A Survey of General Ontologies for the Cross-Industry Domain of Circular Economy

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ABSTRACT

Circular Economy has the goal to reduce value loss and avoid waste by extending the life span of materials and products, including circulating materials or product parts before they become waste. Circular economy models (e.g., circular value networks) are typically complex and networked, involving different cross-industry domains. In the context of a circular value network, multiple actors, such as suppliers, manufacturers, recyclers, and product end-users, may be involved. In addition, there may be various flows of resources, energy, information and value throughout the network. This means that we face the challenge that the data and information from cross-industry domains in a circular economy model are not built on common ground, and as a result are difficult to understand and use for both humans and machines. Using ontologies to represent domain knowledge can enable actors and stakeholders from different industries in the circular economy to communicate using a common language. The knowledge domains involved include circular economy, sustainability, materials, products, manufacturing, and logistics. The objective of this paper is to investigate the landscape of current ontologies for these domains. This will enable us to in the future explore what existing knowledge can be adapted or used to develop ontologies for circular value networks.

CCS CONCEPTS

• **Computing methodologies → Knowledge representation and reasoning**; • **General and reference** → *Surveys and overviews*; • **Applied computing** → *Industry and manufacturing*.

KEYWORDS

Circular Economy, Cross-Industry Domain, Ontology, Standard

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1 INTRODUCTION

Circular Economy (CE) as defined by the European Union, is a model of production and consumption, which aims to share, lease, reuse, repair, refurbish and recycle existing materials and products as long as possible [39]. In this way, materials or product parts can be circulated before they become waste, which will reduce value loss and avoid waste. Taking into account a product's entire life cycle is necessary to design and enable a CE model. This includes answering questions such as what raw materials are needed, how the materials are dealt with in the manufacturing process, how the products are distributed in a supply chain, what strategies can be used for recycling products and materials in different end of life scenarios. In order to address these concerns, stakeholders from various industry domains need to be involved, including material suppliers, manufacturers, end-users, and recyclers. Therefore, sharing data in a secure, quality assured, and automated way among these industry actors is necessary in a CE model. However, there remains a gap to be filled. There is a challenge in making decentralized data and information from actors across industry-domains understandable and usable by both humans and machines. As stated in [5], leveraging open standards for semantic data interoperability and establishing a shared network of ontologies for data documentation is a starting point to address such a semantic interoperability challenge, and the aim of our ongoing project *Onto-DESIDE*.[1]

An ontology network [56] is a set of interrelated ontologies, built using a modular architecture, in order to separate concerns and allow for ontology use and reuse at the right level of granularity and expressivity. In several research domains standard ontologies or ontology networks have been developed, such as the Semantic Sensor Networks (SOSA/SSN) ontology network [19], which is a

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[1] https://ontodeside.eu

W3C (World Wide Web Consortium)[2] and OGC (Open Geospatial Consortium)[3] standard, and the OBO Foundry[4] in biomedicine [52], emerging as a de-facto standard in the biomedical field. Additionally, FAIR (Findable, Accessible, Interoperable, Reusable) principles [63] should be taken into account when we apply ontology-based techniques in the CE domain, to avoid reinventing the wheel and instead making resources reusable.

The purpose of the work presented in this paper, conducted in the context of the *Onto-DESIDE* project, is to provide a comprehensive overview of existing ontologies from general domains that need to be connected when setting up and implementing a circular value network, as well as ongoing efforts and standards that can affect future ontology development in the area. To fulfill this aim we have conducted a semi-structured survey, retrieving related ontologies and ontology projects, as well as related standards. The remainder of the paper is organized as follows. Section 2 provides background information on CE and circular value networks. Section 3 introduces the methodology used to conduct the survey. In Section 4, we present the identified ontologies and discuss some characteristics of these ontologies, as well as provide a list of related standards, and other ongoing related work. In Section 5, we then briefly discuss how these ontologies can contribute to the CE domain and what challenges should be noted. Finally, in Section 6, we present concluding remarks and directions for future work.

2 BACKGROUND

This section provides background information on CE and circular value networks.

2.1 Sustainability and Circular Economy

In traditional linear economy models, raw materials, products, and all other resources are collected, manufactured, and transformed on a linear pathway until they are discarded as waste. There was commonly little consideration of the environmental footprint of the resources or the consequences of using different raw materials. As discussed in [25], certain traditional materials also contain toxic or critical raw materials of which usage should be avoided or eliminated. CE, different from the linear economy, has been proposed to keep materials in use as long as possible and close the loop of production patterns [15], to also reduce waste as much as possible. To achieve sustainability in terms of the product life cycle, different aspects of CE models should be considered, such as the flows of resources, information, energy, and value. For instance, a CE model should be able to identify materials and products throughout their life cycles so that they can be traced, analysed, and properly (re)used through various circular strategies.

2.2 Circular Value Networks

In the CE domain, *Value Network* [40, 58] is an emerging term used to indicate the complex and networked nature of circular value chains. A circular value network may consist of complex configurations of multiple actors, who may play different roles in various flows, also in ways not previously seen in linear value chains of a linear economy model.

The first building block of a circular value network is the complex configurations of multiple actors, e.g., organizations or individuals [6]. A number of different actors may be involved, taking on roles such as raw material suppliers, producers, manufacturers, logistics and transport companies, recyclers, and product end-users. Various types of organizations are also involved, such as departments responsible for product development, recycling organizations, marketing departments, and supply chain departments. In addition, their collaboration is affected by other actors, such as legislators, infrastructure providers, and standardization bodies.

The second building block is the flows of *resources*, *information*, *energy*, and *value* [6]. Essentially, a resource flow is the path different resources can take when transformed from materials, to components of products or goods, to final consumer products, through the economy. Ideally including the circular flow back to reusable product (components) and materials. An information flow in digital systems means dealing with sharing, managing, and analyzing data generated by (or for) other flows, e.g., the resource flows. For instance, in a digital system, we may need to track the location of resources by using Internet of Things (IOT)-based technologies [24], creating a flow of location information that follows the resource through its life cycle. Different activities performed by different actors in a circular value network then generate value for the resources, e.g., products. A value flow describes which actors create or deliver what kind of value, as well as who eventually captures the value. An energy flow describes where energy is generated, dissipated or consumed along with (and due to) other flows. Although these concepts have been widely acknowledged within the transformation to a more circular economy, it should be noted that there does not today exist a single unifying framework or approach that integrates or links them. However some standardization efforts are ongoing, such as by the technical committee ISO/TC 323.[5]

3 METHODOLOGY

This section presents the methodology that we used to conduct the survey. During the whole process five knowledge engineers and one domain expert from the recycling and CE domain were involved. We first formulated the research question that we want to answer throughout the survey (Section 3.1), that guided the survey setup. We then identified the relevant domains and topics for the survey (Section 3.2). We collected ontologies from public ontology or vocabulary repositories and by searching Google and Google Scholar (Section 3.3). Furthermore, we extracted characteristics of the collected ontologies that were used for conducting a first analysis of the ontologies, as outlined in Section 3.4.

3.1 Research Question

We first formulated a research question, to which we intend to provide an answer by conducting this survey and its subsequent analysis. As introduced in Section 2, a CE model may involve multiple cross-industry domains. Therefore the research question is:

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[2] https://www.w3.org

[3] https://www.ogc.org

[4] https://obofoundry.org

[5] https://www.iso.org/committee/7203984.html

- Are there existing ontologies modeling such cross-industry domains? If so, what are the characteristics of these ontologies and how may these ontologies be used or adapted for knowledge representation in the CE domain?

Note that this question is only partially answered by the paper, since we only briefly analyze the content of the ontologies. Further work is needed to study the details of each ontology, their compatibility etc. However, this survey paper presents a prerequisite to answering the questions, i.e., an overview of the area.

3.2 Focus Domains

As presented in Section 2, a model for CE involves actors from different domains such as materials, manufacturing, production, logistics and supply chain. Based on discussions among knowledge engineers and domain experts, we identified several main domains in which we want to investigate the relevant existing ontologies. These focus domains are *Circular Economy*, *Sustainability*, *Materials*, *Manufacturing*, *Products* and *Logistics*.

These domains relate to the general setting of CE. Although specific industry segments (e.g., *textile industry* and *food production*) may have an interest in CE, in this paper we only consider specific ontologies in these industry domains if the ontologies also support *cross-industry* CE scenarios, i.e., cover general concepts applicable across industries. Furthermore, we identified topics for each domain, as shown in Table 1. These topics helped us to label each collected ontology with a more detailed label than merely the overall domain, when looking at the detailed content of each ontology.

Table 1: Focus Domains.

Domain	Label	Topics
Circular Economy	CE	business models, resource recovery, waste, recycling, circularity assessment
Sustainability	SU	sustainability goals, performance, environment, energy
Materials	MAT	raw materials, material composition
Manufacturing	MAN	manufacturing process
Products	PR	product life cycle
Logistics	LO	distribution, production, supply chain

3.3 Collecting Ontologies

We collected ontologies in two complementary ways. First, we collected ontologies for all the domains shown in Table 1 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 keywords for the CE domain.

For the Google searches, 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*.

We additionally searched for ontologies in the following public ontology or vocabulary repositories: MatPortal[6] (containing 21 ontologies in total), IndustryPortal[7] (52 ontologies in total), OntoCommons ontology catalogue[8] (37 ontologies in total), Ontobee[9] (259 ontologies in total), and Linked Open Vocabularies[10] (LOV, 782 vocabularies in total). For the first four repositories, we looked at each ontology in the repositories and decided 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, before assessing the relevance of the found ontologies.

3.4 Analysis Perspectives

Our initial analysis of the collected ontologies relates to qualitative and quantitative aspects. For the quantitative aspects, we used the ROBOT tool [20] to compute ontology metrics. These metrics include, e.g., the numbers of concepts (or classes), axioms, relations (or properties), and general concept inclusions. By analysing these metrics, we aim to obtain a better understanding of different ontologies regarding what design choices were made for developing the ontologies and how they can be reused or re-engineered for CE use cases. 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 the CE. However, we acknowledge that a deeper analysis of the ontologies is needed in the future, to properly assess their relations, overlap, potential incompatibility etc.

4 OVERVIEW OF EXISTING ONTOLOGIES

In this section, we categorize the collected ontologies into ontologies related to (1) Circular Economy and Sustainability (Section 4.1), (2) Manufacturing, Products, and Logistics (Section 4.2), and (3) Materials (Section 4.3). Our survey resulted in a list of 37 downloadable ontologies, which are presented in Table 2 and Table 3, and we additionally provide an online catalogue to keep track of these ontologies and ontology-related work in a public repository with a permanent w3id URL.[11] The 37 ontologies are all available in OWL, and three of them also have SKOS or OBO versions, as shown in Table 3. Further, we discuss what general ontologies are reused in these ontologies, and we list existing standards related to CE which might provide terms for developing ontologies in this field (Section 4.4). We also briefly introduce ontology-related work for which we did not find downloadable links, and ongoing research projects focusing on developing ontologies in CE (Section 4.5).

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[6] https://matportal.org
[7] http://industryportal.enit.fr
[8] https://data.ontocommons.linkeddata.es
[9] https://ontobee.org
[10] https://lov.linkeddata.es/dataset/lov
[11] http://w3id.org/CEON/catalogue

Table 2: Domains of the relevant ontologies.

Domain	AMO [36]	BCAO [37]	BiOnto [4]	BONSAI-core [16]	BPO [62]	BUILDMAT [59]	BWMD-Domain [49]	CAMO [47]	CEO [47]	CHAMP [51]	COMPOSITION [45]	ENVO [7]	GPO [55]	GRACE [28]	IMANO [22]	IOF-core [14]	ManuService [32]	MASON [29]	MATONTO [9]	MDO [31]	MPO [43]	MSDL [1]	MSO-OFM [8]	NMRVOCAB [35]	PRONTO [60]	PSS [33]	ROMAIN [21]	SAREF [12]	SAREF4ENVR [11]	SAREF4ENVI [42]	SAREF4INMA [13]	SDGIO [44]	SCONTO [61]	SCOR [41]	UNSPSC [17]	VERONTO [54]	Z-BRE4K [10]	Total
CE		✓	✓					✓	✓																													4
SU			✓	✓								✓																	✓	✓		✓						6
MAT	✓					✓	✓	✓								✓			✓	✓	✓			✓														9
MAN	✓						✓			✓	✓		✓	✓		✓	✓	✓				✓	✓			✓					✓					✓	✓	15
PR	✓			✓	✓					✓				✓			✓								✓	✓									✓	✓		10
LO											✓		✓		✓		✓						✓				✓						✓	✓				8
General																												✓										1

4.1 Ontologies related to Circular Economy and Sustainability

In Table 2, we have assigned labels CE and SU to ontologies related to *Circular Economy* or *Sustainability*, respectively, according to the domains presented in Table 1. 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 cases in specific industry domains, and fall outside the scope of this paper. However, in [47] two ontologies have been established to facilitate material circulation within the CE 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 CE area, but also focus specifically on the construction domain. CEO reuses existing ontologies such as GeoSPARQL [3]. CAMO categorizes specific materials, products and activities for CE. The usage of CEO and CAMO is furthermore investigated in [48] for representing textile data.

Nevertheless, there are a few more ontologies that deal with CE, targeting more specific use cases. For instance, the Building Circularity Assessment Ontology (BCAO) [37], focuses on the construction industry and links the data and information from different manufacturer products to support decision making while considering circularity. For instance, BCAO models a product as made of material which is produced by an organization. This can be considered a generic enough representation to be used also in other industries. Further, BiOnto [4] from the BIOVOICES project,[12] aims to build a shared and common terminology in the bioeconomy domain so that multiple different stakeholders can provide information according to the ontology. Then the BONSAI-core ontology [16] 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 of an electricity production activity, and such an activity produces electricity (output). The aim of the BONSAI project[13] is to support product comparisons and decisions by representing product footprints. These ontologies all cover specific aspects in the context of CE, which may be reusable outside their specific domains, but do not in themselves consider cross-industry scenarios, nor do they cover all the elements of CE and circular value networks (as described in Section 2.2).

Moving towards the sustainability topic, the Environment Ontology (ENVO) [7] 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*. Such concepts may provide a link between CE and specific effects on sustainability, e.g., through specifying effects on environmental systems, or values created. A bit more general, the Sustainable Development Goals Interface Ontology (SDGIO) [44] intends to represent knowledge related to the sustainable development goals [27] as well as their targets and indicators. SDGIO reuses a number of existing ontologies from different domains such as ENVO as introduced above. Although CE in itself does not necessarily entail sustainability, it is usually seen as the end goal, and thus CE ontologies will need to relate to sustainability goals and effects at different levels.

Finally, more in detail, the Smart Appliances REFerence ontology (SAREF) [12] has a focus on the smart appliances domain, modeling concepts such as device, measurement, service, property and function. SAREF4ENVI [42] extends SAREF to describe different physical objects, devices and their characteristics. SAREF4ENER [11] extends SAREF to represent energy management such as energy efficiency optimization and describes, e.g., specific power sequences. This family of ontologies may be relevant to further detail the instrumentation and effects of circular value networks.

4.2 Ontologies related to Manufacturing, Products, and Logistics

In a circular value network, a resource can be realized in different states. These states can be identified as particles (materials), parts (components) and products (finished goods) [6]. Operations

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[12] https://www.biovoices.eu

[13] https://bonsai.uno

Table 3: Ontology Characteristics.

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

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 optimize the management of products in their life cycles by, for instance, reducing the distribution, redistribution and monitoring maintenance cost. Thus, the domains of *Manufacturing*, *Products*, and *Logistics* as presented in Table 1, are tightly connected and we discuss general ontologies for all these domains in this section. We use the labels MAN, PR, LO, respectively. Among the 37 collected ontologies shown in Table 2, 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, which is something we may need to trace in the CE domain. For instance, AMO (Additive Manufacturing Ontology) [36] focuses on modeling different manufacturing processes relevant to additive products as well as their physics-based models. BWMD-Domain ontology [49] contains definitions of different manufacturing processes such as casting and coating. MAnufacturing’s Semantics ONtology (MASON) [29] 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 loss of volume or not, which is also relevant for CE. Collaborative Manufacturing Services Ontology (COMPOSITION) [45] concerns collaborative manufacturing services that include human operations, logistics operations and manufacturing operations by reusing MASON. Manufacturing

Service Description Language (MSDL) [1] focuses on manufacturing services in the mechanical machines. Manufacturing acts are categorized as shaping processes and non-shaping processes based on whether they alter the shape of the input materials or not.

In addition to modeling different manufacturing processes, several ontologies focus on modeling relevant general concepts and/or relationships that relate to such processes. The IOF-core ontology [14] 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) [55] focuses on modeling 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. Overall, there are several ontologies modeling various aspects of manufacturing processes, that may all be relevant to capture and trace the handling of materials, components, and products throughout a circular value network.

Other relevant related concepts, are modeled by ontologies such as SAREF4INMA [13], which extends SAREF to capture knowledge in the manufacturing domain. 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) [8] 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 [10], additionally, is an ontology providing annotations and descriptions to represent manufacturing system performance.

Among the ontologies introduced above, we find that several ontologies (e.g., COMPOSITION, GPO, MSO-OFM) also concern the logistics and supply chain domains. There are additionally ontologies focusing on logistics-related domains specifically, such as Industrial MAintenance Management Ontology (IMAMO) [22], Reference Ontology for Industrial Maintenance (ROMAIN) [21], Supply Chain Ontology (SCONTO) [61] and Supply Chain Operation Reference (SCOR) [41]. IMAMO and ROMAIN focus on modeling domain knowledge for maintenance in the context of the logistics domain. IMAMO contains general concepts such as equipment, maintenance task and maintenance strategy, to support interoperability among different applications requiring maintenance within the same industrial environment. ROMAIN extends the material entity in BFO [2] with a new concept *maintainable item* as well as relevant concepts such as maintenance strategy, plan and action. SCONTO and SCOR on the other hand focus on modeling domain knowledge for supply chains, in the context of logistics. SCOR provides vocabularies to represent the supply chain operations reference standard. For instance, it models different processes in a supply chain system such as delivery, planning and return processes. SCONTO 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 organizations as well as areas such as production and sales. Similar to SCOR, the process part also includes delivery, planning and return. Resources can here be financial resources, human resources and material resources. At an abstract level, circular value networks have a lot in common with traditional supply chains, hence, these supply chain and logistics ontologies are highly relevant for CE, modeling the resources and information flows.

Additionally, some ontologies specifically focus on representing knowledge for the product domain. Building Product Ontology (BPO) [62] has a focus on building products modeling, for instance, how different product components can be assembled. However, the notion of composition of a product is more general than the construction domain only. Product Ontology (PRONTO) [60] 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. Furthermore, the Universal Standard Products and Services Classification (UNSPSC) [17] holds detailed classifications on products and services in the scope of the global marketplace. Product is also a central concept in CE, but the level of detail to which is has to be modeled, and how to classify products may differ depending on industry domains.

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.

The ManuService ontology [32] models manufacturing concepts at a general level, 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, hence, spanning over several of the previous categories (annotated with MAN, PR and LO labels). In addition, several ontologies focus on both the manufacturing and product domains. Coordinated Holistic Alignment of Manufacturing Processes (CHAMP) [51] represents knowledge of product life cycles, aiming at integrating data within different industrial organizations, as well as across them. It uses a number of existing ontologies such as BFO [2] and the Common Core Ontologies [46]. The GRACE ontology [28], in turn, 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) [33] represents domain knowledge that relates to different aspects of products and product service systems, such as the provider of a product or a product service system, and different resources needed for a product service system (e.g., manufacturing resources, business resources, hardware and software resources). Finally, VERsioning ONTOlogy (VERONTO) [54] is an ontology for representing temporal events, which can also affect product information over time.

As can be noted by the amount of ontologies listed in these categories, and their overlaps, the area of manufacturing, products, and logistics is one where a multitude of ontologies have been proposed already (as opposed to the CE domain itself). This means that more work is needed to assess these ontologies in detail, concerning both their potential use in CE modeling, as well as their compatibility for inclusion in the same ontology network.

4.3 Ontologies related to Materials

As mentioned in Section 2.2, in a circular value network a resource flow can ensure that materials become components and products in sustainable ways, but also that materials can again be retrieved and recycled starting from those existing components and products. Therefore, representing knowledge of materials is an essential building block in a CE ontology network. Ontologies related to this domain are labeled with MAT.

Our previous work presented in [25, 26, 30] has investigated existing ontologies related to the materials science domain. The currently ongoing EU-funded project OntoCommons[14] also conducted a survey of existing ontologies in a set of domains, where one domain is materials science and engineering. Three ontologies in these surveys (BWMD-Domain ontology, MatOnto and MPO) are relevant for our purposes, and therefore included in our survey. Additionally, six other ontologies were collected. In Table 2, we have assigned the label MAT to these ontologies.

The BWMD-Domain ontology (also labeled MAN), based on BFO [2], contains definitions of different material structures (e.g., meso structure, micro structure and macro structure) and different engineering material types (e.g., composite material, metallic material, organic material) which can provide general information of materials for the CE domain. The MATONTO (MatOnto Ontology) [9] models different material properties, e.g., amount of substance, and flexural strength as measured properties. MPO (Material Properties Ontology) [43] 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 the BWMD-Domain ontology and MPO, BUILDMAT [59] also represents materials with a focus on building components, as well as general material properties and material types. MDO (Materials Design Ontology) [26, 31] contains a structure module describing composition information of materials, which is essential in the circular value network context, e.g., when a recycling decision is to be taken. AMO, CAMO and IOF-core ontology were already described earlier as they were also labeled with other domains, but additionally contain concepts related to materials.

Overall, the materials domain is also relatively well covered by existing ontologies. However, the main challenge is to ensure modeling of materials for CE at the right level of detail and granularity. Different industry domains may have different needs and perspectives. Thus, in the materials domain, ontologies must also be assessed further in terms of potential in the CE context, and compared in detail to ensure compatibility with each other.

4.4 General Level Ontologies and Standards

Some ontologies, as shown in Table 3, reuse existing foundational ontologies (e.g., BFO [2], EMMO[15]) or general level ontologies (e.g., SAREF [12]). The usage of foundational ontologies provides a common ground to enable interoperability among different domains. Ontologies based on the same foundational ontology make certain common ontological commitments. BFO is the most frequently reused foundational ontology among the collected ontologies. We also find that several domain ontologies reuse the Common Core Ontologies for representing general concepts and their relations. While alignment to foundational, or general level, ontologies ensure compatibility and improves interoperability, there is also a trade-off with respect to reusability, an in some cases also understandability and efficiency. Hence, while CE ontologies should also be aligned to common foundational and general level ontologies to the extent possible, it is not obvious how to achieve the best trade-off between reusability and efficiency etc. on one hand, and interoperability on the other hand.

Further, considering human understandability and reuse of already agreed conceptualisations, then in order to develop high-quality and complete ontologies it is also necessary to take the corresponding standards (e.g., ISO standards), and EU policies, laws and regulations related to both CE and general domains into account as non-ontological resources. One use of these resources is as a basis for extracting relevant terms for a specific domain. They can also provide context and restrictions for the concepts in ontologies. For instance, ISO/DIS 59004 intends to define key terminology, establishes CE principles and provides guidance for CE 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. Meanwhile, there are also different types of EU policies, legislation, and regulations that can provide candidate terms for developing ontologies. For instance, the EU taxonomy for sustainable activities provides a list of terms as well as the criteria for environmentally sustainable economic activities. As a further example, the EU legislation directive 2009/125/EC29 contains a list of definitions for concepts such as life cycle, reuse, and recycling, and also states the ecodesign requirements for energy-related products. We provide a collection of such standards and other relevant non-ontological resources in Table 4, in Appendix A. When building new CE ontologies, or integrating existing ontologies, these standards and related documents, need to be taken into account.

4.5 Related Work and Ongoing Projects

In addition to the existing available ontologies in the CE domain, there are some CE-related ongoing projects that aim to develop and/or use ontologies. In this section we refer to some ongoing projects as well as ontologies that are not currently publicly available online.

In the context of CE, a material passport refers to tools or methods that can trace materials, so that the materials can be easily located, extracted, or recycled for instance. Therefore, to enable materials passport-based techniques, is an important key in CE [23]. Materials Passport Ontology [23], reusing CEO and CAMO, is developed to help share data and trace materials. An ontology focusing on enabling material passports for construction materials at the city scale, is proposed in [53]. To represent waste-to-resource paths by considering economical and environmental effects, an ontology-based method is proposed in [38], focusing on chemical wastes and recycling. Focusing on business models, an ontology for the

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[14] https://ontocommons.eu

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

Strongly Sustainable Business Model has been proposed in [57] by emphasising sustainability.

In [50], an ontology is developed as the basis of Circular Economy Monitor (CEM) to describe the information and data as a core ontology to formalize materials flows. A CE business model related ontology is proposed in [34] with a focus on tracking, monitoring and analysing products in real time based on Internet of Things (IOT)-based technologies. The idea of the business model is to support decision making such as reusing, repairing, re-manufacturing or recycling resources. The ontology presented in [18] aims to share information regarding resources to enable circularity in industrial ecosystems with a focus on the idea of eco-industrial parks. The above examples are efforts[16] to enable the usage of ontologies for CE in practice, but where the ontologies are not yet publicly available.

Furthermore, a number of ongoing research projects aim at developing ontologies, or related vocabularies and data models, for circular value networks focusing on different industry domains such as construction and electronics. *Onto-DESIDE* aims at enabling decentralized industry data sharing by developing an ontology network representing circular value networks as such. This survey was conducted in the context of *Onto-DESIDE* as a starting point towards developing the ontology network. The *CircThread*[17] project aims at exploring how to enable circular data exchange in a product context. Further, *CIRPASS*[18] also focuses on cross-domain data exchange, and a product data model for digital product passports (DPP). DPPs are being put forward by the EU as the next standards and requirements in order to promote the transition towards a more circular economy.

5 DISCUSSION

Although there are quite a number of existing ontologies from different cross-industry domains that are relevant to the CE domain, we find that there are still some open issues to be addressed when using these ontologies as background resources in developing an ontology network for CE and 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 surveyed in our work 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 developed should therefore be bridge concepts that connect different domain ontologies, and allows interoperability between the different perspectives.

The ontologies collected in this survey are also modeled quite differently in terms of the ontology metrics shown in Table 3. 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 27 ontologies that contain data property definitions and 21 ontologies that contain individuals. As mentioned in Section 4.4, different foundational ontologies (e.g., BFO and EMMO) and general level ontologies (e.g., SAREF) are reused by some domain ontologies. This means that different ontological commitments are made by different ontologies and care should be taken when using these ontologies together in a network.

Further, in contrast to domains such as biology, materials science, and industrial manufacturing, where many ontologies have been developed and catalogued in public repositories, CE is a relatively new domain in terms of focusing on using Semantic Web-based techniques. This means that CE ontologies are not as findable and accessible as they could be and thus do not satisfy the FAIR principles [63] well yet. This is evident from the number of papers describing CE ontologies that were found, but where the ontology itself was not actually accessible online. By cataloguing existing ontologies related to CE in a public repository with a permanent w3id URL, we somewhat improve the findability and accessibility for CE-related ontologies, and intend to maintain this as a future reference resource.

6 CONCLUDING REMARKS AND OUTLOOK

Establishing a shared network of ontologies for data documentation is an essential step for enabling the scale-up of digitalization in the CE domain. To study how existing cross-industry domain ontologies can be used or adapted for knowledge representation in the CE domain, we conducted a survey of general ontologies for the cross-industry domains. These studied knowledge domains include the central CE domain itself, and cross-industry domains including *sustainability*, *materials*, *manufacturing*, *products* and *logistics*.

As a next step in the *Onto-DESIDE* project, we will develop an ontology network providing a shared vocabulary for data documentation, as well as a decentralized digital platform that enables collaboration and data sharing in a secure, quality assured, and automated way. The project includes three industry use cases in construction, electronics and textile for which circular value network-based data sharing will be demonstrated and evaluated. Such an ontology network will contain core ontologies in terms of modeling CE, capturing the notion of a circular value network, as well as the knowledge to be shared in such networks, e.g., core ontologies representing cross-industry concepts, and ontologies for the specific industry use cases. As outlined in this paper, for the CE domain itself this will entail to design and publish (in a FAIR manner) some new core ontologies, while for related cross-industry concepts such as products and materials, we will focus on some bridge concepts, and in-dept analysis and alignment of existing ontologies.

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[16] We also list these in the public repository and intend to update their information when links to the ontologies are provided.

[17] https://circthread.com

[18] https://cirpassproject.eu/

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A RELEVANT STANDARDS, REGULATIONS AND POLICIES.

Table 4: Relevant Standards, Regulations and Policies.

Name	Domain	Description
ISO/DIS 59004 Circular Economy – Terminology, Principles and Guidance for Implementation[19] (under development)	CE	An ongoing work that defines key terminology, establishes circular economy principles, and provides guidance for its implementation by using a framework and areas of action.
ISO/DIS 59010 Circular Economy — Guidance on the transition of business models and value networks[20] (under development)	CE	The standard intends to provide guidelines for organizations seeking to transition their business models and value networks from linear to circular.
ISO/DIS 59020 Circular Economy — Measuring and assessing circularity[21] (under development)	CE	The standard intends to provide guidance on how the circularity performance can be measured and assessed using circularity indicators in objective, comprehensive and reliable ways.
ISO/CD 59040 Circular Economy — Product Circularity Data Sheet[22] (under development)	CE	The standard intends to guide how to improve the accuracy and completeness of circular economy related information by using a Product Circularity Data Sheet.
EU taxonomy for sustainable activities[23]	CE	Definitions of the terms in CE and criteria for environmentally sustainable economic activities.
EU critical raw materials list[24]	CE	The list contains 91 critical raw materials.
Product Circularity Data Sheet (PCDS)[25]	CE	A standardized digital fingerprint for sharing trusted data on the circularity characteristics of products across supply chains.
ISO/TC 297 Waste collection and transportation management[26]	General	The standard concerns machines, equipment and management systems for collection, temporary storage and transportation of solid and sanitary liquid waste and recyclables.
ISO/TC 154 Processes, data elements and documents in commerce, industry and administration[27]	General	The standard concerns supporting data used for information interchange between and within individual organizations and support for standardization activities in the field of industrial data.
ISO 14001:2015 Environmental management system – Requirements with guidance for use[28]	General	The standard describes the requirements for an environmental management system aiming at enhancing environmental performance.
ISO 9000:2015 Quality management systems-Fundamentals and vocabulary[29]	General	The standard describes the fundamental concepts and principles of quality management.
ISO 9001:2015 Quality management system – Requirements[30]	General	The standard covers a number of principles in terms of quality management with a strong customer focus.
ISO 50001:2018 Energy management systems — Requirements with guidance for use[31]	General	The standard provides a practical way to improve energy use, through the development of an energy management system.
EU law and legislation (directive 2009/125/EC29)[32]	General	The directive states the Ecodesign requirements for energy-related products.
GS1 Global Traceability Standard[33]	General	The standard focuses on designing interoperable traceability systems for supply chains in different domains such as food service, technical service, and humanitarian logistics.
Ecodesign requirements[34]	General	Minimum requirements that certain products must comply with in terms of energy efficiency, to reduce negative environmental impact.

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[19] https://www.iso.org/standard/80648.html
[20] https://www.iso.org/standard/80649.html
[21] https://www.iso.org/standard/80650.html
[22] https://www.iso.org/standard/82339.html
[23] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32020R0852
[24] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en
[25] https://pcds.lu/pcds-system/
[26] https://www.iso.org/committee/5902445.html
[27] https://www.iso.org/committee/53186.html
[28] https://www.iso.org/standard/60857.html
[29] https://www.iso.org/standard/45481.html
[30] https://www.iso.org/standard/62085.html
[31] https://www.iso.org/standard/69426.html
[32] https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32009L0125
[33] https://www.gs1.org/standards/gs1-global-traceability-standard/current-standard
[34] https://europa.eu/youreurope/business/product-requirements/compliance/ecodesign/index_en.htm