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ONTO-DESIDE

DELIVERABLE

Ontology network architecture, methodology and alignment plan - v.2

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PROJECT INFORMATION

Project summary

Circular economy aims at reducing value loss and avoiding waste, by circulating materials or product parts before they become waste. Today, lack of support for sharing data in a secure, quality assured, and automated way is one of the main obstacles that industry actors point to when creating new circular value networks. Together with using different terminologies and not having explicit definitions of the concepts that appear in data, this makes it very difficult to create new ecosystems of actors in Europe today. This project will address the core challenges of making decentralized data and information understandable and usable for humans as well as machines. The project will leverage open standards for semantic data interoperability in establishing a shared vocabulary (ontology network) for data documentation, as well as a decentralized digital platform that enables collaboration in a secure and privacy-preserving manner.

The project addresses several open research problems, including the development of ontologies that need to model a wide range of different materials and products, not only providing vertical interoperability but also horizontal interoperability, for cross-industry value networks. As well as transdisciplinary research on methods to find, analyze and assess new circular value chain configurations opened by considering resource, information, value and energy flows as an integral part of the same complex system. Three industry use cases, from radically different industry domains, act as drivers for the research and development activities, as well as test beds and demonstrators for the cross-industry applicability of the results. The developed solutions will allow for automation of planning, management, and execution of circular value networks, at a European scale, and beyond. The project thereby supports acceleration of the digital and green transitions, automating the discovery and formation of new collaborations in the circular economy.

Project start date and duration

1st of June 2022, 36 months

Project consortium

No	Partner	Abbreviation	Country
1	Linköping University	LIU	Sweden
2	Interuniversitair Micro-Electronica Centrum	IMEC	Belgium
3	Concular Ug Haftungsbeschrankt	CON	Germany
4	+Impakt Luxembourg Sarl	POS	Luxembourg
5	Circularise Bv	CIRC	The Netherlands
6	Universitaet Hamburg	UHAM	Germany
7	Circular.Fashion Ug (Haftungsbeschrankt)	FAS	Germany
8	Lindner Group Kg	LIN	Germany
9	Ragn-Sells Recycling Ab	RS	Sweden
10	Texon Italia Srl	TEXON	Italy
11	Rare Earths Industry Association	REIA	Belgium

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Contents

Abbreviations

Abbreviation	Explanation
CE	Circular Economy
CQ	Competency Question
CS	Contextual Statement
CVN	Circular Value Network
Dx.x	Deliverable x.x
EOSC	European Open Science Cloud
FAIR	Findability, Accessibility, Interoperability, Reusability
ISO	International Organization for Standardization
LOV	Linked Open Vocabularies
ODP	Ontology Design Pattern
OGC	Open Geospatial Consortium
OWL	Web Ontology Language
RDF	Resource Description Framework
RR	Reasoning Requirement
URI	Uniform Resource Identifier
W3C	World Wide Web Consortium
WP	Work Package
XD	eXtreme Design
OM	Ontology Matching

Summary

This deliverable describes the ongoing research work conducted in WP3, as part of the first and second project iteration, and leading up to the current set of ontology modules reported in D3.4. The deliverable covers the four main activities performed in WP3, which include (1) designing and setting up the methodology for ontology development, alignment and FAIR ontology publishing, (2) performing an extensive survey of existing research and existing ontologies, as well as policies and standards, that the Onto-DESIDE ontology network needs to take into account, and potentially align to, (3) developing the set of ontological requirements that lead to the outline of an ontology network architecture and a set of ontology modules that were delivered in D3.4, and (4) analysing and outlining the potential for ontology alignments, and developing an intitial ontology alignment strategy and methodology.

The methodology of this work package is based on an existing, agile and iterative, ontology engineering methodology. This methodology is analysed and some adaptations are being made to make it more fit-for-purpose in the context of this project. A set of adaptations are discussed in this deliverable.

Next, when analysing the existing research and ontologies found in our survey, we note that a main notion missing in Circular Economy (CE) ontologies is the circular value network (CVN) itself. A circular value network consists of collaborating actors, implementing some circular strategies, therefore "actor" is a central concept, as well as their capabilities and processes for implementing the strategies. Still, most existing ontologies focus heavily on the material flows, material composition of products and components, and digital product passports. We, hence, observe that there are some additional concepts to model to be able to create a digital representation of such networks themselves, i.e., enabling the creation of a digital twin of a circular value network. Therefore, our ontological requirements specifically covers this aspect, and such modules are a central part of the ontology network.

On the other hand, many of the other core concepts, such as products, processes and materials have been modelled in many existing ontologies. In these cases, the challenge is more related to creating appropriate alignments to those ontologies, as well as being able to represent the contextual nature of some of these concepts in our ontology network. For instance, what one stakeholder in a circular value network may consider a product, i.e., something they put on the market and sell, might very well be considered a component or even material by another stakeholder. Additionally, challenges involve to be able to appropriately align to the emerging standards in the CE domain, and to existing ontologies.

Next steps in WP3, following D3.2, include the evaluation of the second release of the ontology network, continuing the development in the final project iteration, and the publishing of an extended version of the survey results in a scientific journal.

1 Introduction

Semantic interoperability of data is one of the biggest barriers towards data sharing in the Circular Economy (CE) domain [66]. This means that although concrete data formats may be agreed and standardised, at the syntactic level, it is still difficult to interpret the data correctly, and thereby data from different organisations can often not be integrated and used together. The Onto-DESIDE project will provide the technical foundations for semantic interoperability in information flows that has the potential to transform digitalisation and data sharing to support a (more) CE. The project makes use of open standards for semantic data interoperability in establishing a shared vocabulary, i.e., a network of ontologies for data documentation, as well as a decentralized digital platform that enables collaboration in a secure and confidential manner. Ontologies are a key enabler for semantic interoperability since they can provide formal definitions of concepts and their relations, for describing the data to be exchanged. As well as provide a way of expressing alignments, i.e., relations, between existing standards and models. What this project will develop is at its basis a technology for allowing data sharing about materials, components, and products, as well as actors, capabilities and processes, as part of circular value networks (CVNs), at a global scale and across industry domains. Metadata and structures for transforming data into information (semantic descriptions, vocabularies) will be open, and comply with FAIR principles (Findability, Accessibility, Interoperability, and Reusability), to enable the highest possible degree of semantic interoperability and automation in data sharing.

This deliverable presents the initial work in Onto-DESIDE WP3, which is dedicated to provide the necessary ontologies to enable semantic interoperability. The deliverable is specifically concerned with the ontology engineering methodology, strategies for ontology alignment and publishing, and the requirements of the ontology network itself. This is the second version of the deliverable, presenting results from the first and second project iteration. This concretely means that the deliverable reports results from the first project iteration as well as our setup and plans outlined in the second project iteration. However, ontology requirements are still to be considered as preliminary, since they are not fully validated and updated for the third and final project iteration, i.e., this is a living set of requirements. More details on the methodological aspects and limitations can be found in the methodology description in Chapter 3.

1.1 Motivation

In order to enable the creation of digital twins of circular value networks, and enable automation in both the discovery, setup and execution of such networks, a formal definition of the entities involved in such networks is needed. In the simplest case, this may be merely to be able to transfer trustworthy, semantically well-defined and documented data about the materials, components, and products themselves between actors, e.g., a deconstruction company allows data about the deconstructed building parts to be accessed by the recycling company that receives these parts, who can then make appropriate plans and decisions based on their recycling potential (c.f. D2.1 user story CUS11: Planning). However, more complex scenarios also exist, for instance when setting up new circular value networks. An example could be when trying to understand if the rest material from the production in one manufacturing company could be used by someone else, potentially in a completely different industry domain (c.f. D2.1 CUS4: Rest Material from Production). This requires both information about the potential actors that may use the material, their types and capabilities, as well as input requirements for various production processes. In our overall project description we have envisioned this as the potential of having "blueprints", or archetypes, of typical circular value networks, where roles can then be filled by concrete actors and concrete materials, components, and products. Hence, although we do not necessarily envision that explicit data about complete value networks exist in a data store anywhere, actors will need to be able to retrieve also semantically well-defined data about other actors, their needs and capabilities, in order to support some degree of automation when discovering, assessing, setting up and executing parts of a circular value network.

To enable such data to be understood by both humans and machines, it should be semantically well described and documented, i.e., by being linked to an ontology. Using a shared ontology enables actors to achieve not only syntactic interoperability, e.g., shared or standardised file formats, but also semantic interoperability, i.e., ensuring a well-defined meaning of the data content itself. Although in the best case the actors share the same ontology, even if that is not the case, having such semantic data documentations at least allows actors to retrieve the intended meaning, and potentially map and align it to their own ontologies and data models in a reliable way. Hence, although this project will also work towards standardisation of these ontologies, as a first step merely having a formal definition of the semantics will be useful in itself.

Further, since the domain of circular economy and circular value networks is very broad, and may involve actors and products in any industry domain, it is obvious that creating one single ontology to encompass all possible data to be documented is infeasible. Hence, the focus is here on an ontology network. An ontology network is a "*collection of ontologies related together via a variety of relationships, such as alignment, modularization, version, and dependency*" [89]. This enables users to include the necessary parts of the network applicable to their use cases, without having to use a huge monolithic ontology, which both improves understandability, learnability, and reuse potential. It also enables us to reuse, and align to, numerous existing ontologies, some of which are already (de-facto) standards in certain fields.

1.2 Deliverable Objectives

In Onto-DESIDE, WP3 is responsible for developing one of the core outcomes of the project, the ontology network for data documentation and its alignment to relevant standards and existing ontologies, but also to manage the documentation and FAIR publishing of the ontologies. The objectives of this second version of the deliverable, and the corresponding work in WP3 are setting the stage for the ontology network being developed through both an extensive review of the state-of-the-art and related work, describing the methodology of the further development of the ontology network, as well as the architecture of the core modules needed in the ontology network as well as plans for their alignments to other ontologies.

The deliverable reports preliminary results, in the sense that work is still ongoing until the end of the project, e.g., validating and updating the ontological requirements and the ontology modules (i.e. CEON) with the domain experts in the project. The currently reported results have been validated through the WP6 evaluation of the first project iteration, but will be further evaluated and updated in the final project iteration.

1.3 Tasks and Document Outline

WP3 consists of 4 separate, but interrelated, tasks. Task 3.1 concerns the ontology development methodology. The methodological setup for the ontology development will consist of both a variant of an existing ontology engineering methodology, specifically tailored for the project setup, as well as detailed guidelines for ontology specialisation (i.e. extending the ontology network) and population (i.e. mapping data to the ontology) to be used within the three industry use cases in WP6. The methodology will also be aligned to the overall project research methodology specified in WP2, and the circularity metabolism concept of WP5. Since not all principles of the original methodology are immediately applicable to our project, we discuss how the methodology has been adapted to suit our specific context. Included in this deliverable related to Task 3.1 is a presentation of the original methodology, called eXtreme Design (XD), as well as a discussion of the adaptations needed for the project context. Further methodology development will take place throughout the project, and the extension methodology will be presented as part of the training material of WP7 at the end of the project.

Task 3.2 concerns the ontology modelling itself, resulting in our ontology network (CEON). The focus of this task is on carrying out the actual modelling of the ontology network, by using the modelling methodology from Task 3.1, based on requirements (user stories) from WP2, contextualised by the use case descriptions produced in WP6, that are then transformed into ontological requirements. The modelling includes both highly reusable generic ontology modules, which could be viewed as a form of Ontology Design Patterns (ODP) forming a core module library (ODP catalogue), as well as more CE specific ontology modules as specialisations and extensions of the generic ones. The latter also includes alignment modules, relating our modules to existing ontologies. Quality assurance of the ontology modules is performed through ontology testing and validation activities, before releasing each module, although the ontology network should still be considered as a prototype and subject to change until the final release at the end of the project. While we outline the intended ontology architecture and topics of the current set of core modules in this deliverable, the actual ontology modules are delivered and described in detail in D3.3-3.4 and their subsequent updates.

Task 3.3 focuses on ontology alignment, which is a central issue in a cross-domain interoperability effort such as the Onto-DESIDE project. The task will ensure proper alignment to existing ontologies, such as OntoCommons core and EMMO ontologies, and integration with other domain ontologies, such as existing product and materials ontologies. Specific alignment modules will be produced, and ontology debugging and completion tools will be used for extending and ensuring the quality of the alignments. However, in this deliverable only the overall strategy is described, while details on the actual alignment modules will be included in D3.5-3.6.

Finally, Task 3.4 is concerned with FAIR ontology publishing and maintenance. Ontology publishing is conducted according to the FAIR principles, and using an open platform, i.e., GitHub. All ontology modules are properly documented, for ease of use and increased reuse, version control. As well as a change request and management system, i.e., through using GitHub issue tracking. Included in this deliverable is a description of the current publishing pipeline, and the main principles underlying it. The task will also develop a plan for ontology maintenance and evolution beyond the project lifetime, including both methodological and practical/technical aspects, although this is still future work.

This deliverable presents the current status and results of the four tasks described above, i.e. the ontology development methodology, the overall ontology network architecture and current core ontology modules, as well as alignment strategies and an overview of existing ontologies, and our publishing strategy. This is the second version of the deliverable, still presenting preliminary results, which will be further extended and refined until the end of the project. Hence, the main purpose of this deliverable is setting the stage for further work in WP3 in the final project iteration.

The remainder of the document is structured as follows: In Chapter 2 we introduce some of the basic notions and technologies used in the remainder of the document, e.g., ontologies, ontology modules and networks, as well as some background on ontology engineering, ODPs and the XD methodology. This chapter is intended for readers not already familiar with these concepts. Next, we present our adapted methodology and the research process applied so far in WP3 in Chapter 3. Chapters 4, 5 and 6 then present our preliminary results, on one hand providing an overview of the existing research and ontologies found so far, and on the other hand our set of requirements and the initial outline of the second version of the ontology network (i.e. a brief overview of CEON, further described in D3.4), together with alignment plans. Finally, some concluding remarks are made in Chapter 7.

2 Background

In order for this deliverable to be understandable by a broad audience, including researchers and practitioner in the circular economy field, in this chapter we briefly introduce some of the basic notions used in this work and the deliverable. From the perspective of knowledge representation, we introduce ontologies in Section 2.1. Then in Section 2.2, we introduce ontology engineering with a focus on ontology development.

2.1 Ontologies

The term ontology is used in several fields, including both philosophy and computer science. In this project we focus on the computer science-related notion of ontology. There are multiple definitions of the term "ontology", even within the field of computer science, but one of the most commonly cited definitions states that an ontology is an "*explicit specification of a conceptualization*" [34]. Some later definitions have also added aspects, such that the ontology should represent a *shared* conceptualisation, and that the explicit specification should be *formal*, in the sense of being expressed in some (logical) language with formal semantics. Another common definition explains it like this: "*An ontology is a logical theory accounting for the intended meaning of a formal vocabulary, i.e., its ontological commitment to a particular conceptualisation of the world. The intended models of a logical language using such a vocabulary are constrained by its ontological commitment. An ontology indirectly reflects this commitment by approximating these intended models.*" [36]. More informally, this means that and ontology in computer science is an artefact, that consists of a formal structure that explicitly defines the concepts and relations between concepts existing within some domain, or related to a specific application. Depending on how narrow and well-specified the definitions in the ontology are, the ontology could make more or less ontological commitments.

To explain this a bit more, let's take an example of a small (naïve) ontology relating to university courses. This ontology may contain the three concepts "Person", "University" and "Course". In addition to these concepts, the ontology would contain relevant relations between the concepts, such as that a course is given at a certain university, and that persons take courses. An informal illustration of such an ontology, in the form of a simple conceptual diagram, can be seen in Figure 1. This ontology can now be used to annotate, or describe, data by expressing that certain instances are of the type "Person" and others have the type "University", for instance, and that certain relations from the ontology hold between the instances, i.e. specific persons are related to specific courses via the "takes"-relation. So far, this is not very different from adding descriptive column headings to a data table, in case of tabular data, except for the fact that data can be seen as a graph. However, in the case of ontologies, named concepts and relations are only the starting point, because when implementing this conceptual model in a formal logical language, we can also add further formal definitions and restriction on these concepts and relations, i.e. we can express general *axioms*. Such things could for instance be to define a new concept based on restrictions over existing ones, e.g. to say that students are exactly those persons who are enrolled at some university or who take some course, subsequently allowing an inference engine to automatically classify instances of person as being students or not. Or to restrict the types of things for which the relations apply, e.g. saying that the "given at" relation always relates a university to a course. However, the more such axioms that are added, the more we extend the ontological commitment of the ontology. The benefit is that we can then draw more conclusions based on the ontology, i.e. perform automatic inferencing, such as consistency checking or finding new facts that are derivable from our data, as in the case of finding out who is a student above. The drawback is that such axioms rarely hold universally, but merely in a restricted domain. For instance, if we express that all courses are given by a university, we exclude evening classes given by other types of organisations, and even lower grade courses given by schools and other kinds education establishments. Concepts, relations and axioms that make sense in one domain, may not make sense if that domain is extended, or if the domain is exchanged for another one. Hence, the ontology becomes less reusable outside the originally intended domain(s) and task(s). This trade-off is important to note, and will be discussed further when we discuss ontology engineering methodology and modularisation of ontologies.

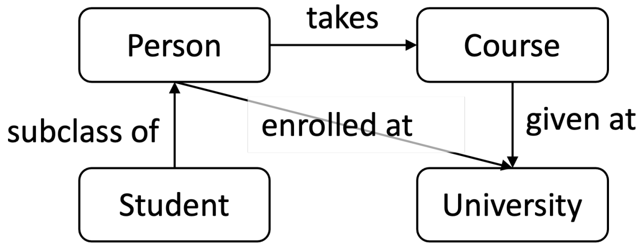

Figure 1: A small sample ontology, illustrated through an informal conceptual diagram. Concepts are represented at "boxes" and the arrows represent "relations" between concepts.

Different logical formalisms exist for representing and reasoning with ontologies, each one having its own benefits and drawbacks. The choice of representation should be made based on the requirements of the ontology, but also standardisation and tool availability may influence such a decision. However, with the emergence of the W3C standards RDF[1] [81] (for graph data) and RDFS/OWL (for ontology representation), the predominant formalism is nowadays OWL (Web Ontology Language) [69]. Especially in cases where ontologies and data will be shared over the Web, or at least using Web technologies, RDFS/OWL is considered the best choice. Therefore, also in this project we focus on ontologies expressed using these standard languages. RDFS is a basic ontology language, only allowing to express a few primitives, such as classes (concepts), subclass relations with specific semantics (allowing to express a taxonomy, i.e. hierarchy, of concepts and their subconcepts, such as the relation in the figure above where every "Student" is also a "Person"), general relations (object- and datatype properties), annotations such as labels and comments etc. OWL adds further expressivity and inferencing capabilities on top of RDFS. However, it is again important to note the trade-offs. Adding complex expressions to the ontology increases the complexity, and hence both reduces the efficiency of inferences over the ontology (e.g. increased computing time), as well as increases the time for humans to understand and assess the ontology, and narrows the domain where the ontology can be reused. On the other hand, increased expressivity of the ontology may give benefits in terms of more precise definitions and more opportunity for both consistency checking, and drawing new conclusions from existing data. Similarly, the scope of the ontology needs to be carefully considered, since a larger or more detailed ontology may be more useful in a specific case, but may again be less reusable and harder to grasp for non-experts. In an ontology development project it is therefore essential to carefully analyse the ontological requirements at hand, i.e. both in terms of what classes, properties and axioms are actually needed in the ontology (scope and expressivity), as well as other requirements, such as how much emphasis should be put on reusability, extensibility, and understandability of the ontology. Consequently, ontological requirements play a crucial role also in our ontology development effort in Onto-DESIDE.

2.2 Ontology Engineering

In order to structure the process of creating an ontology, and to ensure the quality of the resulting ontology, several methodologies for creating ontologies have emerged. Examples of commonly referenced ontology engineering methodologies include METHONTOLOGY [26], ontology development 101 [67], the method for developing enterprise ontologies by Gruninger & Fox [35] (also the first to introduce the notion of Competency Questions as ontology requirements), and the NeOn family of methods [90]. More recent methodologies commonly focus on an *agile process*, such as eXtreme Design (XD) [9], SAMOD [70], and the modular ontology development suggested in [86] (as a variant of XD), *test-driven development* [46], or on the *iterative evolution* of ontologies, such as DILIGENT [73]. Each methodology has its own benefits and drawbacks, and is suitable for certain development contexts and less suitable for others. For instance, the earlier methodologies were

[1] Original version of the standard was established already in 1999. RDF specifies a data model for representation of graph data using other Web standards, such as URIs for globally unique identifiers and data linking, and comes with a dedicated query language, SPARQL.

often describing a waterfall-like process, where careful scoping, listing of all terms to be covered, and agreeing on all definitions in the ontology, should precede the implementation of the ontology axioms. However, often this is neither suitable nor practically feasible, since most project requirements evolve, and tangible results are needed early on, in order to be able to test other components of some system or dataset that is to use the ontology. Hence, most often an iterative and incremental process is nowadays used to develop ontologies. This is also why in this project we have decided to use a variant of the XD methodology, to benefit from its focus on both incremental and iterative development, as well as modularisation of the resulting ontologies.

2.2.1 Modularisation and Ontology Design Patterns

The NeOn project was probably the first to introduce the notion of an *ontology network*, as mentioned in the introduction to this deliverable. Nowadays, most ontologies consist of an ontology network in some way, e.g. importing or relating to external ontologies, or consist of a set of modules focusing on various sub-domains of the overall ontology. Modularisation is supported by OWL in terms of the `owl:imports` statement, which effectively imports all axioms of an external ontology into the current one. This can be used in order to further extend and specialise an ontology (module), without affecting the module being imported. Note that an import statement effectively imports all axioms of the external ontology, and they cannot be modified, since the import is done based on the ontology URI, i.e. by pointing to the location of the ontology online. This on one hand ensures that the import always fetches the current version of an ontology, but this can also be a drawback if the ontology changes, since it is not always clear what axioms the importing ontology will contain at any given time. However, for modularisation of an own set of ontology modules, where we are in control over all those modules, `owl:imports` works well.

For the ontology users, e.g. developers creating an application or an interface based on the ontology, there may be an increased complexity in understanding the ontology if it has a large transitive import closure. Instead, separate alignment modules can be created anticipating the need to sometimes reuse an external ontology. In this way, the ontology user can choose to add that alignment module, and consequently the import(s), on a per-need basis, rather than having it as mandatory part of the ontology. In this way, the Onto-DESIDE project aims to manage the large amount of external and related ontologies that have been identified, which is discussed later in this deliverable.

However, apart from the technical concerns and motivations for modularisation discussed above. Modularisation can also be seen as a way to separate concerns, and focus on one modelling aspect (or small sub-domain) at a time. This helps the ontology engineer to focus, and treat a manageable amount of ontological requirements at a time. This is essential when applying an incremental and agile ontology engineering methodolody, such as XD.

In addition to modularisation, we also briefly introduce the notion of Ontology Design Patterns. Ontology Design Patterns (ODPs) [10, 27, 28] were originally proposed partly as a result of observing how difficult it is to reuse a large ontology. This observation even includes foundational ontologies clearly designed for being reused as the basis for building other ontologies. Issues include that it is difficult to get an overview of such large ontologies, foresee effects of changes or extensions to them, and it is also rarely the case that you as an ontology engineer, or the set of requirements you have for your ontology engineering task at hand, will fully agree with all the ontological commitments that are made in such a large ontology. However, not reusing any well-established practices at all, and not aligning yourself at least partly to existing ontologies, will create problems in interoperability and potentially also understandability of your ontology. Hence, there is a trade-off between interoperability on one hand and overcommitment and conflicting requirements on the other hand, where ODPs as small general “conceptual building blocks” offer one way to manage this trade-off. Hence, the idea of reusing, applying and sharing small patterns instead of complete ontologies, applies in many contexts.

There are many different types of ODPs, and they can be reused and applied in many different ways [10, 27, 28]. Even when considering only what is called Content ODPs, i.e., ODPs that focus on modelling solutions on the conceptual level and may constitute “building blocks” for your ontology, which we target here, there are a variety of ways that these can be reused and applied. At one end of the scale, ODPs can be used similarly to design patterns in architecture, or how patterns many times are used in software engineering, i.e., as mere inspiration and a conceptual framework to keep in mind when designing your own solution. An example of this way of applying a pattern would be to read about its basic idea in a book, or an online catalogue, incorporate this idea into your own knowledge, and then proceed to design your artefact according to your own interpretation of that pattern, with any modifications you see fit. This way of reusing patterns is sometimes denoted reuse by analogy.

At the other extreme, some ODPs (in particular Content ODPs) can be directly reusable through their OWL building blocks. This means that there is a small ontology, i.e. an ontology module, readily available that represents the ODP, which one can directly import and use in another ontology. This is similar to reusing an existing ontology, with the main difference that the ODP is usually small, i.e. and ontology module, has clear documentation of its capabilities, consequences, and so on, it is indeed designed for reuse, and ideally makes a minimal ontological commitment outside of its core purpose. This to some extent resembles the way classes from standard software libraries are reused in software engineering. Many ontology engineers also follow some middle path between these extremes, potentially reusing the OWL building blocks of a few well-known and stable ODPs directly, but then creating their own “ODP catalogue”, or perhaps better denoted a module repository (comparable to the reuse of software libraries), for their project for the rest of their needs, or even model the rest of the ontology in a more monolithic way.

To give the reader a more intuitive idea of what an ODP might look like, we provide an example in Figure 2. In the figure, 4 different ways to model roles are provided. Again, the example is set in the context of courses, in this case a teacher who is teaching a course instance as well as a student taking it. In part a) of the figure, a naïve modelling solution is illustrated, with the class "Person" having two subclasses (subconcepts) "Student" and "Teacher". Using this modelling solution, or pattern, we are only able to statically assign roles to people, i.e. an instance (the blue ovals represent instances in our data) can be a student or a teacher, but there is no context given and the role (which is usually time-dependent) is not distinguished from the inherent property of being a person (which is usually not considered time-dependent). Parts b) and c) illustrate two alternatives where the roles are separated from the fact that p1 and p2 are persons. While the roles are modelled explicitly in alternative b), the context of holding a role can still not be represented, e.g. the course. In alternative (or pattern) c) instead the role is not modelled explicitly as a concept, but rather encoded in the naming of the property connecting an individual to a course. Finally, in alternative d) the context of holding a role in a specific course is modelled through reification of an n-ary relation between person, role and course. This last pattern would also allow us to further contextualise the participation, e.g. by perhaps specifying time and location of a person’s participation in a course with a certain role. These modelling alternatives can be seen as different role-ODPs. While they can be reused just as conceptual ideas of how to model, they could also be represented as small modules and readily imported into different ontologies. It should also be noted that while alternative a) is usually discouraged, due to the fact that time-dependent and time-independent aspects are mixed in the taxonomy of classes, among the other alternatives there is not necessarily a universal "best alternative". Rather, which one should be chosen depends on the ontological requirements, and the data that we are going to map to the ontology. Alternative d) results in a quite complex structure of the data graph, e.g. RDF graph, whereby this can reduce query efficiency and understandability of the model, and should not be used by default, unless there are actually requirements motivating it.

2.2.2 eXtreme Design

The eXtreme Design (XD) ontology development methodology [78, 9] was created as one of the first agile ontology engineering methodologies, intending to address the lack of iterative, incremental and modular ontology development methodologies at that time. XD also promotes the reuse, or development, of ODPs, e.g. in the form of a module library, to ensure some interoperability of modules being produced both within and outside of the current ontology project. The overall outline of XD can bee seen in Figure 3.

The first phase of XD concerns **project initiation and scoping**. Apart from general project specification,

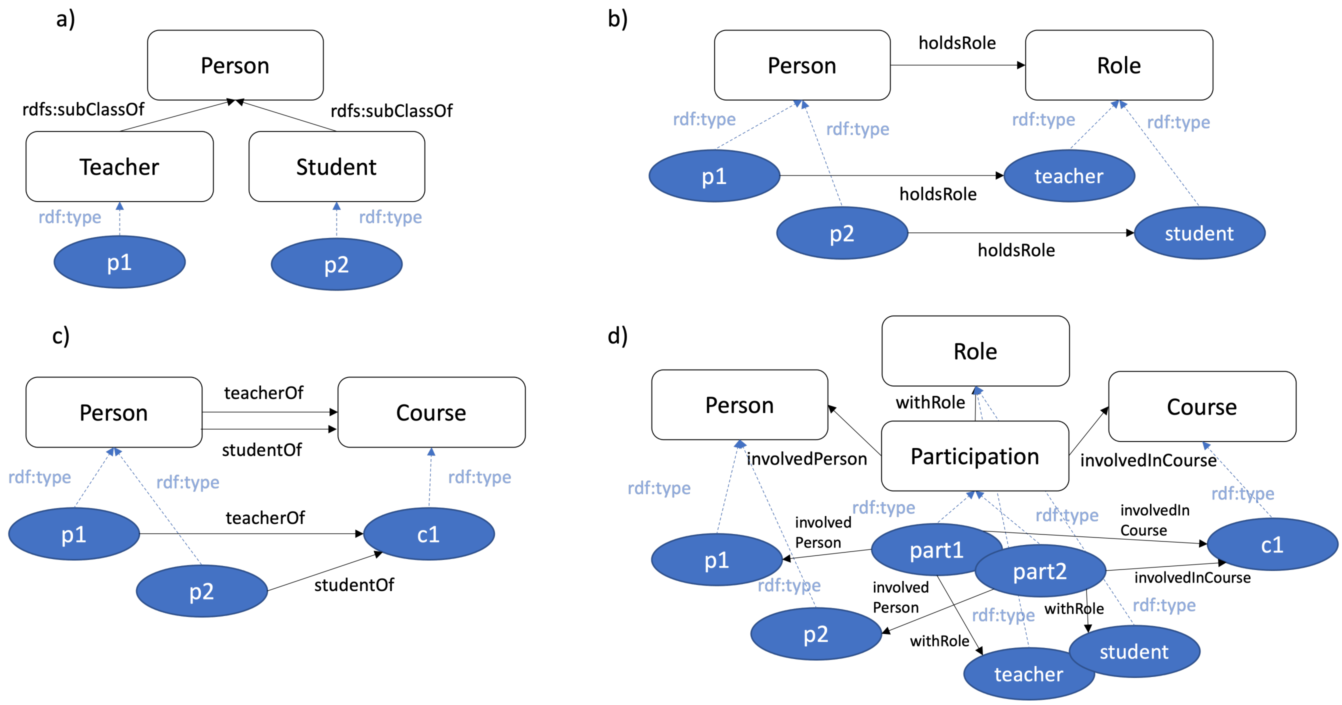

Figure 2: Examples of different ways to model roles, in the context of courses. White boxes represent concepts (classes), and the attached properties (object properties) could be given through domain and range restrictions, for instance. Below, in blue, some example data graphs are given, where ovals represent instances (individuals), and the arrows connecting them indicate RDF triples using those individuals as subjects and objects.

such as setting up project agreements, staffing, distribution of roles among project participants, setup of an appropriate technical environment, decisions on representation languages and frameworks, agreement on procedures, including release plan and integration strategies, as well as a timeline with deadlines and milestones, this also includes deciding on project scope and priorities. While many of these activities are common to any type of development project, one thing that sets ontology engineering apart from, for instance, many software engineering projects, is the need for a deeper understanding of the target domain, even among the (ontology) developers. This is due to the fact that an ontology is a “white box” artefact, hence both developers and users have to understand the inner workings of what is constructed, i.e. ontology concepts, relations, definitions. The consequence of this is that there is a greater need for developing a shared understanding of the domain, its terminology, the intended tasks of the ontology and so on, in an ontology engineering project than in, for instance, many software projects. This is usually achieved through close collaboration with end-users and domain experts, for setting the scope of the ontology, and further in the development cycle.

In general, scoping is very important for ontologies, but it is also very hard to clearly define the scope in terms of the knowledge domain to be modelled. Here the task focus of XD can be very helpful, allowing to focus on the generic tasks that the ontology should support, rather than the domain coverage in terms of concepts, attributes and terminology. This means that the ontology engineers should ask themselves "Is this necessary for the ontology to fulfil its requirements?" when deciding what should be included in the ontology or not, rather than focusing on whether the potential concept, relation or axiom considered is present and valid in the knowledge domain being modelled. In this sense, XD is suitable for contexts where clear tasks of the ontology can be defined, i.e. as functional ontology requirements, and where one wishes to prioritise functionality over completeness of the domain coverage.

Further, before starting the actual development, one needs to agree on the starting point of the project, e.g. in terms of any existing resources to take into account, or even reuse, and how to manage the shared set

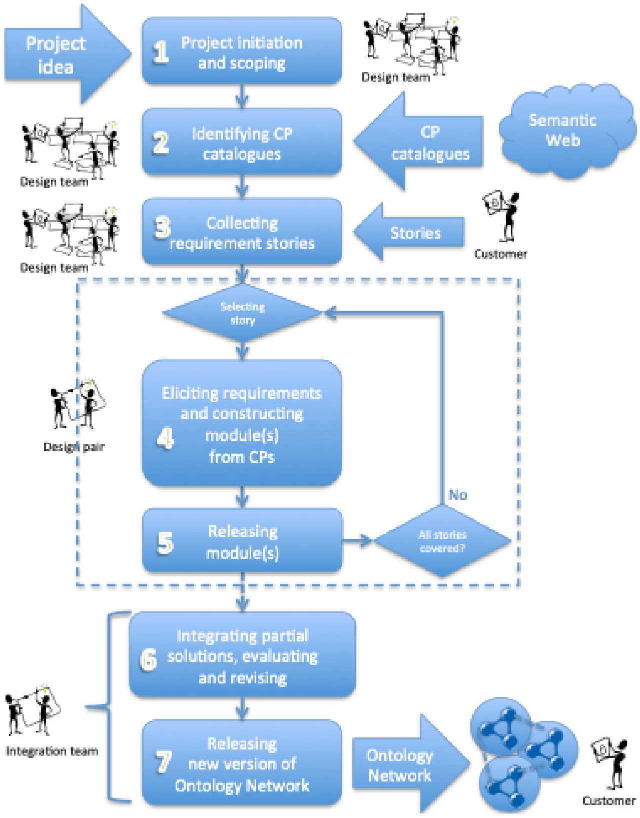

Figure 3: Overall outline of the XD phases and activities as described in [9].

of modules that will emerge during the XD development process. It is rarely the case that ontologies are constructed completely from scratch. Usually there are legacy terminologies to take into account, e.g. including standards and already existing ontologies. How each such resource is to be managed has to be determined at the start of the project, which is one of the focuses of this deliverable, i.e. to provide a map of what existing resources to take into account.

Finally, before starting the development loop, some ontology-focused user stories need to be developed (in this deliverable later called "ontology stories" or simply "stories"). Stories will later lead to the development of the functional requirements of each ontology module, e.g. Competency Questions [35]. Ontology stories can be formulated in different ways, e.g. as examples of data for which the ontology is to act a as a schema, or describing some functionality that is to be realised based on the ontology. The important thing is to keep them short and focused, i.e., on one concrete part of the domain knowledge, one specific task. A typical story might contain anything from 1-2 sentences up to about two brief paragraphs of text. Additionally, stories need to be quite specific in order not to allow for too much interpretation by the ontology engineers. Stories should also be driven entirely by the needs of ontology end-users, and not written with any specific modelling solution in mind.

Since XD is agile and iterative, it is not necessary to develop all stories beforehand, but an initial “backlog” is to be accumulated before starting the development process. This is to ensure that an appropriate prioritisation can be made within the initial set of stories. As the set of stories is allowed to emerge and evolve over time, it is important to also update the plan of what is actually going to be developed and in what order. Once some ontology stories have been collected and prioritised, and their relations to existing ontologies, standards and other resources have been assessed, the concrete development of the ontology modules can begin. As mentioned previously, this is done incrementally, one module at a time. Ideally, each story will correspond to one (or a small set of) ontology modules, however, the situation may also occur that some stories are considered too overlapping, so that their solutions have to be merged. In the original XD methodology requirements elicitation is done separately for each ontology story, by a developer team in collaboration with a "customer", i.e. domain expert or ontology end-user.

Next, the module development loop consists of module development, testing, and release, for one ontology story at a time. This is where the actual development happens, but additionally important activities such as testing and documentation are also prioritised. Once each module is released, it will then be integrated into the overall ontology network, and any needed refactoring will be performed, based on issues identified in integration, or integration testing. This effectively pushes many difficult decisions, e.g. regarding module compatibility and ontology network architecture, to the very end of the development loop. While this creates a fast development loop, where new modules can be released and tested quickly, it instead puts a lot of emphasis on the integration and refactoring, to resolve any conflicts later on. Hence, the modules released have to be viewed as "prototypes", which are then verified and potentially modified, to fit into the overall ontology network.

2.2.3 Ontological Requirements

As ontological requirements are particularly important for our chosen methodology, as well as one of the main focuses of this deliverable, we here describe a bit more in details how such requirements can be elicited and expressed. In XD requirements are elicited mainly from the ontology stories, that are produced in collaboration with domain experts and end-users. However, it is also important to validate all the requirements with those domain experts before starting the modelling, to ensure that a correct understanding of the stories have been gained, that terminology is appropriate and so that no important notions have been missed.

Although XD does not focus on first collecting all the domain terminology before modelling, terms and naming of things in the ontology modules are still an important aspect. Therefore a glossary of terms can be collected, simultaneous with the development of the requirements. Later, the coverage of these terms and alignment to the terminology of the stories can be verified based on this glossary.

The main requirements of an ontology are the Competency Questions (CQs) that the ontology should be able to answer. CQs [35, 9] are probably the most well-known category of ontological requirements, which was recognised already at the very beginning of the knowledge engineering tradition. CQs express typical tasks of the ontology, i.e., typical queries it should be able to answer, and are expressed as natural language sentences, e.g. questions. Referring to our initial example of a small ontology, illustrated in Figure 1, some CQs could have been "What courses do a specific person take?", "In which university is a specific course given?" and "Is this person a student?". However, note that CQs should not express all possible things one could ask, given the domain, but merely those things that we actually need to answer by directly using the ontology, or by querying the data annotated by the ontology. This in order to properly set the scope of the ontology to its intended task(s).

However, CQs on their own do not always suffice in order to clearly specify what is required from the ontology [9], therefore XD also specifies two additional requirement categories: Contextual Statements (CS), and Reasoning Requirements (RR). These are added to the CQs in order to completely specify the requirements, asking: "Are there any constraints that should be enforced over this knowledge, or any common-sense notions that are to be introduced to complement the knowledge needed to answer the CQ?" - Answers are CS, and "Is all the information needed to answer the CQ going to be entered explicitly into the knowledge base, or is there some inferences required either in order to derive the answer to the CQ or that should be derived as a consequence of the response?" - Answers are RR. Note that both of these questions refer to the CQ, hence the CQs are the requirements that set the scope of the module to be built and drive the need for additional requirements. However, CS and RR are sometimes needed in order to precisely specify the additional axioms of the entities mentioned in the CQs that are needed in order for the ontology to perform a certain task. Considering a CS, the task may be consistency checking, or identity resolution - in addition to answering the CQ. While considering an RR, the task may for example be classification of instances, in order to then be able to answer the CQ based on the inferred knowledge. To exemplify these two additional types of requirements we again refer to our initial example in Figure 1, where a CS related to the CQ "In which university is a specific course given?" might state that each course has to have exactly one university where it is given. An RR related to the CQ "Is this person a student?" could in turn be that persons are not going to be stored in the knowledge base as students or not, but that this will be inferred on-demand, based on whether they are enrolled in any university and/or take any courses.

2.3 Ontology Alignment

In recent years, many domains have witnessed ontologies to be used for domain knowledge representation (e.g., in materials science [47] and bioinformatics [88]). Although ontologies help in communications among domain experts and organizations by establishing a common terminology, interoperability and reusability challenges arise when we need to understand same or similar domain knowledge modeled in different ontologies or connect different ontologies for applications. One example is that a company may need to use community standard ontologies as well as company-specific ontologies [23], which is a common scenario in the biomedical domain. Another example is when we need to analyze or integrate data from different sources where the data is modeled or annotated based on different ontologies [23]. Such challenges also appear in the CE domain since there are more CE-specific and industry domain-specific ontologies emerging. For instance, if an industry scenario requires applying CE strategies modeled in different ontologies, it is important to understand how such strategies differ from or connect to each other. Furthermore, as circular value networks often connect across industry domains, it is important to understand how CE-specific ontologies align with specific domain ontologies (e.g., materials, products, and manufacturing) so that the relationships between these ontologies can be better understood, and reused if needed.

It has been realized that finding mappings or correspondences between concepts and relationships in different ontologies is important, to address such interoperability and reusability challenges. The task of finding and representing such mappings is what is here called ontology alignment. Ontology alignment is an active research field. Since 2004, the Ontology Alignment Evaluation Initiative (OAEI)[2] has organized annual evaluation campaigns for ontology matching technologies. OAEI provides test cases for comparing and evaluating ontology matching systems. These test cases include ontologies to be matched and reference alignments, covering a broad range of diverse domains (e.g., biomedical, materials science, nutrition science, and biodiversity use cases). Additionally, OAEI focuses on evaluating how systems handle different matching scenarios, such as T-Box/schema matching (e.g., concepts like materials or products), instance matching (e.g., specific instances of materials and products), multilingual matching, and interaction-based matching. Most conventional ontology matching systems (although not all), such as AML [25] and LogMap [43], produce alignments based on computing similarity values between entities (e.g., concepts, relationships and instances) in ontologies [23]. A typical ontology matching framework (e.g., as seen in [23, 49]) includes pre-processing, matching based on (combinations of) different strategies including using background knowledge, lexical matching strategies, structure-based strategies and filtering over candidate mappings. Additionally, some systems incorporate reasoning, debugging, and user interaction to detect inconsistencies, remove errors, and potentially add new mappings. Recent years have witnessed the emergence of ontology matching systems based on language models such as AMD [98]. These systems may utilize pre-trained language models or large language models (LLMs), which can better understand and use word semantics for matching tasks [39]. For the former, the systems compute similarity values of entities based on their embeddings, while for the latter, they may verbalize entities into text and incorporate this text into prompts presented to LLMs to generate mappings.

In Onto-DESIDE, we exploit alignment methods and tools to on one hand explore the landscape of ontologies and their interrelations, compatibility etc., and in addition to publish concrete alignments that can be reused for combining our ontology network with other pre-existing ontologies. This is explained further in the coming chapters.

[2] OAEI: http://oaei.ontologymatching.org

3 Methodology

In this chapter we first briefly remind the reader about the overall research methodology of the project (Section 3.1), and then we describe the research process applied in WP3. As the foundation for our work in WP3, we are conducting an extensive survey of both research literature as well as existing ontologies and related standards (in close relation with the work on standards in WP2), in order to properly ground our work in the state-of-the-art and to make sure we build on existing results. The survey methodology is described in Section 3.2. Subsequently, we focus on the methodology used to develop and publish ontologies in WP3, starting from WP6 and WP2 resources. Hence, Section 3.3 describes our ontology engineering workflow, inspired by the XD methodology, how we then publish the ontologies is discussed in Section 3.5, and our ontology alignment methodology is described in Section 3.6.

3.1 Project Research Methodology

In this section we briefly remind the reader of the overall project research methodology, in terms of the three project iterations, and their steps. In order to position the work reported in this deliverable in relation to these steps. The overall process can be illustrated as in Figure 4, where each project iteration consists of a needs & requirements analysis steps, followed by research & development, and concluded through evaluation and validation, e.g. technically as well as in our use cases. Overall the project is currently in the middle of the second project iteration, which lasts until M27 of the project duration (August 2024).

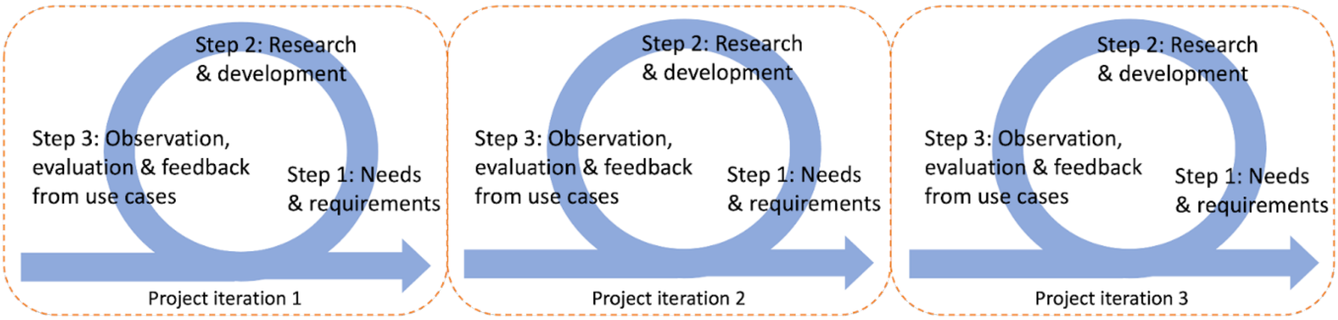

Figure 4: The overall research process of the project, conducted in three iterations.

In the case of WP3, we rely on the needs and requirements analysis done in WP2 and WP6, as reported in D6.1-2 and subsequently D2.1-2. Based on these needs and requirements, we have completed a first project iteration, including an evaluation (as reported in D6.7), and are currently in the second research and development step. The WP3 research has consisted of conducting several surveys, to map the state-of-research in this area (i.e. both surveying current research literature, and existing ontologies and standards). The development consisted in developing a set of ontological requirements, based on the input from WP6 and 2, refining them in the second iteration, and subsequently develop an ontology network architecture and a set of core ontology modules. All these results have gone through the first iteration of the third step, i.e. the one of observation, evaluation, and gathering feedback on these results, for instance from the use cases. However, the results are still work in progress, since a year of the project remains, including the evaluation phase of the second project iteration, so all the results presented in this deliverable have to still be considered as preliminary. The results of the second evaluation and validation (ending in M27) will then feed into the final iteration, and be part of the needs and requirements that are taken into account for the next iteration of WP3.

3.2 Survey Methodology

In order to become aware of the state-of-the-art, and properly take into account related research, we are carrying out several types of structured surveys in the context of WP3. The methodologies used for these surveys are presented in this section, but the work is still to be completed during the next few months.

3.2.1 Literature Survey Methodology

In order to get a comprehensive picture of related research, and state-of-the-art in semantic technologies for CE we are conducting a structured literature survey. However, the survey is not yet completed, in terms of a deeper analysis of the articles found. Nevertheless, we briefly describe the methodology of the structured literature survey, leading up to the identification of a first set of papers, which have also been used as input for the ontology and standards survey described below. The full analysis of the survey results will be published in a research article submitted to an appropriate scientific journal before the end of activities in WP3 (i.e. before M33).

The survey is conducted by searching a set of complementary databases, e.g. Scopus, Web of Science, and Business Source Premiere. Google scholar is used as a complement, which aggregates a multitude of sources, including most common publication venues in computer science, e.g. IEEE, ACM, as well as publishing houses such as Springer, Elsevier, which are not all indexed by the above mentioned databases. Using Google scholar is particularly important when trying to find ontology development efforts, since some ontologies and ontology projects are only described in white papers, project reports etc., and not published in peer-reviewed venues. By including the complete Google Scholar search results we ensure that no bias is introduced by Google algorithms, i.e. we are not filtering based on any Google notion of "relevance". However, on the other hand, for the survey of scientific literature, Google scholar results have to be used with care, hence, extra verification steps have been applied, verifying the accuracy of the documents, in terms of actually being published and peer reviewed, before including them in the list of articles to analyse.

The search query used consists of two parts, one part related to Circular Economy and one part related to semantic technologies. For the first part we simply used the key phrase *"circular economy"*, since this term is the most frequently used in recent years, and adding variations and synonyms proved to mainly generate older results, not relevant for this project, since they instead did not take into account any of the current technologies in focus. For the second part of the query a more complex expression was used:

```
(ontology AND ("semantic interoperability" OR "linked data" OR "data sharing“
OR RDF OR OWL)) OR "knowledge graph" OR "semantic web"
```

Simply using the term "ontology" proved impractical, since that term has several meanings, and is also used in philosophy and theoretically oriented business research to discuss the underlying meaning of things in the world. Hence, it was necessary to combine the ontology-term with more technical terms that indicate the computer science-related use. Further, in recent years the term knowledge graph has become popular, and is sometimes used synonymous to ontology. The term Semantic Web, additionally, is used to capture more general reports of using such technologies, including variations and combinations not specifically mentioning the term ontology or knowledge graph, but using that as a component of a larger system.

Based on this query we retrieved 1441 entries from the databases, together with Google scholar, published until December 2023. Already in the first round of assessment we have tagged the entries retrieved that present ontologies (or ontology development efforts) related to CE, and used this as input to the ontology survey described below. A total of 11 entries presented some type of ontology related effort and these were then passed on as input to the ontologies and standards survey.

To additionally narrow down this set of search results, and identify the ones that represent true positives, in terms of published, peer reviewed articles representing research on applying semantic technologies to CE

#	Inclusion Criteria	Comment
1	Article.	Project reports, books, and theses were excluded.
2	Peer reviewed.	The work needs to be published in a venue, e.g. conference proceedings, journal, book, that claims to have applied a peer-review process.
3	English language.	Articles not in English were excluded for practical reasons.
4	Accessible.	The article needs to be accessible to us, e.g. either online or through ordering it from the university library.
5	Clearly addresses a CE problem.	It is not enough that the solution could be applied to CE, but the article must clearly target that application area.
6	Apply semantic technologies.	The article must clearly assess or apply some semantic technology, such as ontologies, knowledge graphs, or other semantic web solutions, and not merely mention that such solution could be relevant.

Table 1: The set of inclusion criteria used, and explanations of how they have been applied.

problems we have manually filtered them based on a set of inclusion/exclusion criteria. In addition to these criteria also duplicates have been removed, e.g. where both a preprint and the actual published article were initially included in the list of results only the published article was in the end retained. The remaining criteria are represented in Table 1.

Assessment of each criteria has been made by at least two members of the research team in each case, to avoid biased decisions, and was made in the order they are listed in the table. The latter, in order to reduce the number of articles considerably in the first steps, so as to make it feasible to assess their relevance in-depth in relation to the latter criteria. In doubtful cases the article has been retained for the next evaluation step, in order to avoid excluding important work erroneously. While the first 4 criteria are quite clear and well-defined, the last two require a certain amount of subjective judgement, and mentioned in the comments of the table. Inclusion based on the usage of relevant technologies used a very wide notion of "semantic technologies" where all things closely resembling knowledge graphs were included, such as all kinds of graph databases and graph data structures, and ontologies were included even though they may not be implemented using semantic web standards, but rather resemble other kinds of conceptual models (e.g. ER-diagrams or UML models) while still representing concepts and relations in the domain. Additionally, the research reported should in some way have analysed, tested or applied these technologies, rather than merely mention them as possible options, or simply list or survey other approaches using these technologies. Consequently, a survey article could pass the inclusion criteria if it would also include an analysis and synthesis of the results, representing some new framework or insights added on top of the surveyed articles, while merely listing other work, would fail to meet that criteria. Similarly, for the CE criteria it is not enough to discuss Circular Economy in general, or mention it as a possible application field, but the intersection is needed where an actual analysis, testing or application of the technologies in the domain of Circular Economy has be presented. Still, the definition of CE used here was quite broad, including all CE strategies, but excluding articles that only target broader perspectives, such as sustainability in general, product service systems in general, or different kinds of manufacturing approaches without mentioning the target of a CE.

This analysis was done in a rotating manner by a group of five persons related to WP3 in the project. In two phases, every person has read and checked a subset of the entries, then the results were confirmed by other group members to decide on the final inclusion, and difficult cases were discussed in the whole group. This work has resulted in a final list of 109 entries that will be analyzed in the final review and presented as part of the results.

As of writing this, that final analysis is still on going. In this phase we are looking to find common themes to be able to categorize how the different authors have used the relevant technologies and their relation to Circular Economy. As we still have many entries to analyze, it is not possible to make any definite statements on the results but in Section 4.1 we share some initial results from this analysis. In Appendix C, we also list all the entries that are part of the final analysis as to be transparent on what we include in the analysis.

3.2.2 Ontologies and Standards Survey Methodology

Since ontologies are not only presented in research literature, but sometimes published completely separately, an additional effort is needed to properly cover the landscape of existing ontologies. Similarly, standards are not covered in the literature search, due to its focus on databases and indexes of research papers. In this section, we present how we conducted the direct search for ontologies and standards, in addition to the literature search already mentioned.

Focus Domains

A model for CE involves actors from different domains such as raw materials, manufacturing, production, logistics and supply chain. Hence, also ontologies for CE may need to cover such diverse sets of domains, in particular ontologies that should be applicable in scenarios of cross-industry collaboration. In order to set a reasonable scope for the initial set of ontologies to examine we therefore attempted to identify the most central domains of relevance. Based on discussions among knowledge engineers and domain experts, we identified a set of core domains in which we needed to investigate the relevant existing ontologies. These focus domains are *Circular Economy*, *Sustainability*, *Materials*, *Logistics*, *Manufacturing* and *Products*. Additionally, we also focus on the three use case domains which are *Construction*, *Electronics* and *Textiles*. The domains are shown in Table 2 together with some sub-topics that were later used to further describe the focus of the ontologies.

Table 2: Focus Domains.

Domain	Topics	Label
Circular Economy	business models, resource recovery, waste, recycling, circularity assessment	CE
Sustainability	sustainability goals, performance, environment, energy	SU
Materials	raw materials, material composition	MAT
Logistics	distribution, production, supply chain	LO
Manufacturing	manufacturing process	MAN
Products	product life cycle	PR
Construction	building, device	CO
Electronics	electronics, electronical appliances	EL
Textiles	textiles, fiber	TE

Collecting Ontologies

We collected ontologies in three complementary ways. First, we collect ontologies for all the domains shown in Table 2 from public ontology or vocabulary repositories. However, since CE and the use of Semantic Web-based technologies for CE is relatively new, public repositories may not include many relevant ontologies or vocabularies yet. Therefore, we also collected ontologies by searching Google and Google Scholar based on specific ontology keywords for the CE domain. Finally, these results were complemented by the papers with ontology descriptions from the literature survey described previously.

We searched for ontologies in the following public ontology or vocabulary repositories: MatPortal[3] (containing

[3] https://matportal.org

21 ontologies in total), IndustryPortal[4] (52 ontologies in total), OntoCommons ontology catalogue[5] (37 ontologies in total), Ontobee[6] (259 ontologies in total), and Linked Open Vocabularies[7] (LOV, 782 vocabularies in total). For the first four repositories, we looked at each ontology in the repositories one by one and decided for each ontology whether it was relevant to our domains and should be included in our survey. For LOV, we searched the repository using the same keywords as those used for searching Google and Google Scholar (see below), before assessing the relevance of the found ontologies.

For the Google searches specific to ontologies, we used six keywords or key phrases identified through discussion between the domain expert and the knowledge engineers. These keywords or key phrases are *ontologies for circular economy*, *circularity ontology*, *materials ontology in circular economy*, *Semantic Web in circular economy*, *materials passport ontology*, and *ontology for circularity product*.

Ontology Analysis Perspectives and Categories

Once ontologies had been found, we also need to assess them and analyse their characteristics in order to better understand their relevance to the project. The analysis of collected ontologies relates to both qualitative and quantitative aspects. For the quantitative aspects, we used the ROBOT tool [40][8] to compute ontology metrics. These metrics include, e.g. the numbers of concepts (or classes), axioms, relations (or properties). By analyzing these metrics, we aim to obtain a better understanding of different ontologies regarding what design choices were made for developing these ontologies and how we can reuse or re-engineer these ontologies. For the qualitative aspects, we consider characteristics such as availability, domain of interest, and reuse of other ontologies. These characteristics are important for reusing ontologies and connecting them into an ontology network for CE, i.e. the results act as input both for ontology engineering and ontology alignment in the project. Together with the catalogue of ontologies, the result of the analysis can be found in the results chapters, later in this report.

Databases and Repositories for Searching Policies and Standards

However, it is not only already existing ontologies that are relevant and important to relate to. Many other kinds of artefacts also exist, including agreed upon terminology in policy documents and standards, semi-structured resources and data model specifications etc. To find such specifications that are relevant to the general cross-industry domains in the Onto-DESIDE project, we have taken the following organisations' repositories into account for searching:

Table 3: Organizations related to policies and standards.

Organization	Description
ISO[9]	International Organization for Standardization is an independent, non-governmental international organization with a membership of 167 national standards bodies.

[4] http://industryportal.enit.fr
[5] https://data.ontocommons.linkeddata.es
[6] https://ontobee.org
[7] https://lov.linkeddata.es/dataset/lov
[8] http://robot.obolibrary.org
[9] https://www.iso.org/standards-catalogue/browse-by-tc.html

GRI[10]	The Global Reporting Initiative represent global best practice for reporting pub- licly on a range of economic, environmental and social impacts. Sustainability reporting based on the Standards provides information about an organisation's positive or negative contributions to sustainable development. An organisation reporting in accordance with the GRI Standards is required to report how it manages each of its material topics.
EUR-Lex[11]	EUR-Lex is the online gateway to EU Law. It provides the official and most comprehensive access to EU legal documents. It is available in all of the EU's 24 official languages and is updated daily.
European data[12]	The official provider of publishing services to all EU institutions, bodies, and agencies. As such, it is a central point of access to EU law, publications, open data, research results, procurement notices and other official information.
Eurostat[13]	Eurostat produces European statistics in partnership with National Statistical Institutes and other national authorities in the EU Member States. This partnership is known as the European Statistical System (ESS). It also includes the statistical authorities of the European Economic Area (EEA) countries and Switzerland.
ASTM[14]	American Society for Testing and Material is a globally recognized leader in the development and delivery of voluntary consensus standards. Today, over 12,000 ASTM standards are used around the world to improve product quality, enhance health and safety, strengthen market access and trade, and build consumer confidence.
UNECE[15]	The United Nations Economic Commission for Europe (UNECE) was set up in 1947 by ECOSOC. It is one of five regional commissions of the United Nations. Its major aim is to promote pan-European economic integration.
EEA[16]	The European Environment Agency provides sound, independent information on the environment for those involved in developing, adopting, implementing and evaluating environmental policy, and also the general public.

[10] https://www.globalreporting.org/how-to-use-the-gri-standards/gri-standards-english-language/
[11] https://eur-lex.europa.eu/homepage.html
[12] https://data.europa.eu/en
[13] https://ec.europa.eu/eurostat/web/main
[14] https://www.astm.org/
[15] https://www.ungeneva.org/en/organizations/unece
[16] https://www.eea.europa.eu/

In addition, to find existing standards that are specifically relevant to the three project use cases in Onto-DESIDE, we took the following organisations' repositories into account:

Table 4: Standard organizations relevant to the respective use cases of Onto-DESIDE.

Organization	Description and related use case
CP-DS[17]	The CP-DS database is designed to help all interested parties to identify all relevant regulations in the field of dangerous substances in construction products. Related to use case: Construction
EUOS[18]	EUOS thoroughly monitor the global Standardisation landscape, providing a comprehensive and accurate coverage of the most important ICT Standards, Working Groups and Technical Committees that affect the key ICT topics of the Digital Single Market and the EU ICT Rolling Plan for Standardisation. Related to use case: Electronics
ETSI[19]	ETSI provides members with an open, inclusive and collaborative environment. This environment supports the timely development, ratification and testing of globally applicable standards for ICT-enabled systems, applications and services. Related to use case: Electronics
ITU[20]	The International Telecommunication Union facilitate international connectivity in communications networks, we allocate global radio spectrum and satellite orbits, develop the technical standards that ensure networks and technologies seamlessly interconnect, and strive to improve access to ICTs to underserved communities worldwide. Related to use case: Electronics
ITU-T Study Group 5[21]	ITU-T Study Group 5 is responsible for studies on methodologies for evaluating ICT effects on climate change and publishing guidelines for using ICTs in an eco-friendly way. Under its environmental mandate SG5 is also responsible for studying design methodologies to reduce ICTs and e-waste's adverse environmental effects, for example, through recycling of ICT facilities and equipment. Related to use case: Electronics

[17] https://single-market-economy.ec.europa.eu/tools-databases/cp-ds-legislation-substances-construction-products_en
[18] https://www.standict.eu/standards-repository
[19] https://www.etsi.org
[20] https://www.itu.int/en/Pages/default.aspx
[21] https://www.itu.int/en/ITU-T/about/groups/Pages/sg05.aspx

GOTS[22]	Global Organic Textile Standard (GOTS) was founded by four well-reputed organisations: Organic Trade Association (OTA, USA), Internationaler Verband der Naturtextilwirtschaft (IVN, Germany), The Soil Association (UK) and Japan Organic Cotton Association (JOCA, Japan). Two of these (IVN and JOCA) are textile industry organisations, while the other two (OTA and Soil Association) are organic organisations rooted in organic agriculture and food. Together, they hold extensive experience in promoting 'organic' and all had developed individual processing standards for organic textiles. GOTS came about from the desire to harmonise these standards so that they were internationally recognised. Related to use case: Textile

This list is most likely not complete, but has been used as a starting point, based on discussions with domain experts in the project. The overview will be made more complete for the second version of this deliverable, including also a more detailed analysis of the resulting standards. At the moment, we simply list the relevant standards in the result Section 4.2.5.

3.3 Ontology Engineering Methodology

On one hand the ontology engineering methodology in WP3 is part of the project's overall methodology to develop our results. However, in WP3 we also have the objective to further develop the methodology into something that can be useful after the project lifetime, for better guiding future extensions to the ontology network we are building. For instance, when covering new industry domains outside of our three use cases. Therefore, we pay specific attention to the adaptations made to the XD methodology in the project, and discuss their motivations, in order to gather some experinces and guidelines for future use of a similar approach.

However, based on where we are in the overall project, in this deliverable we focus mainly on the project initiation and scoping, identification of existing resources, and requirements analysis, since the method steps that are related to the ontology modelling, integration, and release are still being developed. In addition, we explore the use of modern AI tools for supporting ontology engineering, which has the potential to revolutionise the ontology engineering workflow, especially when attempting to allow domain experts to themselves create and extend ontologies. The study reported here is merely a first attempt to explore this area, not specific to the CE domain, but shows the potential of the methods for future tools, and will be futher explored in the remainder of the project.

3.3.1 Modular modelling and the XD Methodology

Following the discussion in Chapter 2, there is a trade-off between modularity and architectural complexity of the ontology. However, when modelling for the CE domain it is clear that we need to prioritise modularity over a simpler ontology architecture, to (i) increase the reuse potential of the ontologies, (ii) separate concerns and allow for alternative models, and alignments to different related ontologies, for certain specific domains, and (iii) increase the understandability of the notions we are modelling. This clearly follows from the fact that the domain of CE is highly diverse, and it would simply be impossible to model all aspects and all possible industry domains in a single ontology. In fact, we note that even in our project use cases we need to produce some models despite a certain degree of uncertainty, e.g. of exactly what actors would fill each role in the envisioned network. In addition, it is highly likely that circular value networks change over time, so modelling in ways so that changes have minimal effect on the overall solution is essential. Therefore we envision the situation

[22] https://global-standard.org/

where an ontology for a specific use case can be built specifically, or be composed from a library of modules or existing ontologies in that domain, and thus tailored to a specific CE use case, but where interoperability is still ensured by having a set of core modules shared by all the more specific ontology modules. This is the motivation for targeting an ontology network, composed of smaller modules, instead of one (or a set of) larger ontologies, and this is also one of the motivations why the agile XD methodology was chosen as a suitable ontology engineering methodology for the project.

The small set of core modules that are to be shared throughout the ontology network, can be viewed as instances of a set of shared ODPs. However, in practice they will be represented as well-documented ontology modules, but with a minimal ontological commitment to be as reusable as possible. These will constitute the core of the ontology network, and will then be reused and specialised (i.e. extended with further details), aligned to external ontologies etc., to fully cover our complete set of requirements. However, by taking this highly modular approach we ensure that these core modules can also be reused independently of the rest of the ontology network. In the rest of the deliverable, we denote these central components "core ontology modules", rather than ODPs, to indicate that they will not merely be abstract conceptual patterns, but come with a concrete module implementation (in OWL). Hence, they can be reused directly as modules in the ontology network.

Given these overall architecture principles of the ontology network, we then proceeded to adapt the XD methodology to our project context and use cases. Mainly the following four adaptations have so far been considered, in relation to the original description of XD in Chapter 2 and in [9]:

1. Less focus on the initial scoping of the ontology – The scope is allowed to emerge from the emerging set of requirements.
2. No fixed set of external resources identified at the project start – The set of external ontologies and non-ontological resources to relate and align to is allowed to emerge and evolve over time.
3. Increased attention to architectural principles and patterns – A core set of shared modules (representing core ODPs) is first created, as the backbone of the ontology network.
4. A modified process regarding requirements analysis – Requirements are developed outside of the development loop, and core requirements are formulated before modelling of those modules start.

Regarding point (1), the scope of the ontology network has to in our case be determined by its intended use by the various actors in the circular value networks, which are not all known beforehand - in fact, we know very few of them in detail, but mostly we only know their types an functions in the networks. Hence, in our case we can only be sure that the ontology network will need to grow, evolve and change, as new use cases emerge. Therefore, our formulation of the scope is mainly generic, and states that we intend to cover core notions and aspects that are general across all so-far known use cases, e.g. core CE concepts and concepts involved in all three project use cases, and then simply prioritise extensibility and minimal ontological commitments as much as possible, to allow for future extensions and alignments.

Regarding point (2), as our survey results show (discussed later in the deliverable) many new ontologies are being developed, and standards are not yet established and stable, hence, there is not a fixed set of external resources that we need to take into account, and align to. Therefore, we cannot determine this set at the beginning of the development process, but rather we have to allow for an evolving set of related resources. This may mean additional refactoring that will be needed later during the project, if standards or other resources emerge that change the way certain concepts are to be defined. In XD, normally, revisions and refactoring is done mainly based on requirement changes, or based on problems discovered in integration testing, while in our case, such refactoring and revisions will also be triggered directly by external factors.

Regarding point (3), the XD methodology in itself does not normally prescribe any specific ontology architecture principles, apart from modularisation. However, in our case, due to the importance of having highly reusable core modules, that make minimal ontological commitments for maximal reusability, there is a need to design an overall architecture of the ontology network up front. Therefore we diverge from the XD principle of leaving any architectural consideration and integration issues to the integration phase, and instead start by focusing on the core modules and their dependencies, thereafter the intention is to merely develop extensions and specialisations of those modules, as well as alignment modules functioning as bridges to other existing ontology concepts, rather than modifying the core set of modules, unless this is found absolutely necessary.

Finally, regarding point (4), while XD specifies that requirements should not be developed based on ontology stories until that story is ready to be modelled, this is not really a feasible approach in our project, for several reasons. First of all, while we do have continuous access to some domain experts, e.g. from our industry partners in the project, we do not have full coverage of all actors in our use cases described by WP6. Additionally, the industry partners that we do have, do not have effort allocated in WP3 for continuous interaction on ontology requirements. Instead, we partly rely on (i) the written use case descriptions from D6.1 for support in our requirements analysis, complemented by (ii) upcoming sessions for requirements validation with our industry partners, where a larger set of ontology requirements will be validated at once (i.e. not on a per-story basis). In addition, we also want to take advantage of the fact that we already know that stories originating from D2.1 are highly overlapping, a we can therefore avoid lots of refactoring of modules, by already consolidating those requirements before entering the development loop. Therefore we have decided to treat the requirement elicitation and analysis as a separate activity, parallel to the XD development loop, instead of a step conducted in each iteration. Some further details on our requirements analysis process are given in the next subsection.

These four points summarise our current methodological observations, however, it should be considered that so far these are only observations from two project iterations. The validity of these methodology adaptations will now be validated during the final stages of the project.

3.3.2 Requirements Analysis Process

Since the main focus of the initial work in WP3 has been on developing a set of ontological requirements, we here describe a bit more in detail the process followed in this development.

The starting point of the ontological requirements is an initial set of ontology stories based on (1) the user stories in D2.1, contextualised by (2) the use case descriptions in D6.1, as well as emerging standards and policies describing the notion of CE and circular value networks as such. From these stories we have further collected a glossary of terms to be covered by the ontologies, and then developed CQs (Competency Questions) as well as CS and RR (Contextual Statements and Reasoning Requirements respectively) belonging to them.

More concretely, from D2.1 a list of terms was extracted by first simply extracting each noun phrase in the text of the user stories, and also including any sub-terms of that phrase (i.e. the words it is composed of, and any base forms of inflected words). For instance, the noun phrase "manufacturing process" occurs frequently, and while this is a term in itself, it also consists of two sub-terms; "manufacturing" and "process". The result of this process was then transformed into a glossary of terms for the ontology development in our first iteration, by counting the frequency of use and manually assessing the relevance of the terms for CE in general. Any term occurring more than once, and assessed to be relevant for the general CE domain was included. At this stage we have thus filtered out any use case specific terms, even if they occurred frequently within that use case's user stories. Those terms will instead be included in use case specific glossaries (i.e. specific to construction, electronics and textile industries), used for the use case specific ontology extensions in collaboration with WP6. In addition, purely technical terms were excluded, since they were deemed to refer more to the functions of the intended platform, rather than the underlying information the platform should hold. Examples of the latter are terms like "interface", "click", and "query". It should be noted that this list is not final, but will be continuously updated throughout the three project iterations, as well as during the ontology development, where new stories will be added as the project progresses. Nevertheless, the intention is to use this glossary of terms as one source of, for instance, concept and property names, and as a way of assessing the coverage of the ontology network against the needs of the project. As mentioned earlier, the general glossary will also be complemented by use case-specific ones as the work in WP6 progresses.

However, simply listing terms is not enough in terms of ontological requirements. We then proceed to develop the ontology stories mentioned earlier in this section. This was done by taking each user story of D2.1 (and updates from D2.2, including the circularity requirements) and rewriting them into one or more ontology stories, where technical aspects of the platform are left out, and instead the information needs and content aspects are detailed further. In addition, these requirements were cross-checked with the concepts discussed in the emerging ISO 59004 on CE terminology, and generic Circular Value Network concept identified as common to several of the stories. If the story was first formulated as a concrete example, it was then also generalised into instance-free sentences (i.e. mentioning types of things instead of concrete names). Once the story text was sufficiently generalised, a set of requirements (i.e. CQs) were elicited from it.

To perform a first validation of the core Circular Value Network stories (cf. point 2 above), a modelling workshop was also conducted with representatives from all project partners. The participants were divided into groups of about 4-5 people, and were asked to draw a conceptual model of the most important concepts involved in a CVN, and how they are related. Cleaned up (i.e. in terms of visual presentation, no changes were made to the content) versions of these drawings can be seen in the Appendix A, Figures 11-19. These sketches were then compared to the ontology stories written, and the overall list of CVN core concepts identified, to both identify missing concepts and relations, and to question and revise any concepts that were not core according to the workshop participants (i.e. where none of the groups had listed such a concept, or a similar one).

The development of CQs (as well as CS and RR belonging to them) was done by formulating questions to retrieve the data types mentioned in the ontology stories, and their relations, but by additionally using the user stories in D2.1 and D2.2 for setting the scope, i.e., excluding any questions that would not be necessary to fulfil the tasks specified by the D2.1-2 user stories. The latter is important, since we are creating task focused ontology modules that should support typical CE tasks, but not necessarily cover all possible data that could be collected in the domain.

3.3.3 Ontology Development

In this section we outline the currently ongoing work for the actual ontology development process.

For the actual ontology development, we are again slightly adapting XD, i.e., creating a modified version of the XD methodology's design loop. First of all, one of the XD principles of "pair design" is modified in this project, since we do not have the resources (in terms of ontology engineers) to allow them to continuously work in pairs. Instead, we set up a method were ontology modules are created by one ontology engineer and then reviewed by another, in line with the idea of code reviews in software engineering. In this way, ontology engineers still work in pairs, but without the requirement of continuous synchronisation of efforts.

Apart from that, another important shift of focus is the prioritisation of stories, i.e., the development of a set of core modules following an already determined overall architecture of the ontology network in the first iteration of the project. Hence, we set the highest priorities on the ontology stories that were written for describing the core notions of CE. Those modules are based on the cross-cutting concerns identified in D6.1-2 and D2.1-2, and described in the additional set of stories originating from the circularity requirements as explained in the last section. Examples of such concepts include, circular strategies, the actors and flows involved, and the transformations of resources from materials, to components, and products. This gives the project a slightly less agile flavour, however on the other hand, we intend to create a small but effective foundation for the remaining modules, and avoid unnecessary refactoring later on.

3.4 Exploring LLM support for Ontology Engineers

Ontology engineering is a complex and time-consuming task, even with the help of current modelling environments and methodologies. Often the result is error-prone unless developed by experienced ontology engineers.

However, with the emergence of new tools, such as generative AI, inexperienced modellers might receive assistance. We have performed and initial study that investigates the capability of Large Language Models (LLMs) to generate OWL ontologies directly from ontological requirements. Specifically, our research question centres on the potential of LLMs in assisting human modellers, by generating OWL modelling suggestions and alternatives. We experimented with several state-of-the-art models. Our methodology incorporated diverse prompting techniques like Chain of Thoughts (CoT), Graph of Thoughts (GoT), and Decomposed Prompting, along with the Zero-shot method. Results show that currently, GPT-4 is the only model capable of providing suggestions of sufficient quality, and we also note the benefits and drawbacks of the prompting techniques. The detailed results are reported in a conference paper [82].

Overall, we conclude that it seems feasible to use advanced LLMs to generate OWL suggestions, which are at least comparable to the quality of human novice modellers. Our research is a pioneering contribution in this area, being the first to systematically study the ability of LLMs to assist ontology engineers. However, we also note a number of challenges with this approach that does not allow it to immediately be used in the CE domain for the task at hand, e.g. for generating and extending CEON modules. Such drawbacks include that only the commercial models at the moment provide a sufficient result quality to make sense as a support tool, hence, the process is both expensive (due to high API access fees) and far from ideal when it comes to privacy and confidentiality, since any input requirements (ontology stories and CQs) are uploaded to the online model APIs, and thereby incorporated into their training data. Nevertheless, with new models appearing all the time, also open source ones and those that can be run locally, it is only a matter of time until also these LLMs have the capability to create reasonable ontologies. Thereby the task will be further explored during the final year of the project.

3.5 FAIR Ontology Publishing

Once ontologies have been modelled, they also need to be shared with the community. In order to actually be useful, they need to be both findable, accessible, interpretable and interoperable with standards and other ontologies, as well as highly reusable. In general, this holds for all scientific results and artefacts, but perhaps specifically for ontologies that are supposed to act as mediators and provide semantic interoperability in a domain. To guide and support the sharing of scientific results in general, and artefacts in particular, the FAIR principles were proposed [96]. In this section we therefore discuss how the FAIR principles are related to our project, and what aspects are important to take into account, as well as outline some specific methodological practices for the project.

The ontologies developed by the project will be published according to the FAIR principles. However, recent analyses by several researchers and projects [18, 41, 50, 74] come to the conclusion that there are different ways to fulfil the FAIR principles, and it is not always clear exactly what is the best solution. Still, many of the principles are quite naturally fulfilled simply by the fact that the ontology language used, i.e. OWL, is based on Web standards, and use URIs as unique identifiers. Below, the four FAIR principles are discussed one by one, in relation to the ontologies, and then finally, a more technical plan is outlined for how the ontologies will actually be published.

3.5.1 Findability and Accessibility

The ontology network being developed in this project can be viewed partly as a metadata schema for describing actual data to be shared in the circular economy, hence, rich metadata is at the heart of this project, and one of our project goals. In addition, the ontologies produced in WP3 are represented using the W3C standard OWL[23], use URIs as identifiers, and are published using a persistent URI service, i.e. the w3id service[24], while the source files are available both from an open source service (GitHub), and will be registered in indexing

[23] https://www.w3.org/OWL/
[24] https://w3id.org/

services such as LOV[25] and the ODP portal[26], to be even more easily findable.

The use of the ontologies in the open data sharing platform developed in parallel will also support two findability aspects, namely persistent identifiers and indexing of actual circularity data. Regarding accessibility, both data and ontologies should be retrievable through their perfsistent identifiers, and metadata will be available even if data is restricted or no longer available (e.g. through LOV and other indexing services, as mentioned above).

3.5.2 Interoperability

Interoperability of data includes requirements on metadata to use shared vocabularies and languages for knowledge representation, on the vocabularies themselves to follow the FAIR principles, and on containing links to related metadata and vocabularies. These aspects are really at the core of this project, since the main aim of the project is to increase semantic interoperability of data through ontology-based data documentation in the CE setting.

In order to ensure interoperability of the ontologies themselves, the ontologies are based on W3C standards (e.g. represented in OWL), linked to standard ontologies, such as PROV-O, aligned with other relevant industry standards, and will follow the recommendation guidelines by the European Open Science Cloud (EOSC)[27]. Parts of this deliverable reports on our recent survey of related ontologies and standards, in order to ensure semantic interoperability.

3.5.3 Reusability

Reusability, is again the ultimate goal and challenge of this project, i.e. to make data more reusable and more useful for CE. By developing the core of the ontology network in a modular and extensible fashion, we will ensure reusability across industry domains, i.e. the possibility to specialise the ontologies for any industry domain in the future. By developing such specialisations for three specific industry use cases we will exemplify and evaluate the reusability of the ontologies for effective data documentation in concrete usage scenarios. In addition, reusability is about provenance, licensing, and standardisation. The ontology network makes use of the W3C standard PROV-O to express provenance attributes over the data, and the ontologies themselves. We use open licences for the ontologies (CC BY 4.0[28]) and related code (MIT[29]). Further, standardisation is an issue that is also treated in the project through a specific WP2 task. This will ensure that the results are aligned to existing industry standards in our use case domains, as well as to applicable technological standards, e.g. Web standards, and standards for data modelling and knowledge representation. Further, we will investigate the potential of our core ontologies to be developed into a standard set of ontologies for CE, in the context of our standardisation plan developed by WP2 (T2.4).

3.5.4 Publishing Pipeline

The development of the ontology network entails multiple inter-dependent ontologies, several of which will go though multiple development iterations. In order to keep track of such changes, we use a GitHub repository[30] to handle versioning and to create new releases. Proper ontology versioning ensures both consistency and predictability over time, since any reference to a specific version of the ontology will remain valid.

The w3id service is used to provide permanent identifiers for the ontologies under a common namespace (http://w3id.org/CEON/), all of which are aligned with the ontology releases. This provides a way of decoupling

[25] https://lov.linkeddata.es/
[26] http://ontologydesignpatterns.org/
[27] https://open-science-cloud.ec.europa.eu/
[28] https://creativecommons.org/licenses/by/4.0/
[29] https://opensource.org/license/mit
[30] https://github.com/LiUSemWeb/CEON

the identifiers used from any specific domain name or publishing platform, thus providing resilience in the long term, and the identifiers can be redirected as needed. Additionally, the w3id service allows us to support some aspects of content negotiation, allowing the ontologies to be made available according to the requirements of the user (e.g. RDF/XML files when access by an application, human-readable documentation when accessed via a browser).

Documentation is an important aspect when it comes to making ontologies both accessible and understandable. However, creating such documentation can be both labor intensive and time-consuming. In order to streamline this process, the project leverages pyLODE[31] for generating web-friendly documentation directly from the ontology files, thus removing the need for manually creating such content. Additionally, we employ OWL2VOWL[32] and WebVOWL[33] to generate interactive visualizations, providing an easy to understand overview of each ontology. These tools are all available open-source under the MIT licence and are combined into a pipeline that allows ontology documentation to be generated automatically as new ontologies and versions are published, ensuring that the documentation always remains up to date.

3.6 Ontology Alignment Plan and Methods

In this section we present a first methodology for the ontology alignment task, where the purpose is on one hand to make sure our ontology network is properly aligned with relevant existing ontologies in different domains so that cross-domain interoperability can be achieved, but also to explore overlaps, compatibility and incompatibility of our ontologies to existing ones that could be reused for specific use cases.

3.6.1 Ontology Matching Tasks and Alignment Producing Pipeline

As presented in Section 3.2.2, we survey ontologies based on the Circular Economy (CE) domain, five industry domains (sustainability, materials, logistics, manufacturing and products), and their related specific use case domains. Furthermore, we establish three ontology matching tasks. They are (a): producing alignments among CE-specific ontologies, (b): producing alignments between CEON and industry domain-specific ontologies, and (c): producing alignments between CEON and top-level ontologies, such as EMMO (Elementary Multiperspective Material Ontology)[34]. Task a will allow us to further explore the landscape of existing CE ontologies, and make sure that relations among them are clear and as far as possible made explicit. Task b on one hand shows the compatibility of CEON with existing domain-specific ontologies, e.g. in various industry domains as well as with ontologies for specific life-cycle phases, such as manufacturing. The motivation for Task c is that aligning CEON with top-level ontologies allows CEON to alternatively be connect with other domain ontologies through universal knowledge defined by top-level ontologies, rather than through direct alignments. Furthermore, for each task, we formulate a specific question outlined in Table 5. Upon completing each task, we aim to provide an answer to the corresponding question, advancing our understanding of CE knowledge representation and increasing its interoperability and reusability.

To generate alignments among CE-related ontologies in the context of *Onto-DESIDE*, we set up a pipeline, as depicted in Figure 5. This pipeline builds upon general ontology matching frameworks (e.g., [49]), and additionally adds a specific step on publishing alignments in a *FAIR* way. The first step constitutes **matching** ontologies based on three existing matching systems, which are AML [25], LogMap [43], and AMD [98]. AML and LogMap are selected because they are long-term participants in OAEI, and they show state-of-the-art performance in the TBox-matching tracks, hence they will be able to find most of the relevant alignments needed . AMD is a relatively new system based on pre-trained masked language model, and may be able to complement the other two. This choice of tools covers state-of-the-art matching strategies, and should be

[31] https://github.com/RDFLib/pyLODE
[32] https://github.com/VisualDataWeb/OWL2VOWL
[33] https://github.com/VisualDataWeb/WebVOWL
[34] EMMO: https://github.com/emmo-repo/EMMO

sufficient to find most of the possible alignments. Also, AMD does not require significant computing resources as some other LLM-based tools. Another main step is **validation and/or manually matching** in which users validate candidate mappings or manually create new ones. While **Task a** and **Task b**, start from the first step, we use our prior experience in aligning MDO and EMMO, and start **Task c** from the manual matching step. Note that Figure 5 depicts two optional steps – **voting or filtering** and **conflict checking**, which we do not currently use, but they are part of our future alignment plan, in oder to further improve and quality assure the alignments. The goal of the voting or filtering step is to refine the initial set of mapping suggestions yielded in the previous step. For instance, a voting strategy can be based on the number of tools yielding the same mapping, and filtering based on similarity thresholds. The conflict checking step aims to detect and address defects (e.g., inconsistency and incoherence) that may arise when connecting ontologies through alignments. In the future alignment plan, we will use existing reasoning and/debugging tools to check if produced mappings candidates arise any conflicts to the source and target ontologies that are matched. The final step is publishing and maintenance, which is elaborated in the next section.

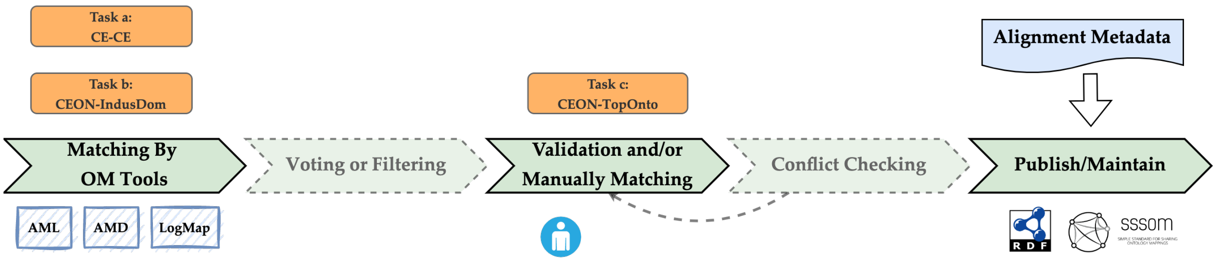

Figure 5: A pipeline producing alignments based on the general framework outlined in [49].

3.6.2 FAIR Ontology Alignments

As discussed in [91] and based on our previous experiences from OAEI, limited attention was so far paid by the research community to generating FAIR ontology alignments. That is, there is a lack of focus on using rich metadata to represent alignments by matching tools, while such rich metadata is on the other hand necessary to ensure trust in mappings, and allow users of the ontology alignment to make informed choices on what alignment is suitable for them. For instance, tools participating in OAEI usually represent a mapping as a quadruple in the form of <source_entity, target_entity, confidence, relation_type>. Alignments between two ontologies would be a set of such quadruples. This manner of representing alignments is easy for linking the source and target ontologies with alignments into an ontology network. However, it fails to keep track of meta-information such as matching strategies used. Addressing this gap, the recently proposed Simple Standard for Sharing Ontological Mappings (SSSOM) [57, 58] defines a set of metadata entries to represent alignments, incorporating details such as mapping justifications (lexical matching, manual mapping) and mapping tools (algorithms used and tool versions). It also allows to annotate mappings with provenance information so that candidate mappings and validated mappings can be distinguished. OAEI has started to focus on providing FAIR alignments and adopting the SSSOM schema to some extent.

We see both advantages and disadvantages of these two options mentioned above for representing align-

Task	Question	Task Aim
a: CE-CE	How can existing CE ontologies be aligned to each other?	Enhance interoperability and knowledge exchange among CE-related ontologies.
b: CEON-IndusDom	What are the common concepts between CEON and specific domain ontologies?	Link CEON knowledge to domain specific knowledge.
c: CEON-TopOnto	How can CEON be aligned to top-level ontologies?	Link CEON knowledge to universal knowledge in top-level ontologies.

Table 5: Ontology Matching Tasks, Questions and Aims.

ments. Therefore in our work, to adhere to the FAIR principles, the alignments will be represented using both the existing OAEI quadruple format and adapted SSSOM metadata. We leverage a subset of the SSSOM schema to annotate the generated alignments. Figure 6 exemplifies the portion of the SSSOM schema[35] used in our alignment publication pipeline. The SSSOM schema draws upon vocabularies from other services such as SKOS[36], LinkML[37] and SEMAPV[38]. Essentially, SSSOM distinguishes mappings based on different entity types involved (e.g., classes, object properties, data properties, named individuals). Each matched entity is represented as an entity reference. Moreover, `EntityReference` can represent source and target ontologies, and mapping justifications by specifying their URIs. SSSOM uses LinkML's definition of `String` and `Double` to represent string and double values such as entity labels, mapping tools, and confidence scores. Table 6 shows mapping examples based on the SSSOM schema, in tabular format. For instance, the first mapping is an equivalence mappings stating that the *Product* concept in CEON is equivalent to (e.g., the cardinality is 1:1) *Product* in DPPO (Digital Product Passport Ontology), where this mapping is produced by the tool AML based on lexical matching methods. Moreover, we publish the alignments by employing a permanent URI[39] as an identifier, established through the w3id service.

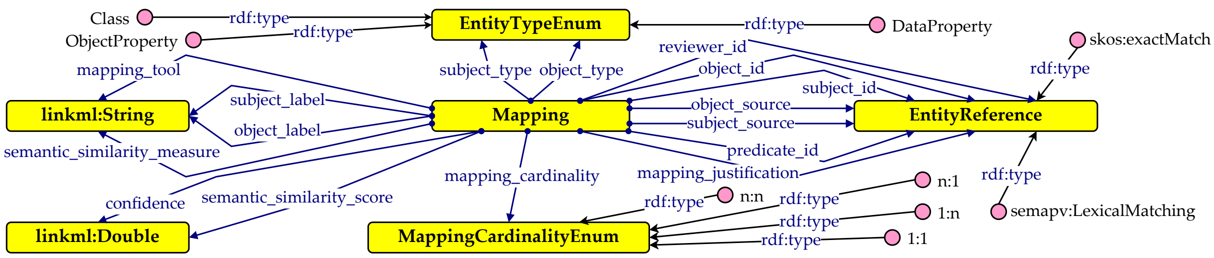

Figure 6: A part of the SSSOM schema.

subject_id	sub_label	predicate_id	object_id	obj_label	justification	confidence	tool	cardinality	reviewer
ceon:Product	Product	exactMatch	dppo:product	product	LexicalMatching	1.0	AML	1:1	HL
ceon:Statement	Statement	relatedMatch	emmo:Information	Information	ManualCuration	–	–	n:1	HL

Table 6: Example SSSOM-based mappings in tabular format (shortcut names are used for some column names).

[35]SSSOM schema: https://github.com/mapping-commons/sssom/blob/master/project/owl/sssom_schema.owl.ttl
[36]Simple Knowledge Organization System: http://www.w3.org/2004/02/skos/
[37]Linked Data Modeling Language: http://w3id.org/linkml
[38]Semantic Mapping Vocabulary: http://w3id.org/semapv/vocab/semapv.owl
[39]The result is published at http://w3id.org/CEON/alignments.

4 Preliminary Result #1 – Survey of the Field

In this chapter we present our results regarding the surveys performed.

4.1 Overview of Existing Research in the Field

The literature survey of the current related research and state of the art in semantic technologies related to the CE field is currently ongoing, hence results presented here are preliminary and only sketches the landscape in broad terms. Currently we are analysing the set of 109 articles that have gone through the process of assuring that they are of high quality and represent a real contribution to the field in terms of applying semantic technologies in relation to CE. The method for this process was described in detail in Chapter 3.2.1.

4.1.1 Literature that make use of semantic technologies for the Circular Economy

When analysing the gathered articles we are looking for patterns in terms of how semantic technologies are applied and in what way they are put to use in the CE field. In the previous steps of the methodology we have discarded work that did not apply the technologies in some way, i.e., merely discussing possibilities of its use in the field of CE was deemed not sufficient. As a consequence of this we are able to see technological patterns in terms of which semantic technologies are used as well as in what context of the CE domain they have been applied. Further, we are also looking for patterns related to which industry domains that are targeted by the work done.

But, firstly we need a way to group different articles, before analysing them in more detail. In this way we are able to say something about patterns in relation to specific contexts in which they have been used. As CE is a cross-industry system, interoperability between industries is integral to its performance. This also relates to one of the core contributions of the Onto-DESIDE project, that of enabling cross-industry collaboration and data sharing. As cross-industry interoperability is central, this is something that we have also tried to capture in how we perform the categorisation and define groups. The current results of this analysis are to be seen as preliminary and will partly change as we move forward. Currently, we have read 45 of 109 articles and based on this we have arrived at the following categorisation.

#	Category	Comment
1	Industry domain	Is the paper addressing multiple industry domains or does it target a specific industry.
2	Circular Economy focus	Is the paper addressing a specific circular strategy or is the focus on multiple strategies that impact multiple stages of a product or material's lifecycle.
3	Use of knowledge representations	What semantic technologies are being used for knowledge representation, and at what level of complexity? E.g., does the approach use knowledge graphs, vocabularies, taxonomies, ontologies or even rules?
4	Semantic application	How are semantic technologies used? E.g., SPARQL queries are executed over a knowledge graph for answering questions, use of ontologies for reasoning, or data integration with IoT and sensors technologies.
5	Business application	Towards what end are the proposed solutions or concepts aimed in terms of business problem they are addressing. E.g., reporting, decision support, process efficiency.

Table 7: The initial set of categories used, and explanations of how they have been described so far.

Each of the 109 articles will be categorised using the categories in this table. As work with reading and analysing the list of articles is ongoing, categories might get added or change.

4.1.2 Emerging patterns

Given the categories presented in Table 7, one category of work done has a broad CE perspective rather than focusing on a specific strategy. Examples of this can be seen in [60] and [83] where both articles discuss multiple strategies within CE and how these interact towards creating a value network. This acknowledges the thinking that a circular economy collaboration consists of different actors that play different roles in reaching the end value. This is also inline with what we have seen in the requirements for the project, as formulated by the project partners and described in D2.2. While on the other hand there are also articles that discuss a specific CE strategy, representing another group of articles, the majority seems to be using semantic technologies in a broader CE perspective.

Another pattern is that of digital product passports and traceability of materials or products. A number of the articles discuss the importance of traceability and lifecycle management of resources, and make use of semantic technologies in this setting, e.g., [83],[22], and [32]. This DPP focus could perhaps also explain a broader perspective on CE, simply because the lifecycle perspective is so prominent. Taking into account the whole lifecycle of a product, there are phases, roles and actions present that map to more than one CE strategy. This is for example visible in [60], where the authors build an OWL ontology representing the lifecycle of a product. This ontology is then used together with an IoT-enabled infrastructure to build a decision support system for different CE strategies.

4.2 Overview of Existing Ontologies and Standards

In this section, we present the result of surveying existing ontologies and standards, where the survey is conducted according to the methodology presented in Section 3.2.2. We introduce general level ontologies (Section 4.2.1, Section 4.2.2 and Section 4.2.3), use case specific ontologies (Section 4.2.4) and standards (Section 4.2.5), respectively. We categorise the collected ontologies into ontologies related to (1) Circular Economy and Sustainability, (2) Manufacturing, Logistics and Products, (3) Materials, (4) Construction, (5) Electronics, and (6) Textiles. We list 52 downloadable ontologies in Table 8 and Table 10, as the main result of the survey, and provide a catalogue to keep track of these ontologies and ontology-related work in a public repository[40]. In Section 4.3, we then briefly discuss how these ontologies can contribute to the CE domain and what challenges should be noted.

4.2.1 Ontologies related to Circular Economy and Sustainability

In Table 8, we have assigned labels CE and SU to ontologies related to Circular Economy or Sustainability, respectively, according to the domains presented in Table 2. Note that some ontologies are assigned more than one label since they relate to several domains.

First of all we note that not many core ontologies for CE can be found. Most target very specific use case in specific industry domains. However, in [83] two ontologies have been established to facilitate material circulation within the circular economy context by developing the Circular Materials and Activities Ontology (CAMO) and Circular Exchange Ontology (CEO). Both ontologies have definitions related to resource, product and activity which are common in the context of circular economy. CEO reuses existing ontologies such as GeoSPARQL[41], having a focus on the construction domain. CAMO categorises specific materials, products and activities for circular economy. The usage of CEO and CAMO is furthermore investigated in [84] for

[40] https://github.com/LiUSemWeb/Circular-Economy-Ontology-Catalogue
[41] http://www.geosparql.org

Table 8: Characteristics of Relevant General Ontologies.

id	Ontology name	Domain
1	AMO (Additive Manufacturing Ontology) [62]	MAN, PR, MAT
2	BCAO (Building Circularity Assessment Ontology) [64]	CE
3	BiOnto (An Ontology for Sustainable Bioeconomy and Bioproducts) [8]	CE, SU
4	BONSAI-core (Big Open Network for Sustainability Assessment Information core ontology) [31]	PR, SU
5	BPO (Building Product Ontology) [95]	PR
6	BUILDMAT (Building Material Ontology) [13]	MAT
7	BWMD-Domain ontology [68]	MAN, MAT
8	CAMO (Circular Materials and Activities Ontology) [83]	CE, MAT
9	CEO (Circular Exchange Ontology) [83]	CE
10	CHAMP (Coordinated Holistic Alignment of Manufacturing Processes) [87]	MAN, PR
11	COMPOSITION (Collaborative Manufacturing Services Ontology) [17]	MAN, LO
12	ENVO (Environment Ontology) [14]	SU
13	GPO (General Process Ontology) [33]	MAN, LO
14	GRACE ontology [52]	MAN, PR
15	IMAMO (Industrial MAintenance Management Ontology) [45]	LO
16	IOF-core ontology [24]	MAN, MAT
17	ManuService ontology [56]	MAN, PR, LO
18	MASON (MAnufacturing's Semantics ONtology) [53]	MAN
19	MATONTO (MatOnto Ontology) [16]	MAT
20	MDO (Materials Design Ontology) [55]	MAT
21	MPO (Material Properties Ontology) [77]	MAT
22	MSDL (Manufacturing Service Description Language) [5]	MAN
23	MSO-OFM (Manufacturing System Ontology / Ontologies for manufacturing and logistics) [65]	MAN, LO
24	NMRRVOCAB (Materials Data Vocabulary) [61]	MAT
25	PRONTO (Product Ontology) [92]	PR
26	PSS (Product Service System) [59]	PR, MAN
27	ROMAIN (Reference Ontology for Industrial Maintenance) [44]	LO
28	SAREF (Smart Appliances REFerence ontology) [20]	General
29	SAREF4ENER (an extension of SAREF for the energy domain) [19]	SU
30	SAREF4ENVI (an extension of SAREF for the environment domain) [76]	SU
31	SAREF4INMA (an extension of SAREF for the industry and manufacturing domains) [21]	MAN
32	SDGIO (Sustainable Development Goals Interface Ontology) [85]	SU
33	SCONTO (Supply Chain Ontology) [93]	LO
34	SCOR (Supply Chain Operation Reference) [71]	LO
35	UNSPSC (Universal Standard Products and Services Classification) [79]	PR
36	VERONTO (VERsioning ONTOlogy) [94]	MAN, PR
37	Z-BRE4K [97]	MAN
38	PMDco (Platform MaterialDigital Core Ontology) [7]	MAT
39	MECH (Materials Mechanics Ontology) [2]	MAT
40	MSEO (Materials Science and Engineering Ontology) [3]	MAT
41	MTO (Mechanical Testing Ontology) [63]	MAT
42	MAMBO (Molecular and Materials Basic Ontology) [72]	MAT
43	DEB (Devices, Experimental Scaffolds, and Biomaterials Ontology) [37]	MAT
44	MWO (MatWerk Ontology) [4]	MAT
45	DPPO (Digital Product Passport Ontology) [42]	CE, PR

Table 9: Ontology Metrics of General Ontologies.

Ontology	Class #	Object Property #	Data Property #	Individual #	Language	Reused ontologies
AMO	293	19	5	139	OWL	BFO, Common Core Ontologies, CHAMP
BCAO	37	19	17	0	OWL	–
BiOnto	780	64	5	0	OWL	–
BONSAI-core	13	13	0	0	OWL	Units of Measure, schema.org, SKOS, Time
BPO	25	22	6	0	OWL	GoodRelations, schema.org, FOAF, SEAS
BUILDMAT	27	56	7	12	OWL	QUDT
BWMD-Domain	772	24	11	0	OWL	BFO, OBO
CAMO	86	17	1	0	OWL	–
CEO	11	18	0	0	OWL	SKOS, Time, PlaceReferenceTheory, GeoSPARQL, SpatioTemporalFeature
CHAMP	2001	253	11	154	OWL	–
COMPOSITION	317	82	71	118	OWL	MSDL, GoodRelations, MASON, schema.org
ENVO	6566	135	1	44	OWL, OBO	BFO, ChEBI, OBO
GPO	106	12	0	0	OWL	EMMO, SKOS
GRACE	21	28	33	45	OWL	–
IMANO	109	4	6	3	OWL	–
IOF-core	93	103	0	0	OWL	BFO, SKOS
ManuService	105	33	183	69	OWL	–
MASON	246	37	18	102	OWL	SWRL
MATONTO	848	83	13	131	OWL	BFO, SKOS, Snap
MDO	37	32	32	2	OWL	QUDT, PROV-O
MPO	140	13	8	0	OWL	SAREF
MSDL	664	641	5	2926	OWL	BFO, OBO-GO, OBO-RO
MSO-OFM	109	57	116	0	OWL	–
NMRVOCAB	3	0	0	994	OWL, SKOS	SKOS
PRONTO	38	31	0	0	OWL	–
PSS	202	6891	0	1	OWL	Common Core Ontologies, BFO, IOF-core
ROMAIN	1056	171	17	357	OWL	BFO, Common Core Ontologies
SAREF	113	63	31	55	OWL	Time
SAREF4ENVR	147	52	45	30	OWL	SAREF
SAREF4ENVI	31	24	12	24	OWL	SAREF
SAREF4INMA	35	24	11	0	OWL	SAREF
SDGIO	907	152	0	470	OWL, OBO	ENVO, ChEBI, BFO, PCO, DOID, SWRL, OBO, UBERON
SCONTO	201	57	0	0	OWL	–
SCOR	285	5	249	224	OWL	schema.org, Ordered List Ontology
UNSPSC	16506	0	0	16500	OWL	–
VERONTO	26	38	9	0	OWL	–
Z-BRE4K	56	53	26	0	OWL	–
PMDco	239	113	15	20	OWL	CHEBI, PROV
MECH	667	130	15	20	OWL	PMDco
MSEO	239	129	3	2	OWL	BFO, SKOS
MTO	211	30	0	0	OWL	BFO, MSEO
MAMBO	57	35	63	21	OWL	BFO
DEB	601	12	109	0	OWL	SKOS
MWO	116	74	29	5	OWL	BFO, EMMO, schema.org, NFDIcore
DPPO	26	22	6	0	OWL	–

representing textile data. Another recently developed ontology targeting at the knowledge representation for the CE domain is the Digital Product Passport ontology network (DPPO) [42]. The goal of DPPO is to provide a digital representation of physical products for capturing information that is relevant to circular products and business models. As far as our survey can determine, these are the existing ontologies closest to what we are developing in Onto-DESIDE.

In addition, there are a few more ontologies that deal with CE, targeting more specific use cases. For instance, the Building Circularity Assessment Ontology (BCAO) [64] focuses on the construction industry and links data and information from different manufacturer products to support decision making while considering circularity. Nevertheless, the scope of many of the general topics of this ontology overlaps with our focus. For instance, in BCAO a product is made of materials which are produced by an organisation, which are also core notions in Onto-DESIDE. Further, BiOnto [8] from the BIOVOICES[42] project, aims to build a shared and common terminology in the domain of bioeconomy so that multiple and different stakeholders can provide information according to the ontology. Then the BONSAI-core ontology [30, 31] focuses on representing activities in product life cycles in which each activity involves input and output flows as well as participating flow objects. For instance, a flow object, coal, within a flow can be an input flow of an electricity production activity and such an activity produces electricity. The aim of the BONSAI project is to support product comparisons and decisions by representing product footprints. The above ontologies cover specific aspects that also appear in our requirements analysis. For instance, the focus on specific use cases such as construction and some circular concerns such as product life cycles. However, our requirements of ontologies in this project have an overall slightly different focus than those of the above ontologies (introduced in Chapter 5). For instance, one of the central modules in the ontology network is supposed to model domain knowledge for circular value networks and such a module is intended to be connected to and used by other modules in the ontology network modelling general domains or domains of specific industry use cases (i.e. construction, electronics and textiles).

Moving towards the sustainability topic, the Environment Ontology (ENVO) [14] specifies a number of essential environment types that could be useful for annotating biological data. For instance, a central concept in ENVO is environmental system with sub-concepts biome and habitat. Although, these are not core concepts in our set of requirements, representing environmental impact and effects may at some point be necessary, e.g. to asses impact of certain steps in a value network. Smart Appliances REFerence ontology (SAREF) [20] has a focus on the smart appliances domain, modelling concepts such as device, measurement, service, property and function. SAREF4ENVI [76] extends SAREF to describe different physical objects, devices and their characteristics, in an environment setting. SAREF4ENER [19] extends SAREF to represent energy management such as energy efficiency optimisation and describes, e.g. specific power sequences. Both these SAREF extensions may be relevant for describing setups in circular value networks.

A bit more general, the Sustainable Development Goals Interface Ontology (SDGIO) [85] intends to represent knowledge related to the sustainable development goals[43] as well as their targets and indicators. SDGIO reuses a number of existing ontologies from different domains such as ENVO [14] in the environment domain.In our ontologies we will need to describe goals of a circular value networks, which in turn may relate to the general sustainable development goals.

4.2.2 Ontologies related to Manufacturing, Product, and Logistics

In a circular value network, a resource can be realised in different states. These states can be identified as particles (materials), parts (components) and products (finished goods) [11]. Operations in terms of manufacturing and logistics can happen in all these three states of resources. For instance, different components need to be assembled into products by manufacturing. A well-designed logistics system can then optimise the management of products in their life cycle by, for instance, reducing the distribution, redistribution and monitoring maintenance cost. Thus, the domains of *Manufacturing*, *Products*, and *Logistics* as presented in Table 2,

[42] https://www.biovoices.eu/about-us/the-scope-/
[43] https://sdgs.un.org/goals

are tightly connected and we discuss the ontologies for all these domains in this section. We use the labels MAN, PR, LO, respectively. Among the collected ontologies shown in Table 8, there are 22 ontologies for these domains. Some of them are assigned with more than one label since they capture knowledge in more than one domain.

First of all, taking the manufacturing domain as an example, several ontologies model different manufacturing processes. For instance, AMO (Additive Manufacturing Ontology) [62] focuses on modelling different manufacturing processes relevant to additive products as well as their physics-based models. BWMD-Domain ontology [68] contains definitions of different manufacturing processes such as casting and coating. MAnufacturing's Semantics ONtology (MASON) [53] concerns what resources (e.g. human resource and material resource), entities (e.g. assembly entity) and operations (e.g. manufacturing operation and logistic operation) are involved within the manufacturing domain. Particularly, it distinguishes different manufacturing processes or operations by taking into account if such an operation results in a loss of volume or not. Collaborative Manufacturing Services Ontology (COMPOSITION) [17] concerns collaborative manufacturing services that include human operations, logistic operations and manufacturing operations by reusing MASON. Manufacturing Service Description Language (MSDL) [5] focuses on manufacturing services in the mechanical machines. Manufacturing acts are categorised as shaping processes and non-shaping processes based on whether they alter the shape of the input material or not. Overall we note that there are many detailed models of manufacturing processes, whereas this project will mainly be concerned with creating alignments and bridge different viewpoints, rather than creating new detailed ontologies in this area.

In addition to modelling different manufacturing processes, several ontologies focus on modelling relevant concepts and/or relationships that relate to such processes. The IOF-core ontology [24] includes common terms and concepts across multiple domains of industry. For instance, in the manufacturing domain, IOF-core describes that a manufacturing process has a machine or person participation, as well as a material entity as input. General Process Ontology (GPO) [33] focuses on modelling processes such as measurement processes taking materials as input and providing information as output, or manufacturing processes having materials entities as both input and output. SAREF4INMA [21] extends SAREF to capture knowledge in the manufacturing domain. For instance, it contains the item and batch concepts to describe factory production, as well as general concepts such as production equipment and factory. Manufacturing System Ontology / Ontologies for manufacturing and logistics (MSO-OFM) [65] models manufacturing and logistics systems by addressing some main aspects such as physical and technological aspects. The physical aspect captures the characteristics of a manufacturing and logistics system in terms of workers, production facilities, equipment and devices. The technological aspect models processes such as how products are processed within the manufacturing and logistics system. Z-BRE4K [97] is an ontology providing annotations and descriptions to represent manufacturing system performance. Similarly as noted before, many ontologies model processes and participation of resources in them, and in Onto-DESIDE we will therefore mainly be concerned with generalising over these, and creating appropriate alignments and bridges between these efforts.

Among the ontologies introduced above, we find that several ontologies also concern the logistics domains (e.g. COMPOSITION, GPO, MSO-OFM). There are also ontologies focusing on the logistics domain specifically such as IMAMO, ROMAIN, SCONTO and SCOR. IMAMO and ROMAIN focus on modelling domain knowledge for maintenance in the context of logistics domain. Industrial Maintenance Management Ontology (IMAMO) [45] contains general concepts such as equipment, maintenance task and maintenance strategy which makes it possible to increase semantic interoperability among different applications requiring maintenances within the same industrial environment. Reference Ontology for Industrial Maintenance (ROMAIN) [44] extends the material entity within BFO with a new concept maintainable item as well as relevant concepts such as maintenance strategy, plan and action. SCONTO and SCOR focus on modelling domain knowledge for supply chain in the context of logistics domain. Supply Chain Operation Reference (SCOR) [71] provides vocabularies to represent the supply chain operations reference standard. For instance, it models different processes in a supply chain system such as deliver, plan and return processes. Supply Chain Ontology (SCONTO) [93] defines supply chain related entities in three dimensions in terms of structures of supply chain systems, processes and resources involved in supply chains. For instance, a supply chain system includes specific markets and organisations as well as areas such as logistics, production and sales. Similar to SCOR, the process part also includes deliver, plan and return. Resources can be financial resources, human resources and material resources. Hence, also for supply-chain modelling and logistics several ontologies exist, for various domains, whereby our role will be mainly to bridge different viewpoints, and make sure CE aspects are appropriately covered.

Additionally, some ontologies specifically focus on representing knowledge for the product domain. Building Product Ontology (BPO) [95] has a focus on building products modelling, for instance, how different components of a product can be assembled. Product Ontology (PRONTO) [92] captures production information in two ways. The abstraction hierarchy level considers a product at three different levels of abstraction: as a product, as a member of a variant set (similar products with certain constraints), and as a member of a family (similar products). The structural level considers the components at each abstraction level. Universal Standard Products and Services Classification (UNSPSC) [79] has detailed classifications on product and services in the scope of global marketplace.

As mentioned before, some ontologies are labeled with more than one domain since they capture knowledge from multiple domains. Some of them have been introduced above (e.g. AMO, BONSAI-core, BWMD-Domain Ontology, COMPOSITION, GPO, IOF-core ontology, MSO-OFM). We introduce the others below. ManuService ontology [56] is modelled in a general level (with MAN, PR and LO labels), focusing on a model for the cloud-based service provision in a cloud-based manufacturing environment. It contains concepts related to product specification (e.g. price specification), quality constraints (e.g. design capability and production capability) and different machines for manufacturing processes.

In addition, several ontologies focus on both the manufacturing and product domains. Coordinated Holistic Alignment of Manufacturing Processes (CHAMP) [87] represents knowledge of product life cycles, aiming at integrating data within different industrial organisations, as well as across them. It uses a number of existing ontologies such as BFO [6] and the Common Core Ontologies[44]. GRACE ontology [52] focuses on describing the knowledge for multi-agent systems that integrate processes and quality control in production lines in distributed manufacturing systems. It contains concept definitions such as product and resource. Product Service System (PSS) [59] represents domain knowledge that relates to different aspects of products and product service systems (PSS) such as the provider for a product or a PSS, and different resources needed for a PSS (e.g. manufacturing resources, business resource, hardware and software resources). VERsioning ONTOlogy (VERONTO) [94] is an ontology for the representation of temporal events that affect product information over time.

To sum up this section, there are numerous ontologies describing most aspects of manufacturing, products and their components, as well as logistics and supply-chains. In these cases, Onto-DESIDE will mainly focus on (1) making sure that the CE viewpoint is appropriately covered, and if needed complement the existing ontologies with certain specific concepts, and (2) create alignment modules, to bridge the use of a selected set of these ontologies together with our core ontology modules.

4.2.3 Ontologies related to Materials

The work presented in [47, 54, 48] has investigated existing ontologies related to the materials science domain. The currently on-going EU project OntoCommons conducted a survey of existing ontologies in identified domains of which one domain is materials science and engineering. Three ontologies in these surveys (BWMD-Domain Ontology, MatOnto and MPO) are clearly relevant for our project (in terms of representing materials composition information) and are included in our survey. Additionally, six other ontologies were collected. In Table 8, we have assigned the label MAT to these ontologies.

BWMD-Domain ontology (also labeled MAN), based on BFO, contains definitions of different material structures (e.g. meso structure, micro structure and macro structure) and different engineering material types (e.g.

[44] https://github.com/CommonCoreOntology/CommonCoreOntologies

composite material, metallic material, organic material) which can provide general information of materials for the circular economy domain. MATONTO (MatOnto Ontology) [16] models different material properties, e.g. amount of substance, and flexural strength as measured properties. MPO (Material Properties Ontology) [77] has a focus on describing materials and their properties for building components (e.g. layer, layer set), with a detailed taxonomy of materials that relate to a building. Similar to BWMD-Domain ontology and MPO, BUILD-MAT [13] also represents materials with a focus on building components, as well as general material properties and material types. MDO (Materials Design Ontology) [55, 48] contains a structure module describing composition information of materials, which is essential in the circular value network context when a recycling operation is taken. The Materials Mechanics Ontology (MECH) [2] captures concepts for the materials fatigue domain as well as general materials science and engineering related concepts. The Devices, Experimental Scaffolds, and Biomaterials Ontology (DEB) [37], focuses on knowledge representation for biomaterials including their design, manufacturing, and biological testing processes. The conceptualisation of DEB is based on text analysis over a biomaterials gold standard corpus. The Platform MaterialDigital Core Ontology (PMDco) [7] has a focus on modeling semantics for materials and their related processes (e.g., mechanical testing process). The Mechanical Testing Ontology (MTO) [63] is developed based on EMMO, focusing on formally representing mechanical testing processes over materials. The Molecular and Materials Basic Ontology (MAMBO) [72] targets at representing domain knowledge for both materials simulations (calculations) and experiments (measurements) which has a potential to improve interoperability of data exchange between simulations and experiments. The Materials Science and Engineering Ontology (MSEO) [3] contains a number of concepts that are related to engineering perspective (e.g., materials related processes and experiment). The MatWerk Ontology (MWO), developed in the NFDI-MatWerk[45] consortium, focuses on digital representation of materials as well as materials' relevant processes. In addition, the ontology includes a number of concepts as sub-concepts of those in BFO, to represent materials structures and properties. The ontologies AMO, CAMO, IOF-Core Ontology were already described earlier as they were also labeled with other domains.

In summary, the materials domain is also a core concern for the Onto-DESIDE ontology network, but again a domain where much work has been done and is ongoing. We will not attempt to remodel all these notions, but reuse as much as possible the existing ontologies. One observation from the CE domain that becomes important is the fact that the notion of "material" itself is quite context-dependent. This means that what is considered a material in one industry domain, is rather considered a product in another, e.g. a fabric is considered a product of a fabric manufacturer, but a material by a fashion brand. Hence, Onto-DESIDE needs to capture this context-dependent notion of materials, components and products, and appropriately align to materials ontologies in the right contexts.

4.2.4 Use Case Specific Ontologies

In addition to survey existing ontologies for the domain as we introduced in the previous sections, we search ontologies that are related to the three use cases in the Onto-DESIDE project, which are the Construction, Electronics and Textiles use cases. The characteristics of these ontologies, as described in our methodology chapter, are shown in Table 10 and Table 11 respectively.

There are five ontologies that relate to the construction domain. RealEstateCore (REC) ontologies [38], including different modules such as agent, building, device and lease is developed for property owners to describe data that are generated from interactions within buildings. The SEAS (Smart Energy Aware Systems) Building Ontology [51], including some modules such as zone, building, represents the smart home domain. The building topology ontology (BOT) [80] represents topological related concepts of a building. Building Ontology [15], extending BOT, furthermore describes relationships among topological concepts such as zones, spaces, and building elements. SAREF4BLDG [75] extends SAREF to describe building related concepts such as physical spaces of a building, and different devices that can exist in a building.

In addition, we find ElectricAppliance ontology and GeniusTex ontology that relate to the electronics and textiles

[45] https://nfdi-matwerk.de

Table 10: Characteristics of Use Case Specific Ontologies.

id	Ontology name	Domain
1	REC (RealEstateCore) [38]	Construction
2	SEAS (The SEAS Building Ontology) [51]	Construction
3	BOT (Building Topology Ontology) [80]	Construction
4	Building Ontology [15]	Construction
5	SAREF4BLDG [75]	Construction
6	ElectricAppliance ontology [1]	Electronics
7	GeniusTex (Smart Textile Ontology) [29]	Textiles

Table 11: Ontology Metrics of Use Case Specific Ontologies.

Ontology	Class #	Object Property #	Data Property #	Individual #	Language	Reused ontologies
REC	179	99	84	297	OWL, SHACL, DTDL	–
SEAS	102	32	3	5	OWL	Procedure Execution ontology
BOT	10	16	1	5	OWL	schema.org
Building Ontology	46	15	19	0	OWL	BOT
SAREF4BLDG	71	179	83	0	OWL	SAREF
ElectricAppliance	44	20	2	88	OWL	–
GeniusTex	77	63	37	73	OWL	SOSA, Unit of Measure

domains, respectively. ElectricAppliance ontology [1] has a classification of different electric appliances (e.g. communication, kitchen, entertainment appliances). GeniusTex (Smart Textile Ontology) [29], focusing on smart textiles domain, has different modules to describe relationships among materials, components, and processes related concepts.

Overall, this part of the survey is probably less complete than the other parts, and will be extended when working on ontology extension in the context of WP6. However, still, we may note that also in these domain some specific ontologies already exist, to which alignments might be created.

4.2.5 Standards for Ontology Development

In order to develop high-quality and complete ontologies, it is also necessary to take the corresponding standards (i.e. ISO standards), and EU policies, laws and regulations into account. A more comprehensive overview of standards is given in D2.7, however, here we focus on standards directly impacting the ontology engineering process.

We list 50 relevant standards, regulations and polices in Table 12. These standardisation efforts can be categorised into five domains which are (1) circular economy, (2) general domain (e.g. environment, energy, quality management), (3) construction, (4) electronics, and (5) textiles. We also label each work as a work at the international level or at the EU level. In total, we have 16 standardisation efforts in the circular economy domain (12 at the global level and 4 at the EU level). Among these, 7 standards are under development. There are 12 efforts in the general domains, 8 in the construction domain, 2 in the electronics domain and 12 in the textiles domain, respectively.

One use of these resources is as a basis for extracting relevant terms for a specific domain. They also provide context and restrictions for the terms in the ontology. For instance, ISO/DIS 59004 defines key terminology, establishes circular economy principles and provides guidance for circular economy implementation. ISO/TC 297, ISO 50001:2018, and ISO 14001:2015 define the fundamentals and vocabularies regarding different aspects such as waste collection, energy management, and environmental management, respectively.

There are also different types of EU policies, legislation, and regulations. For instance, the EU taxonomy for sustainable activities (regulation (EU) 2020/852) provides a list of terms as well as the criteria for environmentally sustainable economic activities.

Table 12: Relevant Standards, Regulations and Policies.

Name	Domain	Level
ISO/DIS 59004 Circular Economy – Terminology, Principles and Guidance for Implementation[46] (under development)	Circular Economy	Global
ISO/DIS 59010 Circular Economy — Guidance on the transition of business models and value networks[47] (under development)	Circular Economy	Global
ISO/DIS 59020 Circular Economy — Measuring and assessing circularity[48] (under development)	Circular Economy	Global
ISO/CD TR 59031 Circular economy – Performance-based approach – Analysis of cases studies[49] (under development)	Circular Economy	Global
ISO/CD TR 59032.2 Circular economy - Review of business model implementation[50] (under development)	Circular Economy	Global
ISO/CD 59040 Circular Economy — Product Circularity Data Sheet[51] (under development)	Circular Economy	Global
ISO/CD 59014 Secondary materials — Principles, sustainability and traceability requirements[52] (under development)	Circular Economy	Global
ISO 14021:2016 Environmental labels and declarations[53]	Circular Economy	Global
Circular Product Data Protocol[54]	Circular Economy	Global
circular.ID Open Data Standard[55]	Circular Economy	Global
Product Circularity Data Sheet (PCDS)[56]	Circular Economy	Global
GS1 Global Traceability Standard (GTS2)[57]	Circular Economy	Global
EU Environment related policies[58]	Circular Economy	EU
EU Circular Economy related policies[59]	Circular Economy	EU
EU taxonomy for sustainable activities (**regulation** (EU) 2020/852)[60]	Circular Economy	EU
EU circular raw materials[61]	Circular Economy	EU
ISO/TC 297 Waste collection and transportation management[62]	General Domain	Global

[46] https://www.iso.org/standard/80648.html
[47] https://www.iso.org/standard/80649.html
[48] https://www.iso.org/standard/80650.html
[49] https://www.iso.org/standard/81183.html
[50] https://www.iso.org/standard/83044.html
[51] https://www.iso.org/standard/82339.html
[52] https://www.iso.org/standard/80694.html
[53] https://www.iso.org/standard/66652.html
[54] https://www.circulardataprotocol.org
[55] https://circularity.id
[56] https://pcds.lu/wp-content/uploads/2020/11/MECO_CEDataSet_PCDS_Public-27072020.pdf
[57] https://www.gs1.org/sites/default/files/docs/traceability/GS1_Global_Traceability_Standard_i2.pdf
[58] https://environment.ec.europa.eu/index_en
[59] https://environment.ec.europa.eu/topics/circular-economy_en
[60] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852
[61] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
[62] https://www.iso.org/committee/5902445.html

ISO/TC 154 Processes, data elements and documents in commerce, industry and administration[63]	General Domain	Global
ISO 14001:2015 Environmental management system – Requirements with guidance for use[64]	General Domain	Global
ISO 14004:2016 Environmental management systems — General guidelines on implementation[65]	General Domain	Global
ISO 14005:2019 Environmental management systems — Guidelines for a flexible approach to phased implementation[66]	General Domain	Global
Ecodesign requirements[67]	General Domain	EU
ISO 9000:2015 Quality management systems – Fundamentals and vocabulary[68]	General Domain	Global
ISO 9001:2015 Quality management system – Requirements[69]	General Domain	Global
ISO 9004:2018 Quality management — Quality of an organization — Guidance to achieve sustained success[70]	General Domain	Global
ISO 50001:2018 Energy management systems — Requirements with guidance for use[71]	General Domain	Global
ISO 50002:2014 Energy audits — Requirements with guidance for use[72]	General Domain	Global
ISO 50003:2021 Energy management systems — Requirements for bodies providing audit and certification of energy management systems[73]	General Domain	Global
ISO 6707-1:2020 Buildings and civil engineering works — Vocabulary — Part 1: General terms[74]	Construction	Global
ISO 6707-2:2017 Buildings and civil engineering works — Vocabulary — Part 2: Contract and communication terms[75]	Construction	Global
ISO 6707-3:2022 Buildings and civil engineering works — Vocabulary — Part 3: Sustainability terms[76]	Construction	Global
ISO 6707-4:2021 Buildings and civil engineering works — Vocabulary — Part 4: Facility management terms[77]	Construction	Global
ISO 16739-1:2018 Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries - Part 1: Data schema[78]	Construction	Global
EU Construction and Demolition Waste Protocol and Guidelines[79]	Construction	EU
Construction Products Regulation (CPR)[80]	Construction	EU
Eurocodes: Standards in construction[81]	Construction	EU

[63] https://www.iso.org/committee/53186.html
[64] https://www.iso.org/standard/60857.html
[65] https://www.iso.org/standard/60856.html
[66] https://www.iso.org/standard/72333.html
[67] https://europa.eu/youreurope/business/product-requirements/compliance/ecodesign/index_en.htm
[68] https://www.iso.org/standard/45481.html
[69] https://www.iso.org/standard/62085.html
[70] https://www.iso.org/standard/70397.html
[71] https://www.iso.org/standard/69426.html
[72] https://www.iso.org/standard/60088.html
[73] https://www.iso.org/standard/77575.html
[74] https://www.iso.org/standard/77077.html
[75] https://www.iso.org/standard/70040.html
[76] https://www.iso.org/standard/80456.html
[77] https://www.iso.org/standard/78714.html
[78] https://www.iso.org/standard/70303.html
[79] https://single-market-economy.ec.europa.eu/news/eu-construction-and-demolition-waste-protocol-2018-09-18_en
[80] https://single-market-economy.ec.europa.eu/sectors/construction/construction-products-regulation-cpr_en
[81] https://eurocodes.jrc.ec.europa.eu/policies-standards/en-eurocodes-and-related-standards

ICS 31 Electronics[82]	Electronics	Global
TL 9000: Quality Management Systems (QMS) for Telecommunications[83]	Electronics	Global
ISO/DIS 5157 Textiles — Environmental aspects — Vocabulary[84] (under development)	Textiles	Global
ISO/DIS 5157 Textiles — Environmental aspects — Vocabulary[85]	Textiles	Global
ISO/CD 19952 Footwear — Vocabulary[86]	Textiles	Global
GOTS (GLOBAL ORGANIC TEXTILE STANDARD) certification[87]	Textiles	Global
Global Recycled Standard (GRS)[88]	Textiles	Global
Recycled Claim Standard (RCS)[89]	Textiles	Global
Trustrace[90]	Textiles	Global
Traceability for Sustainable Garment and Footwear[91]	Textiles	Global
European light industries innovation and technology project[92]	Textiles	EU
EU strategy for sustainable textiles[93]	Textiles	EU
EU strategy for sustainable and circular textiles[94]	Textiles	EU
EU Market Report-Textiles, Apparel, Footwear, and Travel Goods[95]	Textiles	EU

4.3 Survey Discussion

There is sizeable body of research work in terms of applying semantic web technologies to CE. Some take an overall CE perspective, while other work focus more on specific strategies or stages in the product/component/material lifecycle. Our literature survey is still ongoing, however, preliminary results show that related work exists at various levels of complexity. However, the identified gaps of this project still remain, e.g. cross-industry interoperability of CE data, and decentralised data sharing. In a forthcoming survey paper, these results will be further elaborated and related to our current project results.

Although there are quite a number of existing ontologies from different cross-industry domains that are relevant to the circular economy domain, we find that there are still some issues to be addressed when we take these ontologies as background resources when developing an ontology network for circular value networks.

The first issue is that many cross-industry domain ontologies use the same or similar terms to represent concepts that may have different meanings in different domains. For instance, many ontologies contain the material, product, resource, and process concepts. The material concept could be a general concept that models different engineering materials (e.g. NMRRVOCAB) or a specific concept that focuses on representing micro-structural information of materials (e.g. MDO). One of the goals of the Onto-DESIDE project is to address both vertical interoperability and horizontal interoperability. The new concepts we will include in our core modules, i.e., CEON, will connect different domain ontologies.

Further, in contrast to domains such as biology, materials science and industrial manufacturing where many

[82] https://www.iso.org/ics/31/x/
[83] https://isoupdate.com/standards/tl-9000/
[84] https://www.iso.org/standard/80937.html
[85] https://www.iso.org/standard/80937.html
[86] https://www.iso.org/standard/84291.html
[87] https://global-standard.org/certification-and-labelling/certification
[88] https://d2evkimvhatqav.cloudfront.net/documents/global_recycled_standard.pdf
[89] https://textileexchange.org/app/uploads/2021/02/Recycled-Claim-Standard-v2.0.pdf
[90] https://trustrace.com
[91] https://unece.org/trade/traceability-sustainable-garment-and-footwear
[92] https://single-market-economy.ec.europa.eu/sectors/fashion/eliit_en
[93] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12822-EU-strategy-for-sustainable-textiles_en
[94] https://environment.ec.europa.eu/publications/textiles-strategy_en
[95] https://www.trade.gov/textile-and-apparel-market-report-european-union

ontologies have been developed and catalogued in public repositories, circular economy is a relatively new domain in terms of focusing on using Semantic Web-based techniques. This means that circular economy ontologies are not as findable and accessible as they could be and thus do not satisfy the FAIR principles well yet. By cataloguing existing ontologies related to circular economy in a GitHub repository, we improve the findability and accessibility for circular economy related ontologies, and intend to maintain this as a future reference resource. This also means that we were unable to collect usage statistics of the ontologies, e.g. since not all of them are publicly available, nor shared through a common repository with such tracking capabilities.

The ontologies collected in our survey are modelled quite differently in terms of the ontology metrics shown in Table 9. All the ontologies have class definitions (for concepts) ranging from three classes (NMRVOCAB) to 16506 classes (UNSPSC). There are only two ontologies (NMRVOCAB and UNSPSC) without object property definitions (for relations). These two ontologies focus on providing taxonomic information. In addition, we see that there are 34 ontologies that contain data property definitions and 26 ontologies that contain individuals. Some ontologies, as shown in Table 9, reuse existing foundational ontologies (e.g. BFO, EMMO[96]) or general level ontologies (e.g. SAREF). The usage of foundational ontologies provides a common ground to enable interoperability among different domains, however, may also add unnecessary complexity to the ontology network. Ontologies based on the same foundational ontology make certain common ontological commitments, while the opposite may hold if they adhere to different foundations. This means that different ontological commitments are made by different ontologies and care should be taken when using these ontologies together in a network, which is something that we will have to take into account in our forthcoming work in the project.

Overall, this survey provides us with a good foundation ontology development in Onto-DESIDE. We have identified the areas where ontologies and standards already exist, and where the work will be more related to aligning and bridging different viewpoints, rather than developing new ontologies. On the other hand, many ontologies are large and monolithic, and thereby do not go well with a modular approach. This may result in decisions to anyway remodel parts of their content, in order to provide "lighter" models, in terms of the level of details or axiomatisation, and thereby ease the reuse of those concepts. However, by still aligning to the original ontologies, this will not be a way of replacing them, but merely allowing a better way to reuse already existing efforts. Still, some CE notions are not appropriately covered yet, and our core modules will fill this gap. Some of these modules have already been developed and described in D3.4, while others are forthcoming.

[96] https://github.com/emmo-repo/EMMO

5 Preliminary Result #2 – Requirements and Ontology Network Architecture

In this chapter we describe the requirements collected (Section 5.1), and the overall architecture of the current version of our ontology network (Section 5.2). Note that this is still a draft that will be further validated and evaluated in the second and third project iteration, hence, also the set of requirements and the architecture is subject to change throughout the project. So although the ontology modules are already public, they are to be considered as draft versions also in their second release, which is made clear in their documentation. Additionally, we briefly introduce the modules that are modelled in our ontology network (Section 5.3 and Section 5.4).

5.1 Ontology Requirements

One of the core outcomes of WP3 is a set of ontological requirements, developed according to the steps outlined in Section 3.3.2. The full set of ontology stories developed so far, can be found in Appendix B, together with a glossary of terms (consisting of 104 core CE terms) also extracted from the same user stories in D2.1 and its updated version in D2.2. In total there are 61 ontology stories in the current set, directly extracted from D2.1-2 use case requirements, as presented in Tables 16 to 18. Further there are another set of requirements, with 13 ontology stories, presented in Table 15, which originate from the CE requirements in D2.2 and are generalisations of common aspects in the other three tables, as well as taking into account emerging standards and terminology, and feedback from our modelling workshop (sketches presented in Appendix A).

Each story is then associated with a number of CQs, as described in Section 3.3.2, in turn potentially complemented by CS and RR (omitted in Tables 16 to 18 for readability reasons). An example of an ontology story directly extracted from D2.1-2, with related CQs, CS and RR, is provided in Figure 7. An example of a general CE concept story, targeting the concept of a Circular Value Network resource, is provided in Figure 8.

Story CUS0		
Story text	There are several actors involved in a construction use case/circular value flow, each holding some roles in a certain material flow.	
Identified terms	Building, Owner, Building Owner, Manufacturer, Dismantler, Tenderer, Recycler, Deconstruction, Company, Deconstruction Company, Planner, Marketplace	
Origin	D2.1 section 2.1	
CQ	**CS**	**RR**
1. What are the actors involved in this value network?	Each network has at least one actor.	
2. What is the role of this actor in the network?	Each actor involved in a network has to have a role in it. An actor can have several roles. There can be roles where we don't know the actor yet.	If an actor has a role in a value network it is involved in that network.

Figure 7: An example ontology story and its associated requirements, from the set directly extracted from D2.1-2.

While the identified requirements from D2.1 and D2.2, as presented in Appendix B in Tables 16 to 18, cover all three use cases in detail, for the ontology development we do not necessarily attempt to cover all those

Story – CVN concept: Resource		
Story text	Resources are what is worked on in the circular value network (CVN). Resources are used as inputs but could also be outputs from the network, and its steps. For resources that are part of a circular value network they will be of a certain type (is it a product, part or material). Also, for these resources, their composition is ideally known at some level. Resources can also be used in processing steps, but without being the main focus of the value network, e.g. consumables, cathalysts.	
CQ	**CS**	**RR**
1. Give me information about this resource.		
2. What is the type of a specific resource?	Resources are of a certain type.	
2. What is the composition of a specific resource?	Each resource in an CVN has a a composition, although it may be unknown.	Secondary resources are derived from the composition of the primary resources.
2. Which CVN:s use this resource, for what and in what steps?	Each CVN has at least one resource.	

Figure 8: An example ontology story and its associated requirements, from the set derived from cross-cutting concepts related to CE.

requirements. Instead we focus on a core set of modules, to describe the central concepts that have been identified as cross-cutting and relevant for all (or most of the) three use cases. In particular we focus on core CE ontological requirements, e.g., some of those presented separately in Table 15. Next we discuss the overall architecture, and plan, for those modules in Section 5.2.

5.2 Overall Network Architecture

As noted in the previous section, the requirements analysis has resulted in a quite extensive set of ontological requirements. Many of them are use case-specific, in terms of involving specific concepts of an industry domain. Still, many of them can also be generalised, and we note that there are many parallels between the three project use cases.

We have therefore focused on identifying the core topics that need to be covered by ontology modules, using the set of initial requirements. An overview of such topics, in the form of an informal conceptual model is displayed in Figure 9. Note that the boxes do not represent single concepts in an ontology, but rather areas, i.e. topics, that are covered by some ontology module. The dark blue boxes represent modules that are released, in some form, in our current version of the ontology network, i.e., in D3.3 and D3.4. The lines between the boxes represent some common sense relations between the topics, and are in the actual implementation of the ontology network replaced by formal relations between modules, e.g., in some cases `owl:import`, as well as some other alignments, or specific object properties connecting concepts inside the modules.

Some boxes are accompanied by an oval, representing an ODP providing the generic modelling pattern underlying the related module. ODPs are generic, CE-independent modelling patterns, that specify the way that certain aspects are modelled in the core CE modules. In practice, the ODPs are represented as ontology modules, however, conceptually they differ from the other modules in their level of generality and domain independence.

The light blue box with the text "location" represents an important notion that is present in many of the requirement stories, namely spatial locations of things, e.g., resources or actors. However, for this specific topic, we do not release our own module, but rather rely on reusing standard geographical ontologies, such as W3C standards and the OGC standard GeoSPARQL. Also note that this illustration of a conceptual architecture is not comprehensive, in the sense that there are less central topics that will be included in the ontology network, but not as their own modules but rather as concepts within the displayed modules. Such topics include for instance, the different circular strategies that specify the type of networks, their goals, the subdivision of process into phases and steps, the work and energy required to perform such steps etc.

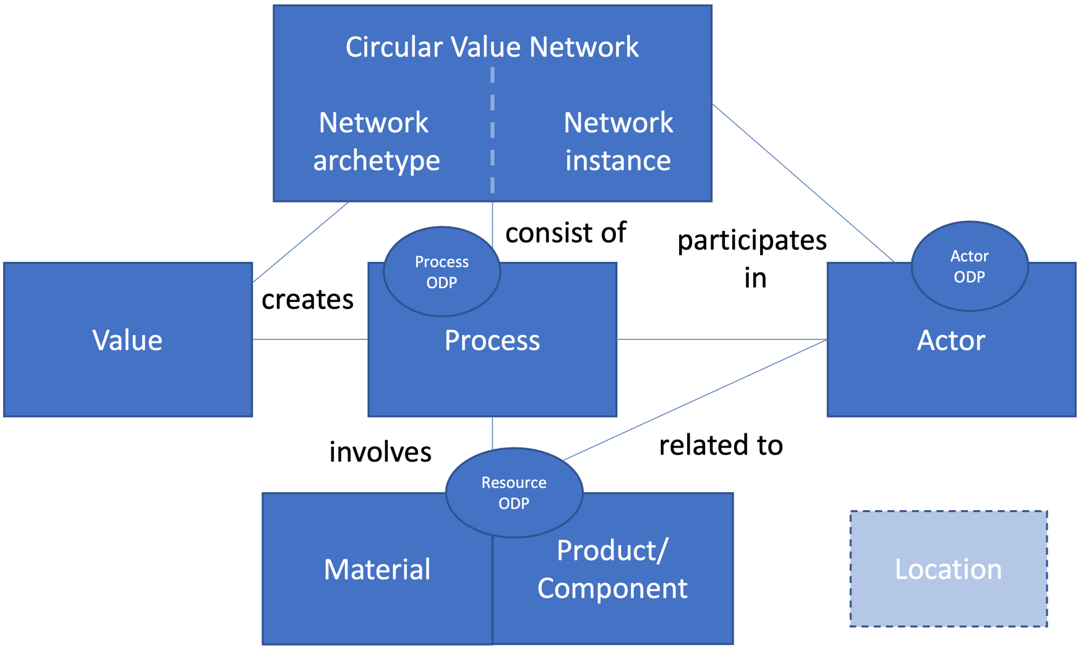

Figure 9: Informal illustration of the core topics of the ontology network.

5.3 Core Cross-Domain Modules

The ontology network, i.e. CEON, was already described and delivered in D3.4, hence, we do not go into details on the modules and their content here. In this section we merely, for the sake of readability, provide a brief description of the set of core modules that have been created, as generic reusable ontology building blocks, as illustrated in Figure 9. These include:

- Circular Value Network
- Value
- Actor (including the Actor ODP)
- Process (including the Process ODP)
- Material and Product (including the Resource ODP)

The current result of our requirements analysis process can be seen in Appendix B, in terms of a set of stories, with associated Competency Questions (as well as CS and RR). For details on the ontologies themselves, we refer to D3.4.

5.3.1 Circular Value Network

This module details the core concept of the ontology network, i.e., the Circular Value Network itself. The value network works according to a blueprint, which describes the planned setup, with needed roles possible to fill by certain actor types, types of circular strategies targeted (e.g. refurbishment of a product), and relations to typical value propositions and goals. However, we also need to be able to model the concrete instance of the blueprint, i.e., an actual value network where the roles are filled by various actors of the appropriate types, with a specific goal, and specific value proposition in mind.

Our starting point for this module is an analysis of several terminologies, ontologies, and emerging standards, including the emerging standards in ISO 59004, the Circularity Thinking methodology and circularity requirement emerging from the work in WP5, as well as a generalisation over the project use cases and requirements in D6.1-2 and D2.1-2. In Table 15 in Appendix B the detailed set of requirements for this module are represented, but they are additionally supported by several requirements in Tables 16 to 18, marked with topics related to circularity and circular economy.

5.3.2 Value

Although value is a very central concept in the Circular Economy, and closely related to the circular value network through its value proposition, value is also a very hard concept to define. Following the discussions on the value concept that is currently ongoing in other fora, e.g., including standardisation bodies, the concept is for now left as a "stub" for further definition and extension in later versions of our ontology network. Hence, we reserve a specific module for this concept, but it is not further detailed in the current version of the ontology network.

5.3.3 Actor (including the Actor ODP)

A circular value network is in essence composed of a set of actors filling certain roles in different phases of the network's flows. Hence, the actors are the ones that actually realise the value network, and perform the work to transform materials, components, and products in the various steps in the value network phases. Similar to the value network itself, also actors are modelled at two levels, i.e., as actor types that can fill certain typical roles in a network, such as a "recycler" or "manufacturer", and the concrete actors, that are usually organisations, that take on those roles in a specific network instantiation. Actors are also to related to their capabilities and competencies, which determines if they are able to fulfil a certain role in a network or not.

5.3.4 Process (including the Process ODP)

Each circular value network realises one or more circular value flows, which can be seen as a process of transforming some resource, e.g. from materials, to components, into products, and then potentially back again. Such processes have different phases, e.g. the phase that takes something from materials to components, or the phase of deconstructing a product into its material composition, and each phase can further be subdivided into smaller steps (pieces of work), which can be performed by different actors. Each step may have inputs and outputs, both in terms of resources, but also work, energy, and information, for instance, and may result in some waste. Steps can be performed by actors, i.e. participants in the value network, with the right capabilities. For these aspects, many existing ontologies exist, and this module will mainly act as a bridge, aligning to such existing models for allowing their integration into the network.

5.3.5 Material and Product (including the Resource ODP)

Resources are at the core of the value network, since they are the things that are needed as input and output of each step. Most prominently the resources are the materials, components, and products that the network aims to manage circularly, but resources can also include the additional materials needed for processing, such as consumables or catalysts, the work and investments needed. Similarly to the case of processes, much work already exist in modelling both products and materials, and their relations, hence this module again mainly acts as a small general bridge module, to be able to properly align to other ontologies.

5.3.5.1 Material

As shown in Figure 9, Material is an essential topic that is a specific kind of resource, highly relevant in many CVNs. This was noted during the process of creating the ontology requirements. As listed in Appendix B, there are a number of material related terms (e.g. Material, Material Composition, Material Type) and most of them are shared by all the three use cases. Therefore, our material module focuses on representing common materials related concepts and relationships, as well as to prepare for the extension with use case specific concepts and relationships (such as concrete concepts for construction materials, fiber for textiles). We also consider how to represent materials composition for these different materials since they might need to be represented with different structural information (i.e. micro-structural or macro-structural). In order to prepare for alignments we follow the general structure of the EMMO top level ontology for materials modelling. For the use case specific parts we may then reuse some concepts or relationships from existing use case specific ontologies as presented in Section 4.2.4 (e.g. Building Ontology, ElectricAppliance ontology, GeniusTex), in the next step of specialising this general module.

5.3.5.2 Product

As we found in the survey of existing ontologies (Section 4.2.2), product is a common concept that appears in many ontologies from different cross-industry domains. An essential modelling task is to represent products and also parts of a product, i.e. components, if needed. Such a need is central because of different operational processes that happen in the product life cycle, i.e. developing the parts, composing them into a product. As listed in Appendix B, we observe this need in all our use cases as well, and this is a core module in our ontology network, as a specialisation of the resource ODP mentioned earlier. Here we take care to also capture the context-dependent nature of these concepts, as discussed earlier, where what one considers a material may be another organisation's product.

5.4 Additional Modules

In addition to the core notions of the CVN itself, that are outlined above. From the ontology stories derived from D2.1-2 and the use case specific test cases developed in our first evaluation cycle, we can find some additional cross-cutting concerns and general concepts that appear in several of the use cases and are needed to bridge between the use case specific notions and the core modules. These include the notion of locations, as well as quantities, units, provenance and the modelling of information statements and collections (e.g. data sheets).

5.4.1 Location

Location appears in many places in the overall list of requirements in Appendix B. Resources have a specific location at a certain point in time, but can also have a point of origin, and a trace of places where it has been. Similarly for actors, information etc. For certain use cases very specific kinds of location information may be needed, such as that something is located on the second floor of a building in a construction use case setting, or the exact coordinates of a crate of products for pick-up. While in other cases location information such as the country of origin of a certain product or material may suffice. Hence, we need both a generic notion of location, but also a "pluggable" structure where more specific models can be added for specific use cases. Location is also a well-studied, although still challenging, concept to model, where we intend to simply reuse existing standard ontologies, rather than building our own.

From the ODP portal[97] we may reuse the highly generic Place pattern[98], which is a notion of place and location extracted from the DOLCE upper ontology. However, for more specific notions related to positioning, we will rely on W3C and OGC standards, such as the Basic Geo Vocabulary[99] and the GeoSPARQL ontology[100]. In the context of WP6 the project will then further investigate what specific location notions are needed for our three use case.

5.4.2 Quantities and Units

When specifying concrete data about products, components and materials, for instance, there is a need to specify the type of quantity a value represents and the units of measure of the concrete values. De facto standard ontologies exist for this purpose, e.g. the QUDT ontology. However, those ontologies are large, and contain quantities and units not necessarily relevant for our project use cases, nor CE in general, hence, for the time being we have replicated relevant parts of those ontologies in separate modules. These modules are not to be seen as part of the core CEON, but as an alignment to and reuse of existing ontologies to bridge the gap to detailed product and materials data.

5.4.3 Provenance and Data sheet

In order to support traceability and support transparency, provenance metadata is an important part. Provenance can be tracked at the level of single statements about products and materials, e.g., the time of measurement of a specific quantity value, or the actor responsible for the statement. I can also be tracked at the level of data sets, e.g. a product data sheet, such as the PCDS, that is issued by a certain actor at a certain point in time. For provenance metadata we are reusing the W3C PROV-O, and in addition modelling the information tracked, e.g., statements and collections of statements, such as a data sheet.

5.5 Published Ontologies

The ontologies are published under the CEON W3ID namespace (`http://w3id.org/CEON/`). The landing page is available at https://w3id.org/CEON/ and for the v.0.2.0 release lists the following ontologies:

Core Modules

- Actor ODP v0.2 available at http://w3id.org/CEON/ontology/actorODP/0.2/
- Circular Value Network v0.1 available at http://w3id.org/CEON/ontology/cvn/0.1/
- Material v0.1 available at http://w3id.org/CEON/ontology/material/0.1/
- Process ODP v0.1 available at http://w3id.org/CEON/ontology/processODP/0.1/

97 https://ontologydesignpatterns.org/
98 http://ontologydesignpatterns.org/wiki/Submissions:Place
99 https://www.w3.org/2003/01/geo/
100 https://opengeospatial.github.io/ogc-geosparql/geosparql11/index.html

- Process v0.1 available at http://w3id.org/CEON/ontology/process/0.1/
- Product v0.2 available at http://w3id.org/CEON/ontology/product/0.2/
- Resource ODP v0.2 available at http://w3id.org/CEON/ontology/resourceODP/0.2/
- Value v0.1 available at http://w3id.org/CEON/ontology/value/0.1/

Other Modules

- Datasheet v0.1 available at http://w3id.org/CEON/ontology/datasheet/0.1/
- Provenance v0.1 available at http://w3id.org/CEON/ontology/provenance/0.1/
- Quantity v0.1 available at http://w3id.org/CEON/ontology/quantity/0.1/
- QUDT v2.1 available at http://w3id.org/CEON/ontology/qudt/2.1/
- QUDT Unit v2.1 available at http://w3id.org/CEON/ontology/qudtunit/2.1/

Use Case Ontologies

- Construction v0.1 available at http://w3id.org/CEON/demo/construction/0.1/
- Electronics v0.1 available at http://w3id.org/CEON/demo/electronics/0.1/
- Textile v0.1 available at http://w3id.org/CEON/demo/textile/0.1/

The ontology documentation is generated automatically and is published along with the ontologies. The documentation pages are presented to any user visiting the ontology URLs using a browser. The documentation includes a description of the ontology, its classes, and its properties. Additionally, the ontology is visualised in an interactive window using VOWL. Figure 10 presents parts of the documentation page for the actor ODP module.

made by pyLODE 3.0.5a with the VocPub profile

Circular Economy Ontology Network (CEON) - Actor ODP

Metadata

IRI
`http://w3id.org/CEON/ontology/actorODP/`

Title
Circular Economy Ontology Network (CEON) - Actor ODP

Creator
Eva Blomqvist

Contributor
Huanyu Li
Mikael Lindecrantz
Robin Keskisärkkä

Date Created
2023-03-17

License
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Version Iri
http://w3id.org/CEON/ontology/actorODP/0.2/

Version Info
0.2

Preferred Namespace Prefix
actorODP

Preferred Namespace Uri
https://w3id.org/CEON/ontoloy/actorODP/

Description
A core ODP of the CEON ontology network, defining aspects of the actor concept.

Covers Requirements
Covers the following requirements from Onto-DESIDE D3.1: CVN-Process-3, CVN-Actor-1,4,6,7, CVN-Competency-3, CVN-Information-4, C11-1, C11-3, E1-6,6,6,9, E4-10

Overview

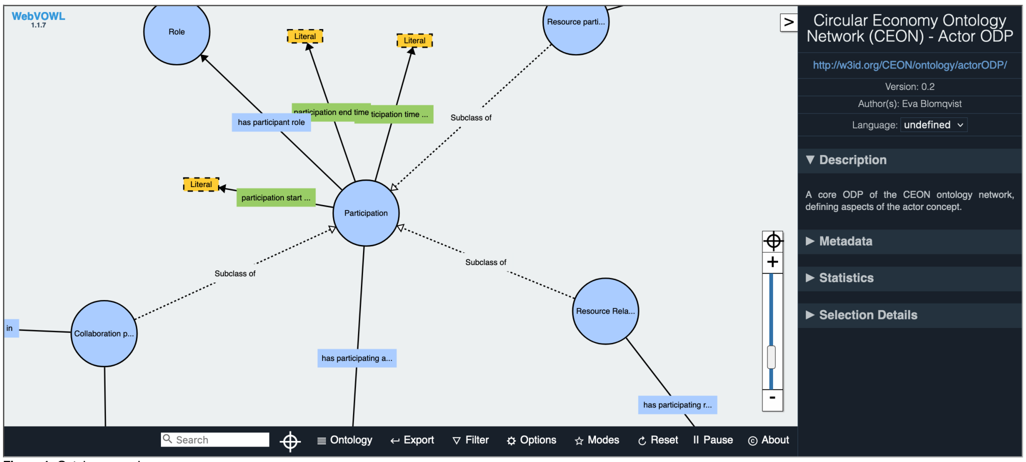

Figure 1: Ontology overview.

Classes

Actor [c]

IRI	`http://w3id.org/CEON/ontology/actorODP/Actor`
Description	An agent able to act in the context of a circular value network, e.g. an organisation, person.
In Domain Of	has actor type [op]
In Range Of	capability of [op] has participating actor [op]

Figure 10: Excerpt of the documentation generated for the Actor ODP module.

6 Preliminary Result #3 — Ontology Alignment Opportunities and First Results

6.1 Initial Results

As presented in Section 3.6, we conduct three ontology matching tasks which are *Task a: CE-CE* producing alignments among CE-specific ontologies, *Task b: CEON-IndusDom* producing alignments between CEON and other industry domain-specific ontologies and *Task c:CEON-TopOnto* producing alignments between CEON and top-level ontologies (e.g., EMMO). In the next paragraphs, we present the initial results for these three tasks, which is also public available at our Github repository[101]. This work has only started, and will continue throughout the project, hence, the main part of alignment validation, analysis, and publishing still remains.

Alignments of Task a: CE-CE.

In this task, there are six ontologies that are pairwise matched. Therefore, in total, we have 15 alignments. Equivalence mappings for the *Product* concept appear in all the alignments, which means all the six CE-specific ontologies model *Product*. Equivalence mappings for the *Material* concept appears in 10 alignments. Equivalence mappings for *Manufacturer* or *Manufacturing* are also commonly found (8 alignments). The alignment between CEON and BiOnto has the largest number of mappings, covering more mappings of concepts such as *Reuse Process*, *Production Process*, and *Recycling Process*.

Alignments of Task b: CEON-IndusDom.

The cross-industry domain ontologies are categorized in terms of five domains which are sustainability, materials, manufacturing, products and logistics domains. In general, there are a number of domain ontologies that reuse the PROV-O ontology[102] and/or the Basic Formal Ontology (BFO)[103] in terms of *Location*, *Entity*, *Agent*, *Person* and *Activity* concepts. Although we classified domain ontologies into five domains according to their applications, these ontologies have in practice more overlapping conceptualizations based on the alignment results, such as the *Material*, *Product*, *Process*, and *Resource* concepts. Almost all materials-related ontologies intend to model information about the composition of materials in terms of, for instance, composing chemical entities and chemical substances.

Alignments of Task c: CEON-TopOnto.

There are eight mappings created manually between CEON and EMMO. Among these mappings there are three subsumption mappings which are *ceon:Datasheet* ⊑ *emmo:DigitalData*, *ceon:Statement* ⊑ *emmo:Information* and *ceon:Process* ⊑ *emmo:Process*. The remaining ones are equivalence mappings including *ceon:Material* ≡ *emmo:Material*, *ceon:Matter* ≡ *emmo:Matter*, *ceon:ChemicalEntity* ≡ *emmo:ChemicalEntity*, *ceon:ChemicalSubstance* ≡ *emmo:ChemicalSubstance*, and *ceon:MolecularEntity* ≡ *emmo:MolecularEntity*. The relatively large overlap is most likely due to that during the development of CEON, we referred to EMMO's *Matter* branch and followed the same structure.

[101] http://w3id.org/CEON/alignments
[102] PROV-O ontology: https://www.w3.org/TR/prov-o/
[103] Basic Formal Ontology (BFO): http://basic-formal-ontology.org

6.2 Discussion and Future Plan

Our current alignment work contains three alignment tasks with corresponding aims. We explored how existing CE-specific ontologies can be aligned to each other. This helps identify semantic connections within the CE domain. Then we aligned our developed CEON with various industry domain ontologies, and EMMO. This allows CEON to connect with a wider range of domain specific knowledge. Additionally, we made the initial and experimental alignment results in various formats available online, which helps improve the interopeability and reusability of current CE-related ontologies.

In the future, we will further explore and broaden our investigation into ontology alignment within the CE domain. First, we will introduce more details to the steps **Voting or Filtering** and **Conflict Checking**, as well as enhance the first step (**Matching By OM Tools**) in our alignment producing pipeline shown in Figure 5. For instance, we intend to include more state-of-the-art ontology matching tools and investigate configurations of such tools. Next, we will investigate voting or filtering strategies to extract reasonable mapping candidates for domain expert validation. Then we will choose some existing tools for checking conflicts. In addition to enhancing our alignment producing pipeline, we will update the ontology base by including new CE-specific and industry domain ontologies as well as other top-level ontologies (e.g., BFO[104]). We are also aware of the issue that aligning ontologies based on different top-level ontologies may bring conflicts since such top-level ontologies may have different ontological commitments. Involving developing teams of top-level ontologies is one way to address the issue as suggested in [12].

[104] https://basic-formal-ontology.org

7 Conclusions

In this deliverable we have described the work in WP3 up to the second project iteration, leading up to the design of our second release of the ontology modules, as reported in D3.4. This work has mainly consisted of (1) adapting and setting up the methodology for ontology development, alignment, and FAIR publishing, (2) performing an extensive survey of existing literature, ontologies, as well as policies and standards, that the Onto-DESIDE ontology network needs to take into account, and potentially align to, (3) develop a set of ontological requirements, derived from both our own set of project requirements reported in D2.1-2, contextualized through the use case descriptions in D6.1-2, as well as policies, emerging standards, and other resources, that lead to the outline of an ontology network architecture and a set of ontology modules that we delivered in D3.4, and (4) setting up an initial alignment plan and pipeline for exploring potential alignments between the CEON and other existing ontologies.

Methodology adaptations are related to the highly agile nature of our project, where we need to be able to for instance adapt to both changing scope, and changing external ontologies and other resources (e.g. standards). On the other hand, more focus has been put on developing an ontology architecture suitable for our specific CE setting, with a set of core modules outlined at the outset of the project, and requirements analysis performed in parallel with the development loop. These latter adaptations are intended to reduce the need for refactoring, and ensure that a highly reusable set of core modules (i.e. ODPs) will be built early in the project. In addition, we have started the work on developing specific support for domain experts in reusing and extending the ontology network, independent of deep ontology expertise. This work includes to explore the use of LLMs to support ontology engineering, and so far resulted in an experiment to compare the performance of current LLMs on the task of ontology modelling from CQs. The conclusion is that using a combination of prompting techniques, LLMs can perform at the same level as a novice modeller, after some initial training. But so far only commercial LLMs can perform the task with sufficient accuracy, which raises issues with confidentiality and costs. However, we foresee that in the very near future also open source LLMs will have similar capabilities, and it will then be possible to build LLM-powered tool support for domain experts modelling independently of ontology engineers.

When analyzing the existing ontologies, we notice that very few have treated the general notion of CE and CVN. This has also been visible in the initial results from the literature survey that we are working on. Although the analysis is not complete we are able to see that only a small portion of the research done up until now, that has made use of semantic technologies, address the overarching CE context. Rather they focus on implementing or evaluating the technology in a specific industry context when at the same time acknowledging that they operate within the CE domain. Hence, our research in this project fills an important research gap, and can bridge solutions that have previously been applied only to a single industry domain at a time.

The few ontologies that have treated CE at a more general level are not published according to FAIR principles, and can therefore mainly be used as inspiration but potentially not in direct alignments. Or they have focused on industry-specific scenarios rather than general aspects. In particular, the main notion that is missing in related CE ontologies is the CVN itself. We note that this is an essential concept to model, if we are to be able to create a digital representation of that network, i.e. describe a digital twin of a value network to allow a certain degree of automation when discovering, setting up and executing new CVNs. Hence, this has been a core focus when developing the ontological requirements, and such modules are a central part of our ontology network. Then we are also creating a number of additional modules related to the network, that represent and further detail the core concepts related to the circular value network, such as actors, processes, resources (including materials, components, and products). We note that the notion of value is also central, but quite elusive and unexplored in terms of its meaning and use in the value network, hence, we set a placeholder for further development regarding the value concept, but at this point do not define and detail it further.

Several parts of the results reported in this deliverable still needs to be further validated with domain experts and end users within the project, including our updated set of ontological requirements. Such validation will be performed as part of completing the second project iteration. Next steps for the work in WP3 will also include to continue the concrete modelling of the outlined modules, which will result in two more releases of the CEON. This work will also be validated against the research data produced in WP6, i.e., in the updated research dataset to be delivered in D6.5, and then evaluated in the context of the use cases together with the overall platform, to complete the second project iteration. During this work, also the methodology will be further detailed, so that the tailored version of XD covers all methodology steps, e.g. also testing, integration, release, and so on. Additionally, the set of ontological requirements should not be seen as fixed at this point, but rather we will allow this set to evolve during the project, in order to take into account new insights from the project use cases, other ongoing projects and initiatives, as well as to properly align to emerging standards.

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Appendices

A Workshop: Concepts of a Circular Value Network

The following figures were sketched by the workshop participants when asked to create an informal conceptual model of a CVN, with its most important concepts. Note that not all groups had time to finish the sketch, hence the lack of relations to some concepts is not to be interpreted as that they are not actually related to anything. These sketches were used to make an initial validation of the coverage of the CVN ontology stories and terminology. Further validation will be preformed in the next period.

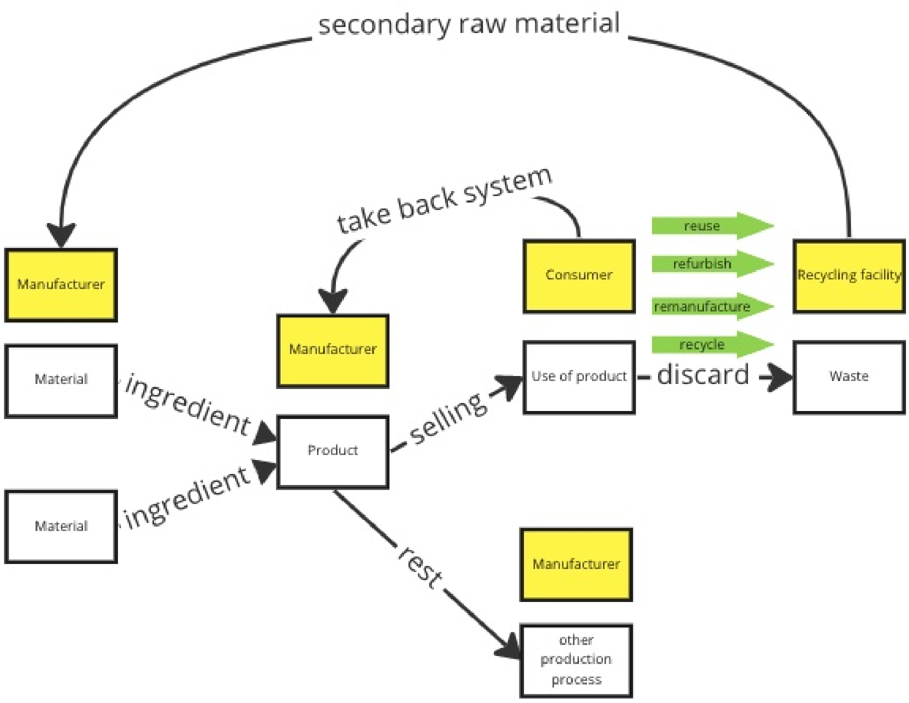

Figure 11: Sketch made by the first group (cleaned up in terms of visual representation, no content changes).

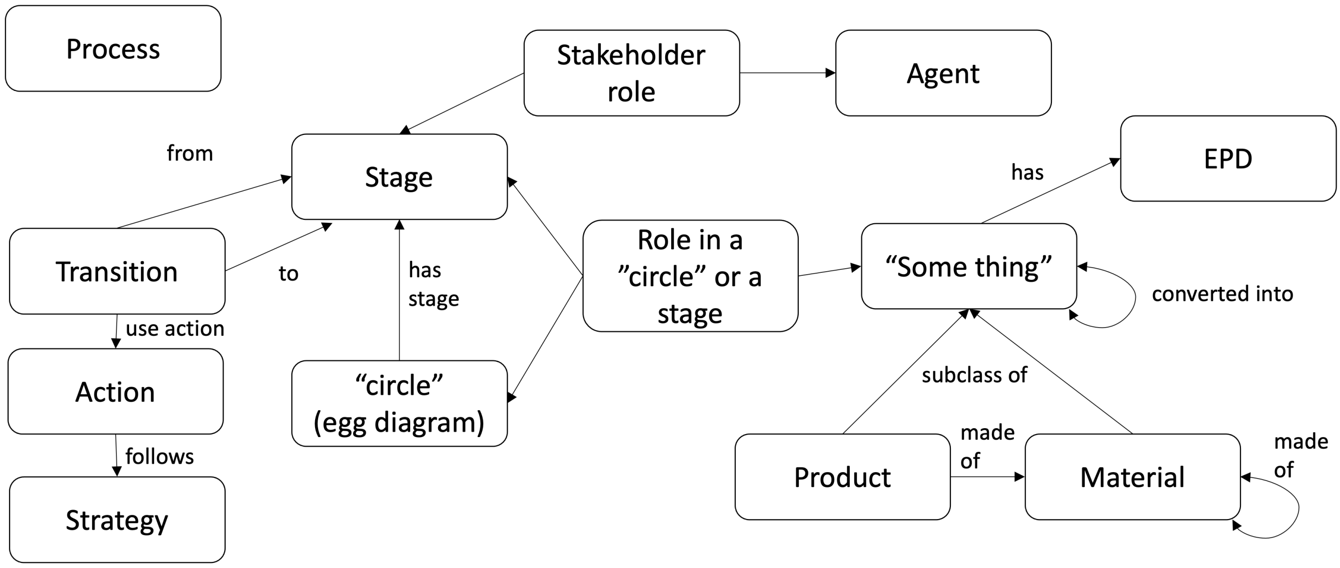

Figure 12: Sketch made by the first group (cleaned up in terms of visual representation, no content changes).

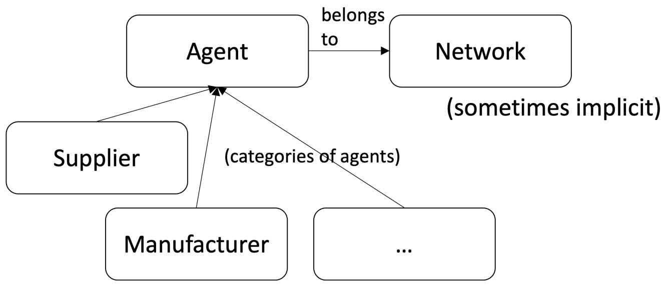

Figure 13: Sketch made by the first group (cleaned up in terms of visual representation, no content changes).

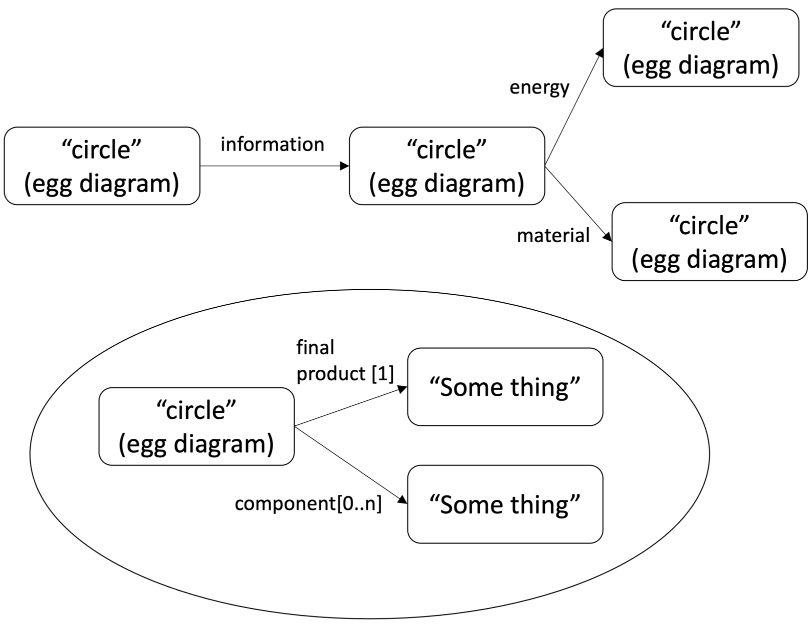

Figure 14: Sketch made by the first group (cleaned up in terms of visual representation, no content changes).

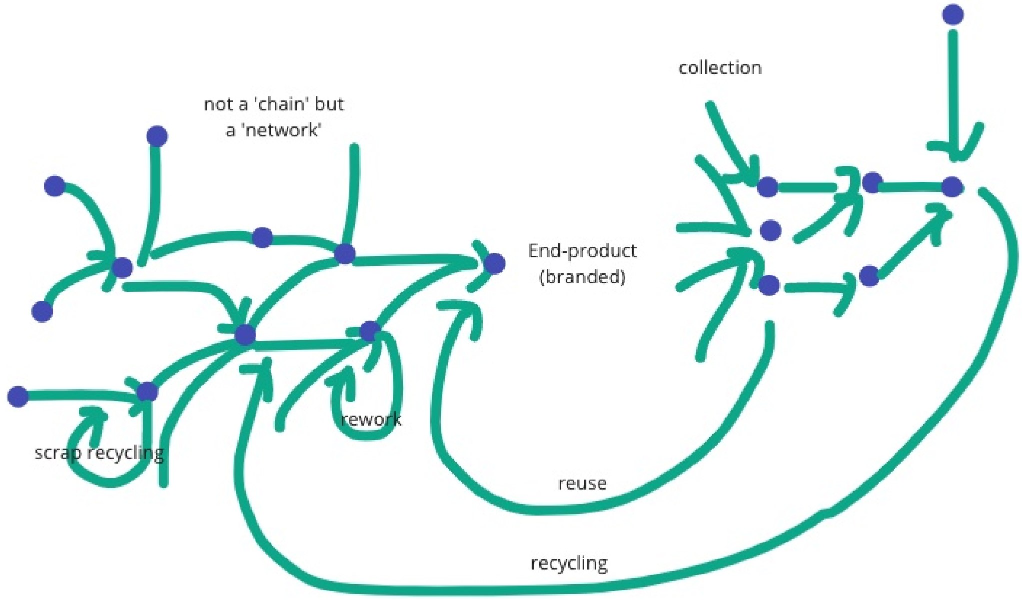

Figure 15: Sketch made by the second group (cleaned up in terms of visual representation, no content changes).

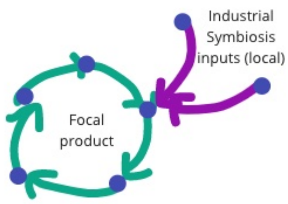

Figure 16: Sketch made by the second group (cleaned up in terms of visual representation, no content changes).

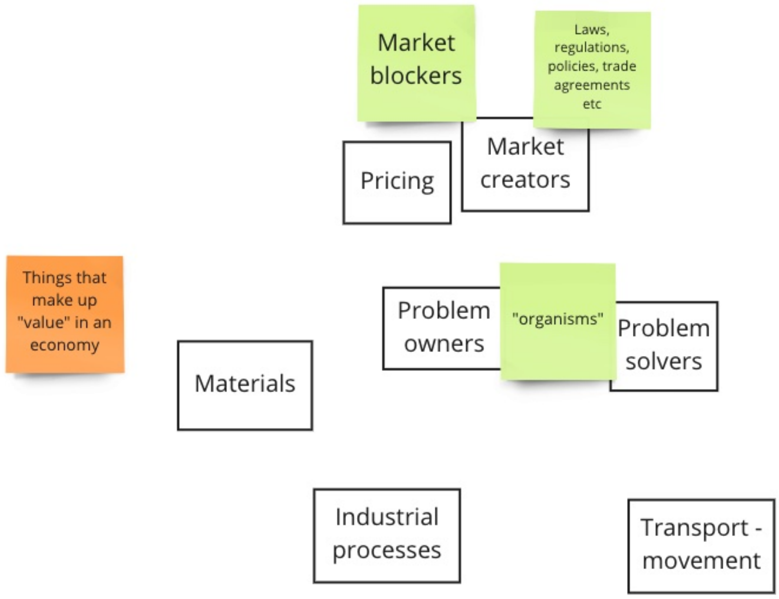

Figure 17: Sketch made by the second group (cleaned up in terms of visual representation, no content changes).

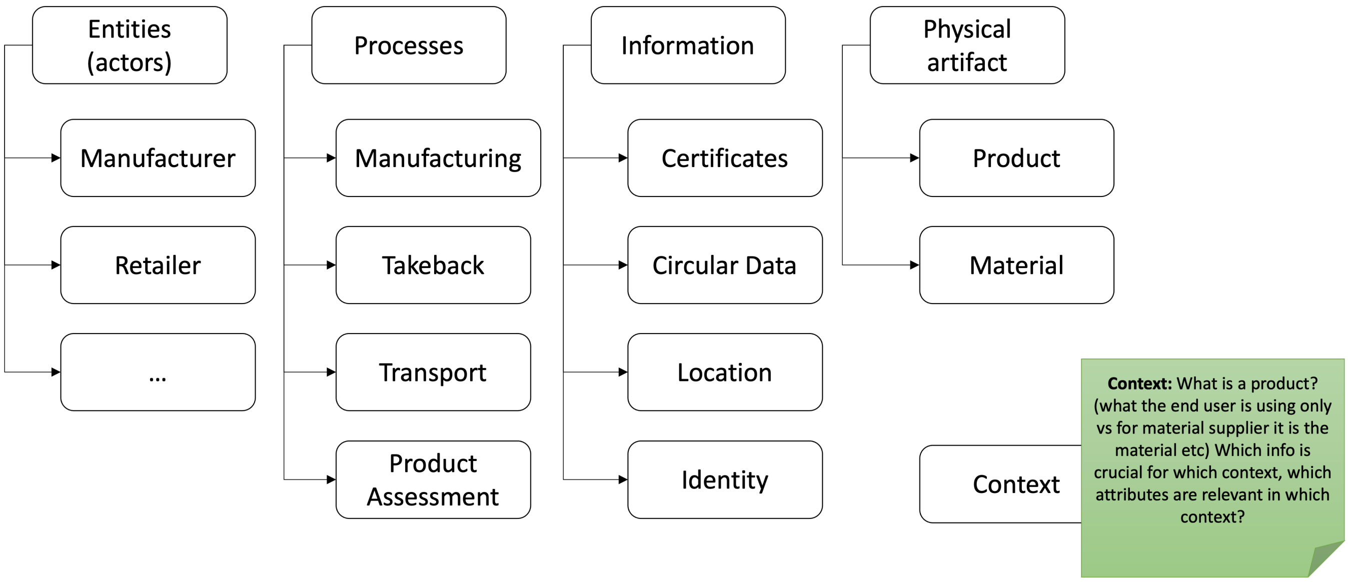

Figure 18: Sketch made by the third group (cleaned up in terms of visual representation, no content changes).

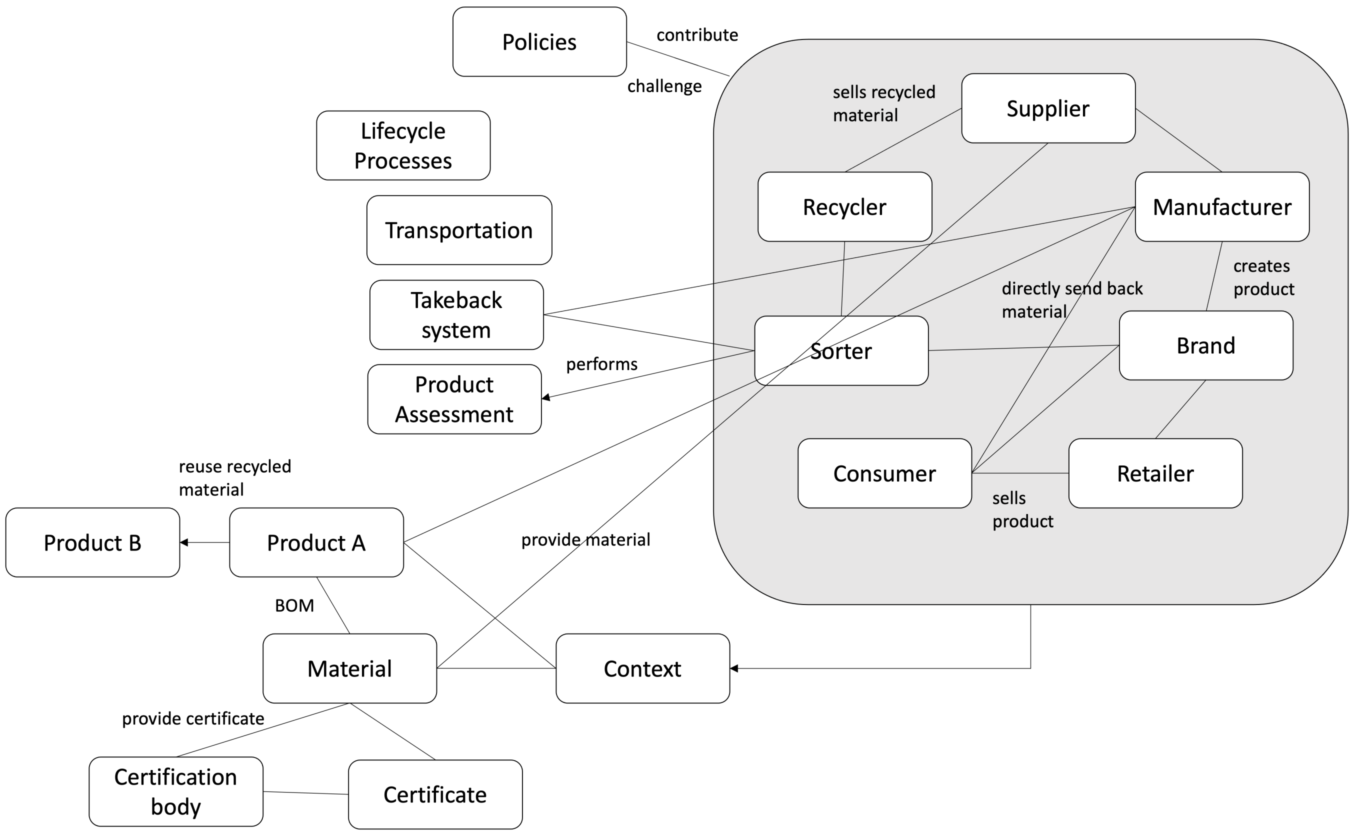

Figure 19: Sketch made by the third group (cleaned up in terms of visual representation, no content changes).

B Glossary of Terms and Ontology Requirements

The following set of terms have been deemed independent of either of the three use cases, i.e. not domain specific to any of the industry domains, they occur more than once in the user stories in D2.1, and have therefore been extracted as the glossary of terms to be covered by the ontologies. Some terms have been merged, which is indicated in parenthesis.

Table 13: Glossary of terms that occur more than once in the user stories in D2.1

Access and Assembly	Assembly Method	Biodegradability	Brand (Brand Name, Label)
Carbon Footprint	Certificate (Certificate Number)	Chemical Composition	Circular Product
Claim	Collector	Color	Company
Compliance (Comply)	Compliance Schema	Component	Composition
Contribution	Correct Way	Cost	Country (Country of Origin)
Cultivated Condition	Customer	Design	Dismantle (Dismantling)
Dismantler	Dispose Guidance	Efficient	End-of-life Scenario
Environmentally Sound Decision	Final product	Financially Sound Decision	Greenwashing
Handle	Hazardous Substance	Improve	Inform
Information	Input	Inventory	Legislation
Location	Manufacturer	Market	Marketplace
Material	Material Composition	Material Content	Material Inventory
Material Name	Material Origin	Material Property	Material Type
Performance	Plan	Planner	Platform
Price	Process	Produced Condition	Product
Product Color	Product Data (Product Information)	Product Name	Product Size
Product Type	Production	Production Process	Proof
Property	Provenance	Quality	Quantity
Raw Material	Recycle	Recycled Content (Recycled Material Content)	Recycled Material
Recycler	Recycling	Refurbish (Refurbishment)	Regulation
Repair	Reuse	Service	Sorter
Stakeholder	Standard	Substance	Supplier
Supply Chain	Supply Chain Stakeholder	Sustainability (Sustainable)	Sustainability Claim
Sustainability Parameter	Sustainable Material	Sustainable Product	Take-back-system
Tender	Tenderer	Transformation Actor	Trustful Data
Upload	User	Variation	

We additionally present the 10 most frequent terms (in order of frequency, from 73 times down to 10), as an indication that these should probably be present in the core ontologies to be created:

Table 14: The 10 most frequent terms.

Product (73)	Material (64)	Sustainability (17)	Information (16)
Composition (14)	Quality (13)	Manufacturer (12)	Production (11)
Supplier (11)	Brand (10)		

Table 15: Ontological requirements for modelling Circular Value Networks, derived from Circularity Requirements in D2.2

Circular Enabler Category	Circular Enablers (story)	CQs	CS	RR
The capacity to understand the system and its relations.	CE1: The capacity to understand interrelations between processes and actors in the system. Implementation actions: The ability to understand all parts of energy (i.e., exergy and anergy). The ability to consider a diverse variety of value forms (incl. economic, environmental, and social)	*CE1-1.* What are the connections and dependencies between actors and processes in a certain value network? *CE1-2.* What is the energy components in this system, e.g. exergy and anergy? *CE1-3.* What are the involved value forms, e.g. economic, social, environmental?	Actors implement processes. Each value network and process consumes or produces some energy and value.	Participation in a value network can be derived from actions and process participation, i.e. collaborations may be implicit. Value and energy may be derived from more detailed processes.
	CE2: The capacity to identify and consider all (relevant) system actors. Implementation actions: The ability to identify connections by analysing (large amounts of) supply chain data.	*CE2-1.* What are the actors (and their roles) in the value network? *CE2-2.* What are the connections and dependencies between actors and materials/components/products in a certain value network?	Actors may be anonymous, or represented by their types.	Participation in a value network can be derived from actions and process participation, i.e. collaborations may be implicit.
	CE3: The capacity to consider processes throughout entire life cycle. Implementation actions: The ability to collect data along entire supply chain. The ability to observe and track materials (in real time) throughout all life cycle phases. The ability to collect and analyse large amount of data fast. The ability to visualise and simulate all processes	*CE3-1.* What is the value network implementing in terms of circular strategies? *CE3-2.* What is the process breakdown of this life cycle (what processes are involved and in what order), across actors? *CE3-3.* What is the status and location of this material at this point in time? *CE3-4.* What are the elements (e.g. steps/work and actors) involved in this process? *CE3-5.* What are the inputs (prerequisites) and outputs (outcomes) of this process/step/process element?	Each physical object has a location, although it may not be known, at a certain point in time.	Overall processes and strategies may be derived from detailed process data.
	CE4: The capacity to understand interrelations with other systems (at different levels). Implementation actions: The ability to identify connections by analysing (large amounts of) supply chain data. The ability to understand carbon intensity and sustainability of energy sources. The ability to visualise and simulate all processes.	*CE4-1.* What are the related circular strategies of this and other related value networks? *CE4-2.* What are the connections and dependencies between actors and materials/components/products in a certain value network? *CE4-3.* What is the carbon intensity and other sustainability factors of this energy source? *CE4-4.* What are the elements (e.g. steps/work and actors) involved in this process?		Connections can be derived from detailed supply chain data. A process can be characterised by its detailed configuration. Carbon intensity and sustainability factors can be to some extent derived from other data, but calculations may be outside the scope of the ontology.

The capacity to evaluate actions & processes	CE5: The capacity to scope (new) combinations of processes. Implementation actions: The ability to analyse the feasibility of resource exchange. The ability to record material specifications and activities in central and standardised unit. The ability to understand the connection of the quality and quantity of flows. The ability to incorporate data from various sources. The ability to visually capture processes. The ability to trace materials back to their origin to evaluate energy consumption. The ability to identify energy requirements of rebound effects from material flows. The ability to consider alternatives for achieving efficiency. The ability to forecast energy demand and supply and assess technical feasibility. The ability to evaluate the economic feasibility of material and energy strategies. The ability to account for social and environmental externalities. The ability to develop holistic value proposition. The ability to identify activities for value creation, capture, and delivery. The ability to develop core objectives. The ability to understand value created, value destroyed, value missed	*CE5-1.* What are the barriers or missing actors/processes/resources to implement a resource exchange/material flow? *CE5-2.* What is the material breakdown of a product or component? *CE5-3.* In what units of measure are values expressed? *CE5-4.* What is the quality of a flow at a specific time? *CE5-5.* What is the quantity of a flow at a specific time? *CE5-6.* From what source does this data originate? *CE5-7.* What are the elements (e.g. steps/work and actors) involved in this process? *CE5-8.* What is the origin and complete trace of this material? *CE5-9.* What is the overall energy consumption to produce this material/component/product? *CE5-10.* What are the rebound effects and added energy requirements of a material flow? *CE5-11.* What are the alternatives to this flow? *CE5-12.* What are the energy demands of this process? *CE5-13.* What are the technical and/or economic requirements of implementing this process/strategy? *CE5-14.* What effects would it have on external social and environmental factors? *CE5-15.* What are the needs in terms of social and environmental factors? *CE5-16.* What is the value proposition of the overall value network and life cycle? *CE5-17.* What are the activities related to this value creation, capture and delivery? *CE5-18.* What are the objectives of this value network/actor/process? *CE5-19.* What is the value created/missed/destroyed by this flow/process?	Every measured quantity value has a timestamp and a unit. Every piece of information has a source. Every material/component product has a breakdown and a set of sources of its components.	Quality can be derived from a set of characteristics relevant for a certain use case. Objectives and value propositions may be implicit.
	CE6: The capacity to understand system barriers and external factors. Implementation actions: The ability to consider macro level energy infrastructure and legislature.	*CE6-1.* What external factors affect this process/actor/value network? *CE6-2.* What is the legal conditions and legislation affecting this actor/object/process? *CE6-3.* What is the energy infrastructure available?		

	CE7: The capacity to understand the effect of (a set of) actions (on the system). Implementation actions: The ability to understand success factors of exchanges. The ability to measure and compare material flows. The ability to evaluate direct and indirect effects. The ability to evaluate energy consumption and carbon emissions. The ability to analyse large amount of data fast. The ability to manage the dynamic and complexity of energy data. The ability to measure rebound effects. The ability to establish (prompt) feedback structures. The ability to measure economic, environmental and social value each. The ability to combine all dimensions of value for a comprehensive evaluation. The ability to assess value created, missed, destroyed.	*CE7-1.* What were the methods/algorithms used to measure or assess a certain value or decision, and what input data was used? *CE7-2.* What are the direct/indirect effects/outcomes of an action? *CE7-3.* Was the (material, information) exchange successful? *CE7-4.* What is the energy consumption of an action/process? *CE7-5.* What is the carbon emission of an action/process? *CE7-6.* At what time did this energy data change, and what is its detailed breakdown? *CE7-7.* What are the potential rebound effects of this action/process? *CE7-8.* What is the economic, environmental and social value created/missed/destroyed by a process?	All processes have some energy consumption and carbon emission, even if unknown or negative. Each process has some associated value. Energy consumption, emissions and value vary over time.	Most effects are not explicit but derivable from direct outputs and inputs of processes.
The capacity to adapt.	CE8: The capacity to acquire and share (new) knowledge. Implementation actions: The ability to track actions and decisions made by system actors. The ability to collect data on energy during all life cycle phases. The ability to incentivize the sharing of data.	*CE8-1.* What are the actions/decisions made by a certain actor at a certain point in time, in relation to a certain collaboration/process/material etc.? *CE8-2.* What is the energy input/usage/surplus during a certain life cycle phase of a material/component/product? *CE8-3.* Why should an actor share certain data?	At least one actor is responsible for each decision/action. Each process/life cycle phase has a certain energy consumption, although it may be unknown.	Energy consumption/surplus may be derivable based on detailed data, if available. Incentives may be implicit.
	CE9: The capacity to develop new configurations. Implementation actions: The ability to understand the qualities and characteristics of a material. The ability to collect and process dynamic and complex energy data quickly. The ability to simulate processes to identify efficiency potential. The ability to define different types of value. The ability to understand underlying needs and wants.	*CE9-1.* What are the characteristics, including quality, of this material? *CE9-2.* What is the data of this energy flow at this point in time? *CE9-3.* How efficient is this process? *CE9-4.* What kinds of value are involved in this collaboration/process? *CE9-5.* What are the needs underlying this value/collaboration/process?	There should be a definition for each kind of value.	Quality of a material in relation to a certain need may be derived from its characteristics. Efficiency of a process might be derivable from the potential outputs given an ideal input and processing situation. Values and needs may be implicit.

The capacity of actors to collaborate.	CE10: The capacity to work together for a shared goal. Implementation actions: The ability to share infrastructure (Hardware and software) for material and energy flows. The ability to align processes. The ability to collaborate for energy recovery. The ability to bring together all energy sector stakeholders. The ability to share information on energy demand and surplus. The ability to collaborate for value (co)creation, value transfer and value capture.	*CE10-1.* What capacity (e.g. competence) is needed from actors in order to collaborate? *CE10-2.* What information is needed to collaborate and align processes? *CE10-3.* What material or energy flow uses a certain (type of) infrastructure? *CE10-4.* What is the infrastructure available to, or held by, a certain actor? *CE10-5.* What capacity of infrastructure is unused and can be shared with others? *CE10-6.* What are the alignments between processes across actors, e.g. matching inputs and outputs, time etc? *CE10-7.* What are the energy outputs of an actor/process? *CE10-8.* What is the potential for energy recovery? *CE10-9.* What energy surplus/demand does an actor have? *CE10-10.* What value can be (co)created/transferred/captured by and actor or a collaboration?	Each process demands or produces some energy.	Unused capacity, energy surplus and demand, process alignments, energy recovery potential may be derivable depending of the data available.
	CE11: The capacity to integrate (relevant) actors throughout entire process. Implementation actions: The ability to incentivize cooperation (on material flows). The ability to establish reciprocal information exchange (on material flows). The ability to allow and encourage active engagement by users (i.e., prosumers) in energy flows. The ability to collect and provide consumption data during use phase. The ability to include stakeholders during identification of value. The ability to integrate stakeholders in (value) evaluation processes.	*CE11-1.* What capacity (e.g. competence) is needed to ingrate an actor in a specific role/position in the network? *CE11-2.* What is the value created (incentive) for a certain actor in a certain collaboration/process? *CE11-3.* What information does a certain actor hold, or have access to? *CE11-4.* What is the access control information for this piece of information/who do I share the information with? *CE11-5.* For what is this information needed/used? *CE11-6.* Who and hos is energy contributed to this process? *CE11-7.* Who is consuming/using this product? *CE11-8.* How is the product used? *CE11-9.* How was usage data collected? *CE11-10.* What is the potential/observed/confirmed value of this material/component/product or process/action/collaboration to a certain actor? *CE11-11.* Who evaluated the value and by what method?	Each participation has some incentive, although it may be implicit. Each piece of information has some access control information.	

The capacity to manage the system.	CE12: The capacity to coordinate processes and actors for the benefit of the system. Implementation actions: The ability to manage risk in case of exchange failure (in material flows). The ability to manage energy exchanges decentralised. The ability to make decisions (on energy flows) automatically. The ability to establish shared vision (on value) and align objectives. The ability to ensure that responsibilities and obligations are met (to create value).	*CE12-1.* Who/what actor is responsible for what part of the processes? *CE12-2.* What capability (e.g. competence) is needed from an actor? *CE12-3.* What is the contingency plan/other possibilities for replacing a material flow in a process? *CE12-4.* Where does this material/component/product come from (source, supplier)? *CE12-5.* Where does the energy needed for a certain process come from (source, supplier)? *CE12-6.* What is the contingency plan/other options for replacing that source of energy? *CE12-7.* What is the best option for energy replacement in this case? *CE12-8.* What is the objective/vision of this circular value network? *CE12-9.* What are the objectives of the actors involved in the network and how are they related to the overall objective/vision? *CE12-10.* What are the obligations and responsibilities of this actor in this collaboration (e.g. circular value network)? *CE12-11.* Have the obligations and responsibilities been met?	Each material/component/product and energy has at least one source.	A CVN may not be centrally coordinated or governed by a formal agreement, hence, most information on responsibilities, objectives etc may only be implicitly derivable from other data. Contingency plans/options and best options may be derivable from descriptions of the needs and characteristics of processes.
	CE13: The capacity to interact and share information with actors in an effective and trustful way. Implementation actions: The ability to share information transparently and traceably. The ability to standardise material information. The ability to verify value creation.	*CE13-1.* Who/what actor is responsible for this information? *CE13-2.* What is the history of changes of this information? *CE13-3.* Who has access to this information? *CE13-4.* Who has accessed this information? *CE13-5.* What standard/metadata standard/format is used for the material data? *CE13-6.* How was this created value verified/is it verified?	Someone is always responsible for each piece of information. Each piece of information has a trace of its history and origin. Each piece of information has some access control information. A claim is unverified until it is stated to be verified, with a certain verification method.	The responsibilities, history, access rights, verification status etc can be inherited from a larger collection of information, e.g. a document or data sheet, so the statements contained in it. Unless something is stated to be verified, it is treated as not verified.

Table 16: Ontological requirements elicited from construction use-case user stories (CUS)

Origin	Ontology Story	CQs	Relevant topics and ontologies
CUS0: (Introduction text)	There are several actors involved in a construction use case/circular value flow, each holding some roles in a certain material flow.	*C0-1.* What are the actors involved in this value network? *C0-2.* What are the roles of this actor in this network?	Circular Operation; Ontologies: circular economy

CUS1: End of life scenarios	Different building materials have different possible end-of-life scenarios. An end-of-life scenario specifies how the material should be handled (e.g. removed from the building, further treatment).	*C1-1.* What is the end-of-life scenarios for this specific building material? *C1-2.* How should the material be handled according to this end-of-life scenario? *C1-3.* What are all the possible end-of-life scenarios of building materials? *C1-4.* What is the product information?	Product, Construction, Building Materials, Circular Operation; Ontologies: product, construction, materials, circular economy
CUS2: Material business case	A business case is a scenario of handling materials and the associated costs an potential revenues. A certain actor, such as a building owner, needs information on economic and environmental costs involved in different end-of-life scenarios of materials, in order to assess such material business cases, their economical and environmental soundness, and make a decision on what actions to take.	*C2-1.* What are the business cases of this material? *C2-2.* What are the end-of-life scenarios of this material? *C2-3.* What are the (economic) costs of this end-of-life scenario of this material? *C2-4.* What are the environmental costs of this end-of-life scenario of this material? *C2-5.* What are environmental impacts of a product? *C2-6.* What is the product information?	Product, Construction, Building Materials, Circular Operation; Ontologies: product, construction, materials, circular economy
CUS3: Inventory	An inventory consists of products (materials) and their quantities and locations, and is produced before dismantling. A product can be resold, refurbished, or enter into a take-back system, after dismantling, by some actors (e.g. building owner, or manufacturer).	*C3-1.* What are the products that are going to be dismantled? *C3-2.* Where are they located and their quantities (or dimensions)? *C3-3.* What materials does a product consist of? *C3-4.* Who is the manufacturer of a certain product? *C3-5.* What take-back-systems are available for a certain product? *C3-6.* Which products does this take-back system cover? *C3-7.* Can this product be resold? *C3-8.* Can this product be refurbished? *C3-9.* What are different operations/process in a take-back-system?	Product, Construction, Circular way of recycling; Ontologies: product, construction, circular economy
CUS4: Rest material from production	The rest materials are remaining materials from the process of manufacturing a product. They can potentially be used in other production processes.	*C4-1.* What are possible ways for offsetting rest materials from production? *C4-2.* What is the product that the materials is used to manufacture? *C4-3.* What is the quantity of a specific remaining material? *C4-4.* What are the business cases of the rest materials? *C4-5.* What processes can this rest material be used as input for? *C4-6.* Are the business cases of the rest materials same as those of the materials used in the manufacturing? *C4-7.* Where is this rest material produced (in the manufacturing process)? *C4-8.* What rest material do I produce? *C4-9.* What is the input of a production process? *C4-10.* What actor needs this input for a production process?	Product, Construction, Building Materials, Circular Operation, Manufacturing; Ontologies: product, construction, materials, circular economy, manufacturing
CUS5: Cost	A cost is caused due to handling a product (e.g. either dismantling or refurbishing). Different costs decide different ways of constructing a take-back system.	*C5-1.* What is the cost of dismantling or refurbishing a specific product? *C5-2.* What are the (economic) costs of a take-back-system for a specific product? *C5-3.* What is the product information?	Product, Construction, Circular Operation(dismantle, refurbishment); Ontologies: product, construction, circular economy
CUS6: Market demand	A decision on refurbishing a product may be based on the market demand of refurbished products of this kind. Depending on different market demands, different take-back system may be designed.	*C6-1.* What is the market demand of a specific refurbished product? *C6-2.* Does the refurbished product have the same manufacturer as the original product? *C6-3.* What are the financial properties of this take-back system? *C6-4.* How is this take-back system designed, what does it contain (actors, processes)?	Product, Construction, Manufacturing, Circular Operation(refurbishment); Ontologies: product, construction, manufacturing, circular economy

CUS7: Dismantling	A dismantler requires information about the location of a product within a building that needs to be dismantled, and the location of the building itself. A product has an appropriate procedure for dismantling that should be followed in order for dismantling to have been performed in a correct way.	*C7-1.* What are different ways of dismantling certain (building) products? *C7-2.* What information does the manufacturer provide about the product, on how to dismantle the product? *C7-3.* Where is a building located? *C7-4.* Where is a certain product located within a certain building? *C7-5.* What is the amount of this product within this building? *C7-6.* Was this product dismantled correctly? According to what procedure?	Product, Construction, Building, Circular Operation (dismantling); Ontologies: product, construction, materials, circular economy
CUS8: Tender	A tenderer requires detailed product information for describing an appropriate dismantling method in a deconstruction tender.	*C8-1.* What information of a product is needed for a deconstruction tender? *C8-2.* What is the information about a certain product, needed for this tender? *C8-3.* What is the (preferred?) dismantling method for this product? *C8-4.* Who is the tendered issuing this tender?	Product, Construction, Manufacturing; Ontologies: product, construction, manufacturing
CUS9: Recycling	A building with planned deconstructions may have products that are planned for retrieval of secondary raw material. A recycler requires information about the plan, including the location of the building and the recycler handles the product (at end-of-life scenario) and retrieves certain secondary raw materials.The secondary raw materials can be used in other productions.	*C9-1.* What are different ways of handling a specific product (end-of-life scenario)? *C9-2.* What are different ways of retrieving specific secondary raw materials? *C9-3.* What buildings are planned for deconstruction? *C9-4.* What products within a building are planned for retrieval of secondary raw material?	Product, Construction, Material, Building, Circular way of recycling; Ontologies: product, construction, materials, circular economy
CUS10: Deconstruction	A deconstruction company is responsible for performing a deconstruction. Deconstruction has to be done in a certain way, depending on the products and the building.	*C10-1.* What is the correct/planned way of deconstruction of a product within a building? *C10-2.* What are different ways of deconstruction for a certain product, given certain conditions? *C10-3.* What buildings are planned for deconstruction? *C10-4.* What products within a building are planned for deconstruction?	Product, Construction, Building, Circular Operation; Ontologies: product, construction, circular economy
CUS11: Marketplace	A marketplace requires detailed product information for marketing and selling products.	*C11-1.* What products are available for selling? *C11-2.* What are the properties of a product (composition, dimensions, quantities, pricing)? *C11-3.* Who owns a products and where is it located?	Product, Construction; Ontologies: product, construction
CUS12: Reuse	Planning for a new building by a planner may include reuse of products or materials from previous product. In order to make reuse decisions, product information such as measurements, qualities and quantities need to be known.	*C12-1.* What is the detailed information of a product (e.g. measurement, quality, quantity)? *C12-2.* Does the product or material fit the plan of the new building? *C12-3.* What reused products does this plan contain?	Product, Construction; Ontologies: product, construction
CUS13: Planning	All actors besides building owner require product information when they perform their operations. Also, they require information about manufacturing process and handling methods for a end-of-life scenario of a product.	*C13-1.* What is the cost, time and location of a service? *C13-2.* What is the product on which the service is performed?	Product, Construction, Manufacturing; Ontologies labeled of product, construction, manufacturing

	An actor needs to have accurate product information, on measurements, composition, qualities, quantities, and location of a product, as well as process and handling details, in order to offer and perform the correct handling and services for the product, at a correct cost and the appropriate time and location.	*C13-3.* What is the detailed information of this product's properties (e.g. measurements, composition, qualities and quantities)? *C13-4.* What is the context of this product (e.g. location, quantities)? *C13-5.* What is the previous handling of this product? *C13-6.* What is the correct handling process of this product? *C13-7.* What are the previous services performed on this product? *C13-8.* What is the appropriate/available services for this product? *C13-9.* What is the cost of handling/performing this service on this product? *C13-10.* At what time can this service be performed?	

Table 17: Ontological requirements elicited from electronics and appliances use-case user stories (EUS)

Origin	Ontology Story	CQs	Relevant topics and ontologies materials
EUS1: Provenance/quality and sustainability of raw materials	The brand using a material wants to be able to have proof of the quality characteristics of the material, as well as the sustainability of the material (traceability and circularity) to check against contracts and pricing, as well as to pass this on to the end-user. This can also include material content, carbon footprint data and production process, regulations.	*E1-1.* What are the quality characteristics of this material?	Logistics (supply chain), Electronics, Materials; Ontologies labeled of logistics, electronics, materials
	The end-user buying a product wants to be able to have proof of the quality characteristics of the material, as well as the sustainability of the material (traceability and circularity) to check against claims and pricing. This can also include material content, carbon footprint data and production process, compliance with regulations.	*E1-2.* What is the carbon footprint of this material?	
	A legislator sets requirements on the quality characteristics of materials, their sustainability (traceability and circularity) and may require that there is proof of the underlying data through the supply chain.	*E1-3.* What is the material content?	

	The supplier offering a material needs to have proof of the quality characteristics of the material, its origin, as well as the sustainability of the material (traceability and circularity) to set up contracts and pricing, as well as to pass this on to the brands and end-users. This can also include material content, carbon footprint data and production process. The supplier must be able to check that they and comply to regulations by a legislator.	*E1-4.* Does this material comply with a certain legislation? *E1-5.* Who is assuring that this proof is correct? *E1-6.* Who is the supplier of this material? *E1-7.* Who is an intermediary of this material? *E1-8.* What is the brand that uses this material? *E1-9.* What end users are involved? *E1-10.* What is the supply chain of this product? *E1-11.* To what extent does this product contain recycled material? *E1-12.* Who supplies and ensures the identity of an actor? *E1-13.* What is the pricing of this material based on? *E1-14.* What does this contract require from the parties and the material? *E1-15.* What does this legislation require from the parties and the material?	
	Information about supplier identities can be secret, and not shared through the supply chain, still there is a need to share (aggregated) data and track provenance of the information on various aspects of the product.	*E1-16.* Is the identity of the supplier of this component or material known/accessible?	
EUS2: Production process	A manufacturer of a product needs to understand the composition and origin of the materials, as well as their production processes, to mitigate risks in the supply chain, analyse and improve the supply chain, ensure compliance with regulations etc. Although some stakeholders in the supply chain may be unknown, data origin and proof of validity is important.	*E2-1.* What are the components of this product?	Product, Electronics, Materials, Manufacturing, Logistics (supply chain); Ontologies labeled of product, electronics, materials, manufacturing, logistics
	A product or material has a material composition, a set of production processes to make it, a provenance trace, a set of stakeholder types handling it in the supply chain, and a location where it was produced.	*E2-2.* What are the materials of this component or product?	
	A product is made up of components, which in turn are made up of materials that have a certain properties, and provenance.	*E2-3.* What is the provenance of this product/component/material? *E2-4.* What is the composition of this material? *E2-5.* What is the origin of this material (e.g. stakeholder, location)? *E2-6.* What are the production processes used to make this material/component/product? *E2-7.* What are the supply chain actors (or types of actors) involved in the trace of this material/component/product? *E2-8.* Does this material/component/product comply with certain regulations? *E2-9.* Is a certain actor known? *E2-10.* Who ensures the proof of this data and what is the origin of this data? *E2-11.* Are there alternative suppliers of this component, material or product? Or alternative products/components/materials to replace the product/component/material? *E2-12.* What is the location of production for this material/component/product?	

EUS3: Quality and compliance	A manufacturer or brand, of a product needs to assess the sustainability performance of the production, based on a number of factors. The sustainability performance contributes in turn to product quality and compliance of legislation and standards.	*E3-1.* What are the circularity and sustainability scores of a product?	Product, Electronics, Circularity, Sustainability, Stakeholders, Logistics (supply chain); Ontologies labeled of product, electronics, circular economy, logistics
	A product is to a certain extent sustainable if it is made up of sustainable materials. To assess the sustainability of a material information is needed about its properties, such as monitored materials, compliance to schemes, recycled content, LCA in supply chain, sustainability of production processes, and carbon accounting data. The sustainability of production processes contributes to the sustainability of a product.	*E3-2.* What information is needed to calculate or represent the circularity and sustainability scores of a product?	
	A compliance schema, such as REACH.	*E3-3.* What are the compliance schemas that my product or material adhere to?	
	Certain materials are considered as monitored materials, based on legislation and standards.	*E3-4.* Does my products require/contain any monitored materials?	
	Recycled material content means to what extent the product contains recycled material, where it comes from, how it has been processed, and what amount.	*E3-5.* What recycled materials does a product have?	
	Carbon accounting data and LCA may be used to assess the carbon footprint of a product.	*E3-6.* What is the carbon footprint of a product?	
	Sustainability of production processes is measured through some ways.	*E3-7.* Is a production process sustainable or not?	
	Claims of carbon neutrality may need to be substantiated by data on carbon footprints of materials, LCA and sustainability of production processes.	*E3-8.* What is the carbon footprint of a material? *E3-9.* What is the LCA of my material/component/product, and how was it calculated? Based on what data?	
EUS4: Product usage	The end-user of a product wants to know how sustainable their product is, so that they know that the quality they paid for is there, and to avoid greenwashing, to act more sustainably and to lower their carbon footprint. This includes material composition, certification of sustainability, and other quality criteria (e.g. made in the EU, sustainably sourced critical materials etc).	*E4-1.* How sustainable is my product (with respect to certain parameters or certifications)?	Product, Electronics, Circular Operation, Circularity, Sustainability; Ontologies labeled of product, electronics, circular economy
	The end-user of a product wants to know how to recycle and refurbish their product, to ensure its optimal performance in all phases of the product life cycle and to act more sustainably and reduce their carbon footprint. This includes dismantling and repair information, material composition, etc.	*E4-2.* How circular is my product (with respect to certain parameters or certifications)? *E4-3.* How should this product be used?	

	To avoid greenwashing and encourage users to buy more sustainable and circular products, accurate sustainability data needs to be provided with the products. This includes product details, e.g. material composition, as well as sustainability parameters such as certifications, quality criteria, and carbon footprint.	*E4-4.* How should this product be used (e.g. to allow optimal performance)? *E4-5.* How should this product be handled (e.g. dismantled, repaired, recycled or refurbished)? *E4-6.* What is the material composition of this product? *E4-7.* What certifications are fulfilled and how? *E4-8.* Who issues these certifications and standards? *E4-9.* Who ensures accuracy of the claims? *E4-10.* Who is the current user/owner of the product? *E4-11.* What is the price of the product?	
EUS5: Product composition	The product is composed of various components, which in turn consist of materials, which have a chemical composition. Some materials may contain hazardous substances. Some materials degrade with time.	*E5-1.* What is the material composition of this product?	Product, Electronics, Materials; Ontologies labeled of product, electronics, materials
	For a recycler to recycle a product one needs first disassembly information, but in addition the process of recycling depends on chemical composition, information on hazardous substances, and degradation of materials.	*E5-2.* What is the chemical composition of this material?	
	For a recycler to recycle a product one needs dismantling information, chemical composition, information on hazardous substances and degradation of materials.	*E5-3.* What hazardous substances does this product/material contain? *E5-4.* What is the degradation properties of this material? *E5-5.* Did the material degrade? *E5-6.* How can I recycle a product with this material composition? *E5-7.* How should this product be disassembled and/or recycled?	
	Efficiency of recycling of a product may depend on the assembly (and disassembly) methods or the components and their material composition. Similarly the safety and security of disassembly and recycling depends on understanding these aspects.	*E5-8.* How efficiently can this product be disassembled and/or recycled? *E5-9.* Is it safe/secure to disassemble and/or recycle this product using a certain process?	
EUS6: Safety	For a recycler to safely recycle a product they need to know if it contains hazardous materials, and how it can be safely and efficiently disassembled and recycled, without harm to the environment nor to humans handling it. This can be represented in disassembly and recycling guidelines, expressed according to compliance schemes, and hazardous substances should be listed in product information.	*E6-1.* What hazardous substances does this product/material contain? *E6-2.* What are the guidelines for disassembly of this product? *E6-3.* What is the material composition of this product? *E6-4.* How can this product be safely recycled? *E6-5.* How can this product be efficiently recycled? *E6-6.* How efficient is a recycling method for this product? *E6-7.* What compliance schemes does this product adhere to? *E6-8.* What threats to human or environmental safety does this product, or its disassembly and/or recycling pose?	Product, Electronics, Materials; Ontologies labeled of product, electronics, materials

Table 18: Ontological requirements elicited from textiles use-case user stories (TUS)

Origin	Story	CQs	Relevant topics and ontologies

TUS1: Access to production data	A customer wants to display the material content of the fibers that a supplier provides. This includes types/categories of fibers, type of material, their origin and country of origin of their raw material, their recycled content, certificates, colors, recycling recommendations, biodegradability (certificates), standards and certification compliance.	*T1-1.* What materials does a fibre contain?*T1-2.* What are the properties of and data about that fibre?	Fiber, Material, Customer, Circular Certificate; Ontologies labeled of textiles, materials, circular economy
TUS2: Access to editable and updatable content *(priority: low)*	The fiber supplier (or transformation actor) will update the fibers that are supplied, sometimes the material content will change without a change of the properties, sometimes also the properties should change. The customers should always get up-to-date information.	*T2-1.* When were material content and/or properties of this fiber changed? *T2-2.* What was the change? *T2-3.* Why did the change happen? Who made the update?	Product, Fiber, Materials, Manufacturing, Performance (circularity, sustainability); Ontologies labeled of product, textiles, materials, manufacturing, circular economy
	A change of fibers' material content and/or properties may be triggered by a change of suppliers. Changes may also affect certificates.	*T2-4.* What were the consequences of the material content change, in terms of fiber properties (e.g. change in colors, performance)? *T2-5.* Give me the latest material content and properties of this fiber.	
TUS3: Integrated product data	A fiber manufacturer or transformation actor will have a library of current and past fibers (products) that they share with others, and should be able to trace the history of those, e.g. when they were uploaded, edited, viewed. Other actors can view the products and contact the manufacturer/transformation actor. The information should also include received certificates, and when they were received.	*T3-1.* What products (fibers) are in my library? *T3-2.* When were they added, updated, and by whom? *T3-3.* What products am I sharing with whom? *T3-4.* Who viewed a product? *T3-5.* Who contacted me when, and about what product?	Product, Fiber, Materials, Manufacturing, Supplier; Ontologies labeled of product, textiles, materials, manufacturing
TUS4: Access to trustful data	Transformation actors will have a library of fibers or materials (products) that they transform. The library including information or data of fibers/materials properties, produced or cultivated conditions.	*T4-1.* What are different produced/cultivated conditions of fibers/materials? *T4-2.* When is a fiber or material (product) going to be removed? *T4-3.* What are different transaction certificates for recycled content? *T4-4.* What substances (products) are included in Restricted Substance List (RSL)? *T4-5.* What compliances do my fibers (products) satisfy?	Fiber, Textile, Materials; Ontologies labeled of textiles, materials
TUS5: Generate material inventory	An inventory should contain basic information to describe a material, such as certificate. This is also for data exchange at the materials level.	*T5-1.* What information of a material is needed to upload to a platform?	Fiber, Textiles, Certificate; Ontologies labeled of textiles, circular economy
TUS6: Sustainability score *(priority: low)*	A product should be described in terms of sustainability and circularity by scores.	*T6-1.* What are the sustainability and circularity scores of a product?	Product, Performance (circularity, sustainability); Ontologies labeled of product, circular economy

TUS7: Circular materials catalogue *(priority: low)*	Information is needed to describe circularity of products and materials	*T7-1.* Does a sustainable/circular product need to have all the components satisfying sustainability/circularity?	Product, Textiles, Materials, Performance (circularity, sustainability); Ontologies labeled of product, textiles, materials, circular economy
TUS8: Component data *(priority: high)*	For a specific product with multiple components, we need to describe how these components are assembled as well as detailed composition of every components, each component should also associated with a number of properties to describe the quality and sustainability.	*T8-1.* What are different assembly methods can be used? *T8-2.* For a specific product, what is the assembly method has been used? *T8-3.* What are the components of a product?	Product, Textiles, Materials, Manufacturing (assembly), Performance (circularity, sustainability); Ontologies labeled of product, textiles, materials, manufacturing, circular economy
TUS9: Certificates	Recycled material is supposed to have certificate or labels. We need to model how to describe materials and certificates.	*T9-1.* Is a material recognized as a recycled material? *T9-2.* What certificates does a material have?	Textiles, Materials, Certificates; Ontologies labeled of textiles, materials, circular economy
TUS10: Materials composition	Similar as the ontology story based on TUS8.	*T10-1.* What resources are used in the assembly process of a fiber and what are the quantities of these resources? *T10-2.* What is the composition of a material? *T10-3.* Has a material been chemically modified? *T10-4.* What properties does a material have?	Product, Textiles, Materials, Fiber, Manufacturing; Ontologies labeled of product, textiles, materials, manufacturing
TUS11: Authentication of data	As a brand I want to access to secure and validated data (i.e., composition of material) through the platform.	*T11-1.* Who is the provider of the information about a material? *T11-2.* How was the information validated?	Validated data. Authentication.
TUS12: Visibility *(priority: low)*	As a brand I want mechanisms that help boost the visibility of sustainability and circularity efforts.	*T12-1.* What are the sustainability actions related to a specific product?	Product sustainability properties.
TUS13: Product availability data	Display available circular and sustainable products in the platform including all product details.	*T13-1.* Is a specific product available? *T13-2.* What are the details of a specific product?	Product data (such as name, brand name, variation, prices, sizes, colors, material category, material type, reverse supply chain information)
TUS14: Brand's take back schemes information	A product could be re-manufactured, therefore a take back scheme/program needs to build to specify why and how a product to be sold back for re-manufacturing.	*T14-1.* What are the reasons for a product to be sold back and re-manufactured?	Product, Textiles, Circular Operation (re-manufacturing, reuse); Ontologies labeled of product, textiles, circular economy
TUS15: Repair and reuse guidance	A product can have repair/reuse guide information so that they can re-sold to second-hand market.	*T15-1.* What is the repair/reuse guidance of a product?	Product, Textiles, Circular Operation (repair, reuse); Ontologies labeled of product, textiles, circular economy

TUS16: Sustainability product data *(priority: low)*	Access sustainability data about products.	*T16-1.* What are the sustainability details for a specific product?	Product information, material composition (high level), circularity information
TUS17: Verified claims	Access trustful and understandable data on circularity and sustainability aspects of specific product (e.g. shoes).	*T17-1.* What are the verified sustainability claims about a product?	Product information, material composition (high level), sustainability claims, circularity information
TUS18: Care guidance	Treatment information of product, maybe specific for clothes or shoes should be modeled.	*T18-1.* What are the treatment of a product (e.g. washing guide, care for)?	Textiles, Shoe treatment; Ontologies labeled of textiles
TUS19: User guidance	A (textiles) product should have a guidance regarding how its elements can be replaced.	*T19-1.* What properties or conditions of a (textiles) product to be considered when replacing the product elements?	
TUS20: Take-back data	A (textiles) product should have a guidance regarding how to be disposed.	*T20-1.* What properties or conditions of a (textiles) product to be considered when disposing the product?	
TUS21: Resale product information	A product can be resold when it comes to the end-of-life scenario.	*T21-1.* Who make the decision of reselling products instead of other recycling operations, and based on what conditions?	
TUS22: Material inventory	Access to material inventory from products.	*T22-1.* What is the material composition of a specific product? *T22-2.* What are the properties of specific materials?	Legal restrictions, material composition (product with name, type, category, country of origin, brand name, year of sale), material composition
TUS23: Disassembly	In the end-of-life of a product, a disassembly operation can be performed to get different components of a product. As specific disassembly method is needed and a guidance of how to disassemble the product is needed.	*T23-1.* What is the disassembly method of a product? *T23-2.* What is the guidance of of disassembly method?	Product, Textiles, Materials, Circular Operation (disassemble); Ontologies labeled of product, textiles, materials, circular economy

C List of entries qualified for the Literature Survey analysis

The following list outlines all the entries that are part of the ongoing final analysis in the literature study on related research and state-of-the-art in semantic technologies.

Authors	Title	Publication year
Foo, Gwendolyn; Kara, Sami; Pagnucco, Maurice	An Ontology-Based Method for Semi-Automatic Disassembly of LCD Monitors and Unexpected Product Types	2021
Otte, J. Neil; Kiritsi, Dimitris; Ali, Munira Mohd; Yang, Ruoyu; Zhang, Binbin; Rudnicki, Ron; Rai, Rahul; Smith, Barry	An ontological approach to representing the product life cycle	2019
Mboli, Julius Sechang; Thakker, Dhavalkumar; Mishra, Jyoti L.	An Internet of Things-enabled decision support system for circular economy business model	2022

Authors	Title	Publication year
Ke, Chao; Jiang, Zhigang; Zhang, Hua; Wang, Yan; Zhu, Shuo	An intelligent design for remanufacturing method based on vector space model and case-based reasoning	2020
Li, Xinyu; Wang, Zuoxu; Chen, Chun-Hsien; Zheng, Pai	A data-driven reversible framework for achieving Sustainable Smart product-service systems	2021
Yu, Jianping; Zhang, Hua; Jiang, Zhigang; Yan, Wei; Wang, Yan; Zhou, Qi	Disassembly task planning for end-of-life automotive traction batteries based on ontology and partial destructive rules	2022
Sauter, E M; Lemmens, R L G; Pauwels, P	CEO and CAMO Ontologies: a circulation medium for materials in the construction industry	
Pourabbasi, Mohadeseh; Shokouhyar, Sajjad	Unveiling a novel model for promoting mobile phone waste management with a social media data analytical approach	2022
Pourabbasi, Mohadeseh; Shokouhyar, Sajjad	Towards a framework to design product service system-based mobile phone waste management: A social media data analysis perspective	2023
Pourabbasi, Mohadeseh; Shokouhyar, Sajjad	Unveiling a novel model for promoting mobile phone waste management with a social media data analytical approach	2022
Maiwald, Martin; Kosmol, Linda; Pieper, Christoph; Schmidt, Thorsten; Magdanz, Alex	Energy simulation in dynamic production networks (ESPRONET): Simulation for industrial symbiosis	2017
Ma, Longzhou; Wu, Xiuli; Kuang, Yuan; Tang, Ying; Xiang, Dong	Knowledge graph-based approach to trace the full life cycle information of decommissioned electromechanical products	2022
Fotopoulou, Eleni; Mandilara, Ioanna; Zafeiropoulos, Anastasios; Laspidou, Chrysi; Adamos, Giannis; Koundouri, Phoebe; Papavassiliou, Symeon	SustainGraph: A knowledge graph for tracking the progress and the interlinking among the sustainable development goals' targets	2022
Bicchielli, Chiara; Biancone, Noemi; Ferri, Fernando; Grifoni, Patrizia	BiOnto: An Ontology for Sustainable Bioeconomy and Bioproducts	2021
Pacheco-López, Adrián; Somoza-Tornos, Ana; Espuña, Antonio; Graells, Moisès	Systematic generation and targeting of chemical recycling pathways: A mixed plastic waste upcycling case study	2021
Papoutsakis, Manos; Fysarakis, Konstantinos; Michalodimitrakis, Emmanouil; Spanoudakis, George; Ioannidis, Sotiris	CIRCE: Architectural Patterns for Circular and Trustworthy By-Design IoT Orchestrations	2022
Gligoric, Nenad; Krco, Srdjan; Hakola, Liisa; Vehmas, Kaisa; De, Suparna; Moessner, Klaus; Jansson, Kristoffer; Polenz, Ingmar; Van Kranenburg, Rob	SmartTags: IoT Product Passport for Circular Economy Based on Printed Sensors and Unique Item-Level Identifiers	2019
Zekhnini, Kamar; Cherrafi, Anass; Bouhaddou, Imane; Benabdellah, Abla Chaouni	Suppliers Selection Ontology for Viable Digital Supply Chain Performance	2021
Turner, C.; Okorie, O.; Emmanouilidis, C.; Oyekan, J.	Circular production and maintenance of automotive parts: An Internet of Things (IoT) data framework and practice review	2022
Magas, Michela; Kiritsis, Dimitris	Industry Commons: an ecosystem approach to horizontal enablers for sustainable cross-domain industrial innovation (a positioning paper)	2022
Klein, Jan-Felix; Wurster, Marco; Stricker, Nicole; Lanza, Gisela; Furmans, Kai	Towards Ontology-based Autonomous Intralogistics for Agile Remanufacturing Production Systems	2021
Akroyd, Jethro; Mosbach, Sebastian; Bhave, Amit; Kraft, Markus	Universal Digital Twin - A Dynamic Knowledge Graph	2021
Soman, Ranjith K.; Kedir, Firehiwot Nesro; Hall, Daniel M	Towards circular cities: directions for a material passport ontology	2022
Schaubroeck, Simon; Dewil, Reginald; Allacker, Karen	Circularity of building stocks: modelling building joints and their disassembly in a 3D city model	2022
Sanchez, Benjamin; Rausch, Christopher; Haas, Carl; Hartmann, Timo	A framework for BIM-based disassembly models to support reuse of building components	2021

Authors	Title	Publication year
Morkunaite, Lina	An Open Data Platform for Early-Stage Building Circularity Assessment	2021
Kedir, Firehiwot; Bucher, David F.; Hall, Daniel M.	A Proposed Material Passport Ontology to Enable Circularity for Industrialized Construction	2021
Kanak, Alper; Arif, Ibrahim; Terzibas, Cagri; Demir, Omer Faruk; Ergun, Salih	BIMyVerse: Towards a Semantic Interpretation of Buildings in the City and Cities in the Universe	2022
Davila Delgado, Juan Manuel; Oyedele, Lukumon O.	BIM data model requirements for asset monitoring and the circular economy	2020
Wierling, August; Schwanitz, Valeria Jana; Altinci, Sebnem; Bałazińska, Maria; Barber, Michael J.; Biresselioglu, Mehmet Efe; Burger-Scheidlin, Christopher; Celino, Massimo; Demir, Muhittin Hakan; Dennis, Richard; Dintzner, Nicolas; El Gammal, Adel; Fernández-Peruchena, Carlos M.; Gilcrease, Winston; Gładysz, Paweł; Hoyer-Klick, Carsten; Joshi, Kevin; Kruczek, Mariusz; Lacroix, David; Markowska, Małgorzata; Mayo-García, Rafael; Morrison, Robbie; Paier, Manfred; Peronato, Giuseppe; Ramakrishnan, Mahendranath; Reid, Janeita; Sciullo, Alessandro; Solak, Berfu; Suna, Demet; Süß, Wolfgang; Unger, Astrid; Fernandez Vanoni, Maria Luisa; Vasiljevic, Nikola	FAIR Metadata Standards for Low Carbon Energy Research—A Review of Practices and How to Advance	2021
Sandhiya, R.; Ramakrishna, Seeram	Investigating the Applicability of Blockchain Technology and Ontology in Plastics Recycling by the Adoption of ZERO Plastic Model	2020
Pacheco-López, Adrián; Somoza-Tornos, Ana; Graells, Moisès; Espuña, Antonio	Synthesis and assessment of waste-to-resource routes for circular economy	2021
Martín Gómez, Alejandro M.; Aguayo González, Francisco; Marcos Bárcena, Mariano	Smart eco-industrial parks: A circular economy implementation based on industrial metabolism	2018
Germano, Stefano; Saunders, Carla; Horrocks, Ian; Lupton, Rick	Use of Semantic Technologies to Inform Progress Toward Zero-Carbon Economy	2021
Favi, Claudio; Campi, Federico; Germani, Michele; Mandolini, Marco	Engineering knowledge formalization and proposition for informatics development towards a CAD-integrated DfX system for product design	2022
Martín Gómez, Alejandro Manuel; Aguayo Gonzalez, Francisco; Lama Ruiz, Juan Ramon; Marcos Barcena, Mariano	METABOLISMO INDUSTRIAL INTELIGENTE EN EL PROYECTO DE PRODUCTOS SOSTENIBLES	2015
Dino, Giovanna Antonella; Rossetti, Piergiorgio; Biglia, Giulio; Sapino, Maria Luisa; Mauro, Francesco Di; Sarkka, Heikki; Coulon, Frederic; Gomes, Diogo; Parejo-Bravo, Lucia; Aranda, Pilar Zapata; Lopez, Antonia Lorenzo; Lopez, Jorge; Garamvolgyi, Erno; Stojanovic, Sandra; Pizza, Antonietta; Feld, Marco De La	SMART GROUND PROJECT: A NEW APPROACH TO DATA ACCESSIBILITY AND COLLECTION FOR RAW MATERIALS AND SECONDARY RAW MATERIALS IN EUROPE	2017
Deng, Quan; Franke, Marco; Lejardi, Edurne Suarez; Rial, Roi Mendez; Thoben, Klaus-Dieter	Development of a Digital Thread Tool for Extending the Useful Life of Capital Items in Manufacturing Companies - an Example Applied for the Refurbishment Protocol	2021
Czvetkó, Tímea; Honti, Gergely; Sebestyén, Viktor; Abonyi, János	The intertwining of world news with Sustainable Development Goals: An effective monitoring tool	2021
Cameron, David B.; Waaler, Arild; Fjøsna, Erlend; Hole, Monica; Psarommatis, Foivos	A semantic systems engineering framework for zero-defect engineering and operations in the continuous process industries	2022
Belaud, Jean-Pierre; Prioux, Nancy; Vialle, Claire; Buche, Patrice; Destercke, Sébastien; Barakat, Abdellatif; Sablayrolles, Caroline	Intensive Data and Knowledge-Driven Approach for Sustainability Analysis: Application to Lignocellulosic Waste Valorization Processes	2022
Barla, Foteini; Lykokanellos, Filopoimin; Kokossis, Antonis C.	Discovering Valorisation Paths in Waste Biorefineries using an Ontology Engineering Approach	2016

Authors	Title	Publication year
Bakogianni, Despina; Skourtanioti, Evangelia; Meimaris, Dimitris; Xevgenos, Dimitris; Loizidou, Maria	Online Brine Platform: a Tool for Enabling Industrial Symbiosis in Saline Wastewater Management Domain	2019
Abdallah AM,Talib AM	Classification of Big Data Security Based on Ontology Web Language	2023
Sileryte R,Wandl A,Van Timmeren A	A bottom-up ontology-based approach to monitor circular economy: Aligning user expectations, tools, data and theory	2023
Boje C,Navarrete T,Kubicki S,Beach T	Linked data for the life cycle assessment of built assets	2023
Baralla G,Pinna A,Tonelli R,Marchesi M	Waste management: A comprehensive state of the art about the rise of blockchain technology	2023
Walunj S,Sintek M,Pahlevannejad P,Plociennik C,Ruskowski M	Ontology-Based Digital Twin Framework for Smart Factories	2023
Wen P,Zhao Y,Liu J	A systematic knowledge graph-based smart management method for operations: A case study of standardized management	2023
Ma Z	Energy metaverse: the conceptual framework with a review of the state-of-the-art methods and technologies	2023
Hey SP,Dellapina M,Lindquist K,Hartog B,LaRoche J	Digital Health Technologies in Clinical Trials: An Ontology-Driven Analysis to Inform Digital Sustainability Policies	2023
Shirol S,Kulkarni A,Agarwal R	Semantic Search for Sustainable Platforms Using Transformers	2023
Jurmu M,Niskanen I,Kinnula A,Kääriäinen J,Ylikerälä M,Räsänen P,Tuikka T	Exploring the Role of Federated Data Spaces in Implementing Twin Transition within Manufacturing Ecosystems	2023
Köck B,Friedl A,Serna Loaiza S,Wukovits W,Mihalyi-Schneider B	Automation of Life Cycle Assessment—A Critical Review of Developments in the Field of Life Cycle Inventory Analysis	2023
Pastor R,Fraga A,López-Cózar L	Interoperable, Smart, and Sustainable Urban Energy Systems	2023
Savić G,Segedinac M,Konjović Z,Vidaković M,Dutina R	Towards a Domain-Neutral Platform for Sustainable Digital Twin Development	2023
Alahmari N,Mehmood R,Alzahrani A,Yigitcanlar T,Corchado JM	Autonomous and Sustainable Service Economies: Data-Driven Optimization of Design and Operations through Discovery of Multi-Perspective Parameters	2023
Kurteva A,McMahon K,Bozzon A,Balkenende R	Semantic Web and its Role in Facilitating ICT Data Sharing for the Circular Economy: An Ontology Survey	2023
Blomqvist E,Li H,Keskisärkkä R,Lindecrantz M,Pour MA,Li Y,Lambrix P	Cross-domain Modelling – A Network of Core Ontologies for the Circular Economy	
Vasileiadis M,Mexis K,Trokanas N,Dalamagas T,Papageorgiou T,Kokossis A	Leveraging Semantics and Machine Learning to Automate Circular Economy Operations for the Scrap Metals Industry	2023
Pacheco-López A,Gómez-Reyes E,Graells M,Espuña A,Somoza-Tornos A	Integrated synthesis, modeling, and assessment (iSMA) of waste-to-resource alternatives towards a circular economy: The case of the chemical recycling of plastic waste management	2023
Yu Y,Yazan DM,Van Den Berg M,Firdausy DR,Junjan V,Iacob ME	Circularity information platform for the built environment	2023
Pour MA,Li H,Armiento R,Lambrix P	Phrase2Onto: A Tool to Support Ontology Extension	2023
Hosseini SA,Fathi A,Shafaat A,Niknam M	A computationally inexpensive method to outsource facility maintenance services through the internet in real-time	2023

Authors	Title	Publication year
Furxhi I,Willighagen E,Evelo C,Costa A,Gardini D,Ammar A	A data reusability assessment in the nanosafety domain based on the NSDRA framework followed by an exploratory quantitative structure activity relationships (QSAR) modeling targeting cellular viability	2023
Layer M,Leidich J,Schwoch S,Saske B,Neubert S,Robl P,Paetzold-Byhain K	Data management of process plants as complex systems: systematic literature review and identification of challenges and opportunities	2024
Varthis E,Poulos M	metaGraphos: a Web-based system for transcribing, proofreading and publishing scanned documents	2023
Echefaj K,Charkaoui A,Cherrafi A,Garza-Reyes JA,Khan SA,Chaouni Benabdellah A	Sustainable and resilient supplier selection in the context of circular economy: an ontology-based model	2023
Mofatteh MY,Pirayesh A,Fatahi Valilai O	Energy Semantic Data Management and Utilization in Smart Grid Networks with Focus on Circular Economy	2022
Claudio Turrin, Federica Acerbi, Antonio Avai, Arnaldo Pagani, Manfredi Giuseppe Pistone, Angelo Marguglio, and Pierluigi Petrali	From Ontologies to Operative Data Models: A Data Model Development Supporting Zero Defect Manufacturing	2023
Ayda Grisiute1, Heidi Silvennoinen, Shiying Li, Arkadiusz Chadzynski, Martin Raubal, Markus Kraft, Aurel von Richthofen, and Pieter Herthogs	A Semantic Spatial Policy Model to Automatically Calculate Allowable Gross Floor Areas in Singapore	2023
Ana Nikolov , Milos Drobnjakovic, and Boonserm Kulvatunyou	Produce It Sustainably: Life Cycle Assessment of a Biomanufacturing Process Through the Ontology Lens	2023
Farghaly, Karim, Jones, Kell.	Enhancing Requirement-Information Mapping for Sustainable Buildings: Introducing the SFIR Ontology	2023
Kiara M. Ascencion Arevalo, Christoph Neunsinger, Roland Zimmermann, Ralph Blum, Kendra Weakly	HOLY: An Ontology Covering the Hydrogen Market	2023
Koloski B,Montariol S,Purver M,Pollak S	Knowledge informed sustainability detection from short financial texts	2022
Mboli J,Thakker D,Mishra J	Artificial Intelligence-Powered Decisions Support System for Circular Economy Business Models:	2023
Giannaris PS,Mastorakis NE	Overview of Taxonomy and Ontology Approaches for the Classification of Blockchain Components	2023
Rimaz MH,Plociennik C,Kunz L,Ruskowski M	Am I in Good Shape? Flexible Way to Validate Asset Administration Shell Data Entry via Shapes Constraint Language	2023
McLamore ES,Datta SP	A Connected World: System-Level Support Through Biosensors	2023
Arff B,Haasis J,Thomas J,Bonenberger C,Höpken W,Stetter R	Analysis and Visualization of Production Bottlenecks as Part of a Digital Twin in Industrial IoT	2023
Moscati A,Johansson P,Kebede R,Pula A,Törngren A	Information Exchange between Construction and Manufacturing Industries to Achieve Circular Economy: A Literature Review and Interviews with Swedish Experts	2023
Saari LM,Jurmu M,Kääriäinen J,Niskanen I,Rantala T,Valtanen K,Ylikerälä M	Digital Product Passport trials to support the concept's introduction in industry	2023
Dang MY,Wang QC,Qi J,Liu G,Li N,Chen WQ	Green Design Evaluation of Electrical and Electronic Equipment Based on Knowledge Graph	2023
Kebede R,Moscati A,Tan H,Johansson P	Circular economy in the built environment: a framework for implementing digital product passports with knowledge graphs	2023
McGinley T,Negendahl K,Smolira P,Jakubowska M,Vejlgaard AB,Karlshøj J	Supporting the OpenBIM transition	2023

Authors	Title	Publication year
Franciosi C,Polenghi A,Lezoche M,Voisin A,Roda I,Macchi M	Semantic Interoperability in Industrial Maintenance-related Applications: Multiple Ontologies Integration towards a Unified BFO-compliant Taxonomy:	2022
Al-Tawil M,Dimitrova V,Thakker D,Abu-Salih B	Emerging Exploration Strategies of Knowledge Graphs	2023
Buche P,Couteaux J,Cufi J,Destercke S,Oudot A	Integrating collective know-how for multicriteria decision support in agrifood chains—application to cheesemaking	2023
Li H,Abd Nikooie Pour M,Li Y,Lindecrantz M,Blomqvist E,Lambrix P	A Survey of General Ontologies for the Cross-Industry Domain of Circular Economy	2023
Kurteva A	Towards FAIR ICT Data Sharing in the Circular Economy with Knowledge Graphs	2023