Decentralized Digital Twins of Circular Value Networks

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Abstract

Semantic interoperability of data is one of the biggest barriers towards data sharing in the Circular Economy (CE). Semantic Web technologies can provide the technical foundations for information flows that will transform European Industry towards a CE, by means of digitalization and data sharing. By leveraging open standards for semantic data interoperability and establishing a shared network of ontologies for data documentation. Ontologies have been applied in many domains, and are widely understood as a key technology to address semantic interoperability. 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, analyze and assess new circular value chain configurations, and form their decentralized digital twins.

Keywords

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

1. Introduction

Semantic interoperability of data is one of the biggest barriers towards data sharing in the Circular Economy (CE)[1]. Semantic Web technologies can provide the technical foundations for information flows that will transform European Industry towards a CE, by means of digitalization 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.

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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 EU-funded project, Onto-DESIDE[2], was started in 2022. Onto-DESIDE will develop a technology for allowing data sharing about materials and products at a global scale. 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[3], 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.

2. Core components of the Onto-DESIDE vison

Within the Onto-DESIDE project, four core components that need to be explored are envisioned:

- A **network of ontologies**[2] for data documentation, that allows for semantic interoperability and supports flexible, automated, decentralized 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 enabling FAIR sharing of data between industry actors, facilitating the initiation of new collaborations in the circular economy.
- **Methods** to find, analyze, and assess new circular value chain configurations opened up by considering resource, information, value, and energy flows as an integral part of

[2]https://ontodeside.eu/

[3]https://www.go-fair.org/fair-principles/

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.

The focus of my research work is on the technological aspects, and in particular those related to Semantic Digital Twins, namely:

1 - An ontology network for data documentation
Based on established technologies and standards (i.e. using the W3C standard OWL[4] 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.

2- The digital twin of circular value networks
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 [3] - 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**. The concept of digital twins has been put to use for many use cases and in many industries [4] and the fundamental theory behind the concept is not a new thing. For instance, one study [5] 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 [6]. 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 [7]. The vision is for Onto-DESIDE to develop these ideas further, by viewing the digital twin as a form of design pattern [8], essentially

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

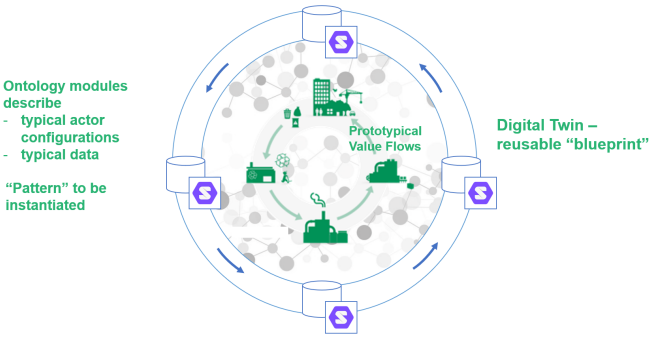

Figure 1: The Onto-DESIDE concept of digital twins

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. 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 [9], Solid for building decentralized applications based on Linked Data principles [10], and incorporating validation and verification methods that provide proofs of data authenticity [11]. Figure 1 aims at visualizing how the envisioned core components of Onto-DESIDE interact to enable the concept of digital twins of circular value networks.

Focusing on the above, further work in the validation part of the project will make up the main setting for evaluating the research questions for my work. The setup of the project are such as that we have set up three industry use-cases where access to real industry data will be used to validate the ontology network and open circularity platform. This will ensure that future results are based on real data and collaboration between real organization, thus contributing to the validity of the results.

3. Related work

Ontologies have been applied in many domains, and are widely understood as a key technology to address semantic interoperability. Standard ontology networks exist in several domains, such as the Semantic Sensor Networks (SOSA/SSN) ontology network [2], which is a W3C and OGC standard, or SAREF[5] as an alternative for smart applications, and the OBO Foundry [12] in biomedicine. No similar effort, or standard, as the ones mentioned above exist neither in the overall CE domain, nor in the more specific subdomains facilitating semantic interoperability of typical CE data categories, such as information about materials, products, capabilities etc.

There are general ontologies for products, such as GoodRelations [13] which is targeted at the online retail market, as well as domain-specific product ontologies, e.g. specifically

[5]https://saref.etsi.org/

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 organizations, from the generic W3C standard ORG-ontology [14], to ontologies focusing on specific business use cases. Still, these do not cover the requirements of the CE, for forming and executing new circular value networks.

A central part of the foreseen ontology network are related to materials models, which can be used to describe both virgin materials, product parts during a product life cycle, and recycled materials. Examples of such efforts includes the Materials Genome Initiative[6], and the API-based effort of Open Databases Integration for Materials Design (OPTIMADE)[7][15]. A recent approach is the Novel Materials Discovery (NOMAD) [16]. However, none of these efforts use ontologies to provide semantic interoperability.

4. Hypothesis and research questions

The main overarching theme for my research work focus on the enablers for data sharing that semantic web technologies provides in the context of the Circular Economy. The main hypothesis I aim to answer are as follows:

Could Semantic web technologies enable data sharing in the Circular Economy and enable the construction of digital twins of circular value networks?

Based on the above hypothesis, three sub-questions are formulated to investigate certain aspects in order to provide evidence towards falsifying or acknowledging this hypothesis:

1. How should ontologies be designed and developed considering the CE context?
2. How can ontology design patterns and ontology modularity support such CE ontologies?
3. How can patterns of circular value networks be captured and reused?

The intention are not to provide a fully comprehensible proof that the hypothesis are valid or not, rather, by providing answers to these questions in the setting of Onto-DESIDE, provide validated results and to point to relevant areas for further research.

5. Current results

The Onto-DESIDE project started in 2022, by September 2023 we are one year into the project. So far, the results have been in the form of project deliverables that are published on the project website at: https://ontodeside.eu/results/[8]. Additionally, a number of research papers have been produced that cover surveys of the current state of ontologies in the domain of CE[9] as

[6] https://www.mgi.gov/
[7] https://www.optimade.org/
[8] https://ontodeside.eu/results/
[9] https://doi.org/10.1145/3543873.3587613

well as the recently held Knowledge Graphs for Sustainability workshop[10] that was held in conjunction with The Web Conference in Austin Texas 2023[11]. Other than building up the needed infrastructure, no results towards answering the three research questions have been produced yet.

6. Evaluation

The main validation of the results in my research will be performed in the context of Onto-DESIDE. In this, we will make use of semantic web technologies to describe and map distributed data in a industry setting, relying on the validation and demonstration of the three industry use-cases in the project. Further on, towards the end of the Onto-DESIDE project and after, additional validations would be setup to provide additional results that could be used to answer the research questions. As of today, I am not able to say in what context these validations could take place.

7. Reflection and future work

Performing this research in the context of the Onto-DESIDE project provide ample opportunity for validating the results in real-world scenarios. As we are early into the project, we are not yet in the position that we are able to validate the research questions, rather focus have been on setting up the needed infrastructure and processes needed in the project. Going forward, end of 2023 and early 2024, we would be able to perform validations using the semantic web technologies outlined in the project and in this paper.

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[10] https://kg4s.org/
[11] https://www2023.thewebconf.org/
[12] https://cordis.europa.eu/project/id/101058682
[13] https://www.ragnsells.com/
[14] https://liu.se/medarbetare/evabl45
[15] https://www.ltu.se/staff/v/vinpar-1.12657

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