic	$h \leftrightarrow d$
13	Accelerate the curation of domain terminologies	Semantic	$h \leftrightarrow d$
14	Delivery of semantics-enabled tooling for non-experts	Semantic	$h \leftrightarrow s$
15	Provision of Translator-support for domain–semantic mediation	Semantic	$h \leftrightarrow s$
16	Formal establishment of the Translator role	Semantic	$h \leftrightarrow o$
17	Semantic-driven standardization support within organizations	Semantic	$h \leftrightarrow o$
18	Targeted outreach to accelerate semantic adoption in industry	Semantic	$h \leftrightarrow o$
19	Definition of FAIR metadata schemas	Syntactic	$d \leftrightarrow d$
20	Standardization of tagging and annotation conventions	Syntactic	$d \leftrightarrow d$
21	Consistent machine-readable encoding of units and quantities	Syntactic	$d \leftrightarrow d$
22	Enforce structural correctness by SHACL engines	Syntactic	$d \leftrightarrow s$
23	Deployment of secure, standards-based APIs for data exchange	Syntactic	$d \leftrightarrow s$
24	VRE-supported ingestion and pipeline architectures	Syntactic	$d \leftrightarrow s$
25	Integration of OCES toolchains into cohesive workflows	Syntactic	$s \leftrightarrow s$
26	Adapters and middlewares for cross-tool syntactic compatibility	Syntactic	$s \leftrightarrow s$
27	Establishment of common project-level syntactic rules	Syntactic	$o \leftrightarrow o$
28	Creation of unified syntax for domain data workflows	Syntactic	$o \leftrightarrow o$
29	Deployment of user-friendly modeling and validation interfaces	Syntactic	$h \leftrightarrow s$
30	Reference syntactic pipeline templates for consistent tool usage	Syntactic	$h \leftrightarrow s$
31	Governance coordination of the standardization bodies	Semiotic	$o \leftrightarrow o$
32	Formation of service marketplaces	Semiotic	$o \leftrightarrow o$
33	Establishment of collaborative open-foundry development practices	Semiotic	$o \leftrightarrow o$
34	Documentations of semantic and syntactic assets	Semiotic	$h \leftrightarrow d$
35	Promote explanation of ontology models and theirs commitments	Semiotic	$h \leftrightarrow d$
36	Publication of semantic-modeling best-practice guidelines	Semiotic	$h \leftrightarrow s$
37	Collaborative environments for joint semantic engineering	Semiotic	$h \leftrightarrow s$
38	Creation of structured training pathways	Semiotic	$h \leftrightarrow o$
39	Formal recognition of Translator career progression	Semiotic	$h \leftrightarrow o$
40	Sustained industry engagement and communication efforts	Semiotic	$h \leftrightarrow o$

project. To show this, we give here examples of specific requirements and corresponding KPIs from a concrete research proposal related to the Knowledge Graph Alliance's work on explainable-AI-readiness [172], which as a whole cannot be shared due to the proposal's confidential nature [173]. They include:

- $d \leftrightarrow d$: Integrate explanation, robustness, and trustworthiness documentation into the knowledge representation formalism by developing a system of ontologies covering all the required epistemic metadata. KPI: All explanations, limitations, and uncertainty metrics can be documented using the ontologies.
- $d \leftrightarrow d$ and $s \leftrightarrow s$: Acquire, harvest, and procure thermophysical property data and metadata and deposit the data in the project's knowledge base. KPIs: acquire $\geq n$ data points from data sources; implement a data harvesting/update protocol.
- $h \leftrightarrow h$: Specify good practices for explainability as well as guidelines and metrics for facilitating and quantifying compliance with these practices. Define, map, and validate sustainability-related metrics. KPIs: Publish a white paper specifying explainable-AI-readiness criteria/metrics for models and data, including computational and data efficiency and sustainability metrics, underwritten by $\geq n$ experts.
- $h \leftrightarrow s$: Implement a metaportal that allows for easy access to functionalities from a single point of entry. KPIs: Data retrieval, extraction, ingest, and models can be accessed by users through the portal; tested with representatives of $\geq n$ groups of stakeholders.
- $o \leftrightarrow s$: Support compliance and valorization potential of the foundation model by enabling unlearning of data (and proofs that data are unlearnt) and bias correction (and proofs that biases are removed); document compliance. KPIs: Practices, criteria, and metrics for epistemic justice and compliance with European regulations, AI Act, and European Approach to AI specified in white paper endorsed by $\geq n$ experts; compliance with all essential criteria documented.

Appendix D. Classification of recommended actions from OntoCommons roadmap

Here (see Table D.11) we list selected recommended actions from OntoCommons Roadmap [171] and map them to the DHOS classification structure from Section 5: this serves to indicate priority actions identified by that project and also as an example of application of the DHOS structure.

Appendix E. Glossary

Here we elucidate some of the key terms used throughout the paper, with the purpose of helping the reader and with no intention of introducing novel definitions. Note that "data", "software", "human" and "organization" are defined in Section 5.1 and for the purposes of that section.

- **Artifact (or asset)**: We use this to denote software and semantic artifacts (including ontologies, alignments and mappings, amongst others).
- **Heterogeneity types**: These are adapted here from [42]. They were originally defined for ontologies, but here we use them in a broader sense. *Syntactic heterogeneity:* Different forms (e.g., file formats, etc.); *Terminological heterogeneity:* Variations in names when referring to the same entities (e.g., due to different natural languages, language variants, or synonyms); *Conceptual (or semantic) heterogeneity:* Differences in modeling the same domain of interest (e.g., due to different granularity, coverage, perspective); *Semiotic (or pragmatic) heterogeneity:* Concerned with how entities are interpreted by people.
- **Interoperability:** A capability of two (or more) (separate) entities to usefully/correctly function together. Multiple types can be identified; in particular, semantic interoperability focuses on useful/correct sharing of meaning/content; syntactic interoperability on form/format and pragmatic interoperability focuses on the relation to the communication environment. In our use of the term, interoperating entities can be of different natures (e.g., human and software, cf. Section 5), and no directionality of the relation is assumed. Interoperability types can match heterogeneity types. Here we follow that approach, but merge terminological and semantic interoperability into one for the purposes of Section 5.
- **Reasoning**: Automatically inferring new (true) statements from given ones. Reasoning is mainly deductive in semantic data models and inductive in data-driven ones [95].
- **(IoT) Thing:** A physical device, as in the Internet of Things (IoT). (Disambiguation note: we use "entity" for something in a more general sense.)

Appendix F. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jii.2026.101116.

Data availability

Data (RDF version of Table A.10) is made available as supplementary material, and also on GitHub (https://github.com/HE-BatCAT/RoDI-supporting-data)

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