# Decentralized Digital Twins of Circular Value Networks - A Position Paper

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## Abstract

Circular economy aims at reducing value loss and avoiding waste, by circulating material 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 attempting to create 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. A solution to these challenges needs to leverage open standards for semantic data interoperability in establishing a shared vocabulary (ontology network) for data documentation, as well as create a decentralized digital platform that enables collaboration in a secure and confidentiality-preserving manner. This vocabulary can then be used to construct digital twins of circular value networks to further enable open collaboration. Once defined, the blueprints of these digital twins will be reusable as templates and can be reused with a different set of actors, or used within a different industry domain. This vision includes a number of 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, analyse and assess new circular value chain configurations, and form their decentralized digital twins. The solutions will allow for automation of planning, management, and execution of circular value networks, at a European scale, and beyond. Thereby supporting the acceleration of the digital and green transitions, automating the discovery and formation of new collaborations in the circular economy.

## Keywords

Circular Economy, Semantic Web, Ontology, Value Networks, Digital twins

*Third International Workshop On Semantic Digital Twins (SeDiT 2022) Co-located with the 19th European Semantic Web Conference (ESWC 2022), Hersonissos, Greece - 29 May 2022*

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# 1. Introduction

Semantic interoperability of data is one of the biggest barriers towards data sharing in the Circular Economy (CE). However, we argue that Semantic Web technologies can provide the technical foundations for information flows that will transform European Industry towards a CE, by means of digitalisation and data sharing. By leveraging open standards for semantic data interoperability and establishing a shared network of ontologies for data documentation, as well as implementing a decentralized digital platform that enables collaboration in a secure and confidentiality-preserving manner this will allow for automation of discovery, planning, management, and execution of cross-industry circular value networks. Combined with automated access control policies for data privacy and confidentiality, this enables automation while protecting company-internal data, and allows data sharing at the right level of granularity.

For putting this in place a forthcoming EU-funded project, Onto-DESIDE, will develop a technology for allowing data sharing about materials and products at a global scale, see Fig. 1. This paper describes the overall vision, and research position from which this project starts, which has also partly been developed in the Swedish Vinnova-project CIRCLA. Since access to verifiable information is central, well-established open standards for secure and confidentiality-preserving information sharing are core components. Ownership and storage of data should remain with the data producer; hence a decentralized approach is necessary. Metadata and structures for transforming data into information (semantic descriptions, i.e. ontologies) will be open, and comply with FAIR principles, to enable the highest possible degree of semantic interoperability and automation in data sharing. For sensitive data, methods allowing for proof of existence of the data can be used, where proofs can be shared while actual data is kept private. Equality, democracy, and ethics are key aspects in collaboration and data sharing, and aspects that will be central in developing the details of the data sharing architecture.

Another aspect is to address the use of these technologies in a business context, and study the circular economy as a complex system to develop integrated tools and methods for further enhancing CE. Although the importance of various 'flows' - namely: resource flows, information flows, value flows, and energy flows - has been widely acknowledged within the transformation to CE, so far they have not been integrated or linked into a single framework or approach [1]. Without such integration or linking it is currently not possible to make robust designs of circular value networks, and to conduct value network coordination towards implementation and operation within industry. Moreover, this should result in robust value networks that are profitable, equitable, and invite long-term collaborations and partnerships. Therefore, apart from the solutions needing to be technically feasible, there is also a need to explore how such value networks can be designed and developed, using the ontologies for data documentation and data sharing, but considering the interplay of resource, information, value and energy flows, i.e considering how the value network will behave as a system. Four core components that need to be explored are envisioned:

- A **network of ontologies** for data documentation, that allows for semantic interoperability and supports flexible, automated, decentralised data sharing between industry actors.
- An **open circularity platform**, i.e. a secure and confidentiality-preserving decentralized data sharing platform allowing the creation of **digital twins** of circular value flows, by

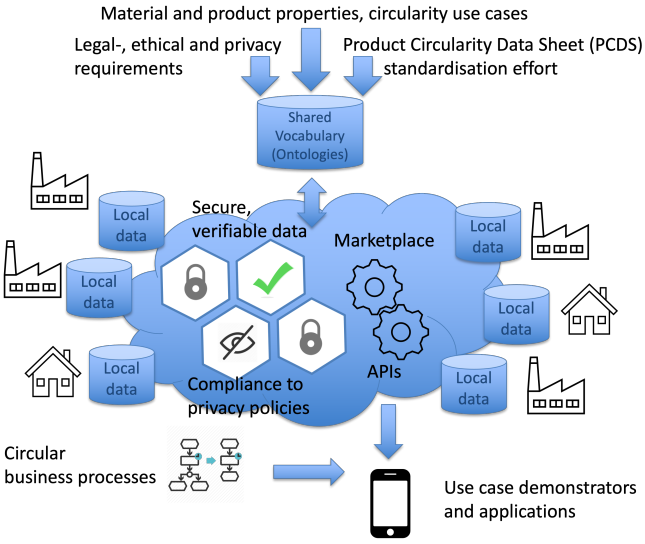


**Figure 1:** The Onto-DESIDE concept – From requirements, via shared vocabularies, to a shared data space for discovery and execution of new circular value flows, and new business models, demonstrated and evaluated in concrete industry use cases.

enabling FAIR sharing of data between industry actors, facilitating the initiation of new collaborations in the circular economy.

- **Methods** to find, analyse, and assess new circular value chain configurations opened up by considering resource, information, value, and energy flows as an integral part of transitioning to a circular metabolism within industrial systems through co-design and co-creation.
- **Validation** - demonstrating and quantifying the potential for increased retainment of value when applying the above outcomes in cross-border and cross-industry sector circular value networks in Europe.

In this paper the focus is on the technological aspects, and in particular those related to Semantic Digital Twins. Hence, next, two of the key concepts underpinning the Onto-DESIDE vision are introduced in more detail, including the state of the art in each area, to establish the novelty and excellence of the research direction. The key concepts, corresponding to the first two core components listed above, are: (1) an ontology network for data documentation, and (2) the "digital twin" in circular economy facilitated by the open circularity platform. The concepts are explained, as well as the vision of how to advance the state of the art of these key concepts.

## 2. Ontologies for data documentation

Ontologies have been applied in many domains, and are widely understood as a key technology to address semantic interoperability. An ontology network [2] 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. Standard ontology networks exist

in several domains, such as the Semantic Sensor Networks (SOSA/SSN) ontology network [3], which is a W3C and OGC standard, or SAREF[1] as an alternative for smart applications, and the OBO Foundry [4] in biomedicine, emerging as a de-facto standard in the biomedical field.

No similar effort, or standard, as the ones mentioned above exist neither in the overall CE domain, nor in the more specific sub-domains facilitating semantic interoperability of typical CE data categories, such as information about materials, products, capabilities etc. There are general ontologies for products, such as the widely used GoodRelations [5], also integrated with schema.org, which is targeted at the online retail market, as well as domain-specific product ontologies, e.g. specifically for construction, or manufacturing industry. However, none of these are built with CE requirements in focus, and do not target product reuse, refurbishing, recycling etc. Similarly, many ontologies have been proposed to model organisations, from the generic W3C standard ORG-ontology [6], to ontologies focusing on specific business use cases. Still, none of these fully cover the requirements of the CE, for forming and executing new circular value networks.

A core part of the needed ontology network is related to materials models, which can be used to describe both virgin materials, product parts during a product life cycle, as well as recycled materials. Interoperability in materials science is traditionally achieved mainly via file-based exchange involving specific formats and, at best, some partial metadata, which is not always guided by an ontology. Examples of such efforts includes the Materials Genome Initiative[2], and the API-based effort of Open Databases Integration for Materials Design (OPTIMADE)[3][7]. A recent approach is the Novel Materials Discovery (NOMAD) [8]. However, none of these efforts use ontologies to provide semantic interoperability.

Nevertheless, also in the materials science domain, recently, an awareness has emerged regarding the importance of semantic interoperability and FAIR principles for data storage and management [9]. Two ontologies representing general materials domain knowledge are ChEBI [10] and EMMO [11]. EMMO is an upper ontology, currently developed by the European Materials Modelling Council, aiming at developing a standard representational ontology framework, but several sub-domain of materials modelling are still not covered, and the ontology aims at being an upper ontology for other ontologies to extend. Recently, in our research we have also developed and published the Materials Design Ontology (MDO) [12], an ontology guided by the schemas of OPTIMADE but intended to provide a semantic interoperability layer in materials science. In summary, the few ontologies that exist have been developed focusing on representing either very general materials domain knowledge, or specific narrow sub-domains. In addition, there is a need to align to current ongoing efforts, such as the IOF[4] and OntoCommons[5], but although it is important to be compatible with these perspectives, in particular upper ontologies, none of these have their focus on the specific cross-domain and cross-industry aspects of CE. Hence, to solve the general challenges of circular value networks there is a need to align and refer to specific other ontologies for more granular representation of certain details within one domain, but keeping the core models generic.

[1] https://saref.etsi.org/
[2] https://www.mgi.gov/
[3] https://www.optimade.org/
[4] https://www.industrialontologies.org/
[5] https://ontocommons.eu/

The work needed is hence to, based on established technologies and standards (i.e. using the W3C standard OWL[6] for ontology representation), develop and evaluate an ontology network for data documentation targeting the cross-industry domain of circular economy. A number of additional challenges not present in any existing efforts will have to be addressed, including the need to cover a wide range of different materials and products, as well as the need not only for vertical interoperability of ontologies but also a minimal level of horizontal interoperability, for cross-industry value networks. These are extremely challenging requirements, where solutions then need to be demonstrated through thorough evaluation in industry use cases. To ensure scalability and separation of concerns in the ontology network, a layered ontology network architecture (e.g. inspired by SOSA/SSN) should be used, as illustrated in Fig. 2, where a set of core Ontology Design Patterns (ODPs) will act as the basic modelling templates for a set of core ontology modules, defining the common concepts shared by several industry domains and use cases. Another challenge is to achieve the right level of axiomatization for each module, making it on one hand highly reusable, but on the other hand also usable for data integration and reasoning. In the figure, the overall architecture is illustrated, where the outer layers import modules from the inner layers, and extend these by specializing and adding axiomatization and alignments.

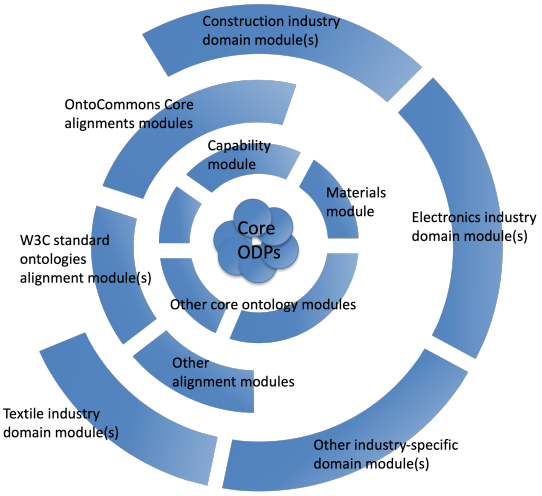


Figure 2: Conceptual illustration of the ontology network architecture which will realize the challenging requirements of both vertical and horizontal interoperability, as well as reusability of value flow digital twin blueprints. Inner circles represent more fundamental concepts, that are reused (e.g. through importing) by the ontologies of the outer circles, hence further specialising the fundamental concepts.

## 3. "Digital twins" in CE - An open circularity platform

While semantic interoperability, and ontology-based data documentation, are essential enablers for large scale CE, it is not enough in itself. Semantically described data also need to be put into use, in automated processes. Today, there is limited data collaboration within industry domains and even less across domains, consequently new circular value networks are only created between known actors that have a certain degree of comfort working together [13] - limiting the possibilities of more high value circulation scenarios. Open collaboration could remedy this, but data and ontologies cannot solve the problem alone. To facilitate open collaboration in a data driven circular economy a new entity is needed; **the digital twin of circularity**.

[6] https://www.w3.org/OWL/

Here we rely on the digital twin definition provided by the Digital Twin Consortium[7], part of the international standards organization, the Object Management Group[8]. The definition states that a digital twin:

- Is a synchronized virtual representation of real-world entities and processes.
- Uses real-time and historical data to represent the past and present and simulate predicted futures.
- Transforms businesses by accelerating holistic understanding, decision-making, and effective action, and is motivated by outcomes, tailored to use cases, powered by integration, built on data and guided by domain knowledge.

The concept of digital twins has been put to use for many use cases and in many industries [14] and the fundamental theory behind the concept is not a new thing. For instance, one study [15] explored the usage of digital twins in the context of a circular value network for remanufacturing in the construction industry. But, the idea of constructing digital twins of circular value networks, with the value network itself, and related 'flows', as the objects in focus, is a novel idea and has not been explored before.

If digital twins are built upon shared ontologies, i.e. the ontology network, once defined, their blueprints are also reusable as templates for a certain type of circular value network, and could at minimal effort be shared with a different set of actors or used within a different industry domain to instantiate new value networks. Previous work that implements such ideas are for example the sectoral circular economy business model patterns within manufacturing companies [16]. Another example, this time from the construction industry, is the concept of making use of Building Information Models (BIM), and BIM objects, to explore the notion of generic capabilities [17]. The vision is for Onto-DESIDE to develop these ideas further, by viewing the digital twin as a form of design pattern [18], essentially blueprints of executable circular value flows applicable in various domains, which is a novel idea. In addition, the use of ontologies to describe such blueprints for digital twins of circular value flows is also both challenging, but promising and novel.

Instead of having each industry domain creating their own circular interconnections over time, however, we argue that the core logic of circularity should be common and manifested in a digital entity that translates between industry domains. Existing Circular Economy standardization efforts, such as ISO WD59004[9] and TC323[10], have begun to address this, but standards also need to be operationalized technically, which is targeted here. By enabling translations between domains, the need for central repositories of information is also reduced, every organization will keep and manage their own data. By building on well established standards for semantically describing, interlinking and sharing data, collaboration is made secure and scalable. Every circular digital twin will share the same fundamental definitions, and functionality is increased through detailing and populating the data documentations with increased granularity, i.e. specialisations of the ontology network and the circularity blueprint, rather than by adding

[7] https://www.digitaltwinconsortium.org/initiatives/the-definition-of-a-digital-twin.htm
[8] https://www.omg.org/
[9] https://www.iso.org/standard/80648.html
[10] https://www.iso.org/committee/7203984.html

complexity through constructing new case-by-case solutions. On its own, the twin represents value to stakeholders by providing the technical infrastructure for making data exchange in complex circular eco-systems manageable, and reusable.

Technically, the digital twin idea will be implemented as an open circularity platform using existing, and emerging, Web technologies, such as RML for semantically annotating and transforming heterogeneous data sources [19], Solid for building decentralized applications based on Linked Data principles [20], and incorporating validation and verification methods that provide proofs of data authenticity [21]. Given a commonly understood ontology, the following three challenges provides a novel decentralized solution:

- Semantic interpretation of existing data, so that actors can rely on existing infrastructure;
- A decentralized network to publish and retrieve semantically annotated data, behind a layer of authentication and authorization, so that actors can share their data with only those partners they are comfortable with;
- A verification method so that collaborating actors can trust the data they are using.

The objective of the platforms is to demonstrate that ontology-based decentralized data sharing can operationalise the idea of a decentralized digital twin, maximally taking advantage of existing IT infrastructures and standards - without compromising access control and trust.

## 4. Summary and Outlook

The employment of semantic ontologies and linked data together with the concept of digital twins to enable open data collaboration in the context of circular economy is a novel idea, and the vision of the Onto-DESIDE project. The project will provide a test bed for exploring and verifying these novel research topics related to the combination of circular economy and digital twins. Industry use cases, in the domains of textile, electronics, and construction, that make use of real business data, will ensure that results are relevant and usable in an operational context, across industry domains. This also provides a good empirical basis for further research on the topics of digital twins and semantic data in the context of the circular economy transition. Next steps in research towards these goals include the development of the envisioned ontology network, including identification of core issues in cross-industry applications of the circular economy, detailing and operationalization of the digital twin concept and its reusable blueprints, using Semantic Web technologies, as well as in parallel develop the methods for finding, analysing and assessing circular value chain configurations in a business ecosystem.

We envision that the thinking and concepts that we present in this paper, as well as what is to be explored in the Onto-DESIDE project, open up for new ideas and paths of research that are needed to facilitate a green transition at scale.

## Acknowledgments

Thanks to all partners in the forthcoming Onto-DESIDE consortium for their contributions to the vision, and the EC for providing funding of this future research (GA under negotiation). Developing this vision was also partly funded by the Swedish Vinnova-project CIRCLA (Dnr. 2021-04323).

## References


[1] F. Blomsma, M. Tennant, R. Ozaki, Making sense of circular economy oriented innovation: from idea to implementation, J. Business, Strategy and the Environment (forthcoming).

[2] Ontology Engineering in a Networked World, Springer, Berlin, Heidelberg, 2012.

[3] A. Haller, K. Janowicz, S. J. Cox, M. Lefrançois, K. Taylor, D. Le Phuoc, J. Lieberman, R. García-Castro, R. Atkinson, C. Stadler, The modular ssn ontology: A joint w3c and ogc standard specifying the semantics of sensors, observations, sampling, and actuation, Semantic Web 10 (2019) 9–32.

[4] B. Smith, M. Ashburner, C. Rosse, J. Bard, W. Bug, W. Ceusters, L. J. Goldberg, K. Eilbeck, A. Ireland, C. J. Mungall, et al., The obo foundry: coordinated evolution of ontologies to support biomedical data integration, Nature biotechnology 25 (2007) 1251–1255.

[5] M. Hepp, Goodrelations: An ontology for describing products and services offers on the web, in: International conference on knowledge engineering and knowledge management, Springer, 2008, pp. 329–346.

[6] The organization ontology - w3c recommendation 16 january 2014, 2014. URL: http://www.w3.org/TR/vocab-org/.

[7] C. W. Andersen, R. Armiento, E. Blokhin, et al., Optimade, an api for exchanging materials data, Scientific Data 8 (2021) 217. doi:10.1038/s41597-021-00974-z.

[8] C. Draxl, M. Scheffler, The nomad laboratory: from data sharing to artificial intelligence, Journal of Physics: Materials 2 (2019) 036001.

[9] P. Lambrix, R. Armiento, A. Delin, H. Li, FAIR Big Data in Materials Design, in: Encyclopedia of Big Data Technologies, Springer, 2022.

[10] K. Degtyarenko, P. De Matos, M. Ennis, J. Hastings, M. Zbinden, A. McNaught, R. Alcántara, M. Darsow, M. Guedj, M. Ashburner, Chebi: a database and ontology for chemical entities of biological interest, Nucleic acids research 36 (2007) D344–D350.

[11] Documentation on materials modelling ontology in uml - emmc csa deliverable 2.7, 2019.

[12] H. Li, R. Armiento, P. Lambrix, An ontology for the materials design domain, in: International Semantic Web Conference, Springer, 2020, pp. 212–227.

[13] G. Bressanelli, F. Adrodegari, M. Perona, N. Saccani, Exploring how usage-focused business models enable circular economy through digital technologies, Sustainability 10 (2018) 639.

[14] A. Fuller, Z. Fan, C. Day, C. Barlow, Digital twin: Enabling technologies, challenges and open research, IEEE access 8 (2020) 108952–108971.

[15] Z. Chen, L. Huang, Digital twin in circular economy: Remanufacturing in construction, in: IOP Conference Series: Earth and Environmental Science, volume 588, IOP Publishing, 2020, p. 032014.

[16] M. P. Pieroni, T. C. McAloone, D. C. Pigosso, Circular economy business model innovation: Sectorial patterns within manufacturing companies, Journal of cleaner production 286 (2021) 124921.

[17] L. A. Akanbi, L. O. Oyedele, K. Omoteso, M. Bilal, O. O. Akinade, A. O. Ajayi, J. M. D. Delgado, H. A. Owolabi, Disassembly and deconstruction analytics system (d-das) for construction in a circular economy, Journal of cleaner production 223 (2019) 386–396.

[18] A. Gangemi, V. Presutti, Ontology design patterns, in: Handbook on ontologies, Springer, 2009, pp. 221–243.

[19] A. Dimou, M. Vander Sande, P. Colpaert, R. Verborgh, E. Mannens, R. Van de Walle, Rml: a generic language for integrated rdf mappings of heterogeneous data, in: LDOW, 2014.

[20] S. C. Group., Solid technical reports, 2021.

[21] D. Burnett, G. Noble, B. Zundel, D. Longley, M. Sporny, Verifiable credentials data model 1.0, 2019.