CEO & CAMO Ontologies: a circulation medium for materials in the construction industry

E.M. Sauter
Geographical Information Management and Applications (GIMA) Programme, The Netherlands

R.L.G. Lemmens
Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands

P. Pauwels
Dept. of Architecture and Urban Planning, Ghent University, Ghent, Belgium

ABSTRACT: This paper evaluates the potential of semantic technologies to facilitate building material circulation in the construction industry within the Circular Economy (CE) context. It suggests building material passports as a data source for the materials to be circulated and then integrates them by means of Linked Data. A common language is proposed to combine and re-use the material data in the CE with the creation of two ontologies: Circular Exchange Ontology (CEO) and the Circular Materials and Activities Ontology (CAMO). The ontologies annotate materials under a CE classification scheme and describe the elements required for material exchange to occur: actors, the activities they perform and the referents of these activities (resources, products, tools and waste). An evaluation of the ontologies is made by means of use case-driven SPARQL queries. Further, a wide-scale evaluation addresses how a decentralized data ecosystem can enable users to publish information and dynamically interact with different repositories to exchange materials. Results indicate that these ontologies can foster a circulation medium between diverse construction industry resources. Future work contemplates validation of both ontologies in a real-world-setting with computer scientists and companies in the construction sector in the Benelux area.

1 INTRODUCTION

The Circular Economy (CE) paradigm proposes a redesign of material flows by keeping materials in circulation, thereby avoiding waste and raw material extraction (Nasir et al., 2017). As such, this paradigm holds a holistic view on supply chains where sustainable and environmental goals are put next to operational and production goals; overall promoting a balance and synergy between ecology and economic growth (Nasir et al., 2017; Genovese et al., 2017)

Nowadays, companies and businesses are increasingly being urged to become circular as the topic gains traction and interest by different countries' governments, academia and private organizations (Nobre & Tavares, 2017). At the end of 2015, the European Union put forth a documented strategy intended to push the CE forward in the activities of production, consumption and waste within five priority areas, one of them being construction and demolition (European Commission, 2015).

The United Nations estimates the construction sector is responsible for 50% raw material consumption in Europe (Drees & Sommer, 2015) and for 25-30% of all waste (European Commission, 2015). "The construction industry has traditionally followed a take-make-dispose process" or linear system (BAM, ARUP, & CE100, 2017, p.7). In contrast, in the CE context, materials should travel following a circular metabolism, where different use cycles replace the concept of disposing.

Circular business models suggest to reduce the uptake of virgin raw materials for economic activities (Nasir et al., 2017), such as reduction of newly mined steel for a building construction, and instead propose to maximize the use of materials already in place in existing buildings. As a result, several projects have been initiated that suggest that buildings should be viewed as 'material asset banks'. In this way, materials for new projects can be sourced from this material deposit and thereby recycled, instead of incurring in new sources.

Some of the lessons learnt from previous applications state that for CE initiatives to be successful, there is a need for an environment that endorses information sharing and knowledge exchange: "There is a lack of information and knowledge resources about products and their associated reuse/refurbish risks" (Winans et al., 2017 p.830).

As a response to the information need, pioneering CE initiatives suggest the creation of material passports to qualify building components. With adequate information stored in building material passports, these material deposits can better be recirculated to other use phases.

According to Spring & Araujo (2017), product passports allow for (1) informed decisions about products' next reuse steps; (2) the creation of markets for reused or disassembled products; and (3) the generation of new service offerings around the product. Although Building Information Modelling (BIM) technologies are currently suggested to store material passports (3XN & GXN Innovation, 2016), including a lot of focus on Product Data Templates and Sheets (CEN TC442 initiative), this technology does not address how to put *material circulation* in action; how to: pose queries over information, handle and integrate large amounts of data from disparate sources, make interconnections and 'smart matches' between the CE actors and their materials.

With the upsurge of topics such as Linked Data and the Internet of Things (IoT), an alternative method may be in reach, that captures building material profiles outside of (but linked to) the BIM realm (while not breaking it). Linked Data is selected due to its ability to connect heterogeneous datasets, and its integrated query potential of the building material profiles across the web; further explained in Section 2.3. Combined with a web service-oriented approach, this technology should allow material data to be published in a highly decentralized manner, thereby allowing complete marketplaces to emerge almost on their own.

There are already a lot of connections between existing technologies of the building environment such as BIM and IoT with Linked Data. For instance, the buildingSMART Linked Data working group is currently occupied with the representation of Building Information Models (BIM) as Linked Data (BuildingSMART, 2017). Furthermore, a building SMART Data Dictionary (bSDD) has been built, in an attempt to classify and link product manufacturer data for the construction industry such as windows, doors etc. Additionally, there are already several ongoing initiatives for building material passports which use BIM models as their data source. Finally, at least three significant ontologies can be named that are of relevance purely from the product modelling domain (less from the CE perspective), namely GoodRelations (Hepp, 2008), the Building Product ontology (W3C, 2017) and the BRICK ontology (Balaji et al., 2016).

The aim of this paper is to investigate the use of semantic technologies, particularly the use of ontologies, to increase building material circulation and actor connectivity across the Circular Economy within the construction sector.

2 LITERATURE REVIEW

A literature review is undertaken to understand the concepts and trends behind the application field (CE within the construction sector) as well as the technology of choice (Linked Data/Semantic Web). The following subsection starts by introducing circular practices, business models and initiatives within the building sector. Next, material passports are introduced in Section 2.2 as they are one of the upcoming data initiatives within the CE. Interviews are performed with members from two of the main material passport initiatives to get primary source information about their developments. Since the platforms are not released at the time of writing, a clearer idea is obtained about their intended formulations. Finally, the Semantic Web and its theoretical principles are presented in Section 2.3.

2.1 *Circular Economy in the Building Sector*

There is a lot of attention within the building sector towards evaluating and measuring a building's environmental performance throughout its lifecycle (European Commission, 2015). This involves Life-Cycle Assessments (LCA) that can estimate the cumulative environmental impacts (consequences and benefits) of construction materials for all the different stages of the product's life cycle (Nasir et al., 2017). In addition to LCA, when circular practices are more formally incorporated, the identification, collection, separation and recovery of valuable materials is improved (European Commission, 2015). This allows for materials to be used over and over again.

Some of the successful circular business models in the construction industry incorporate the performance model e.g. Phillips pay-per-lux model (BAM et al., 2017). This model is "a business agreement in which the customer pays for the use, or the performance, of a product rather than the product itself" (Ellen MacArthur Foundation, 2016 p.15). Users do not own the physical product; this ownership is instead transferred to the manufacturer. This paradigm change upholds an environment where designers, contractors and suppliers are involved in longer term relationships (BAM et al., 2017). This paradigm change aligns well with the changing nature of building projects in central Europe, as they become more and more oriented towards Design-Build-Finance-Maintain-Operate (DBFMO) structures, thereby encouraging strong commitment of all stakeholders throughout the life-cycle of the construction.

Two circular initiatives in the building sector have been investigated here, and individuals carrying out these projects have been interviewed:

1) Buildings as material banks (BAMB): an EU research project involving 15 European companies, research institutes and universities. Through solutions such as the creation of material passports for construction, this project attempts to increase building material value and promote circular solutions (BAMB, 2017).
2) TURNTOO/Madaster: They believe "waste is material without information, so by providing materials with adequate information, we prevent waste and create value" (Turntoo, 2017).

Therefore, Madaster created an online platform that helps create a building material passport through a scalable process.

2.2 *Material Passports: Data for Buildings in the CE*

Winans et al. (2017) suggest knowledge about products must be available. This information about resources and things allows for informed decisions about the products' next usage steps. Material passports are one of the solutions that are beginning to upsurge as a response to this need.

According to Drees & Sommer (2015), material passports help with the integration of recyclable materials in the planning stages and subsequent reuse in construction at the same quality level. They mention it can increase transparency and new business models for the real estate and construction industry, such as flexible remodeling and partial demolition.

Danish architects 3XN & GXN claim that with material passports and other relevant data such as size, number and steel quality of reinforcement bars, the material's quality and reliability for reuse can be documented. This can enhance "exposure to the market and thereby ensure the highest possible market value" (3XN & GXN Innovation, 2016 p.128)

Most initiatives suggest BIM as a technological platform to store material passports. Nonetheless, there are several identified problems with BIM. 3XN & GXN Innovation (2016 p.166) states that "the huge amounts of data will make the BIM models extremely heavy and difficult to handle." Consequently, Kasper Guldager, director of GXN, hints at the need for an intelligent search platform or a "future Google-like search engine will always be able to locate the data" (3XN & GXN Innovation, 2016 p.166)

Similarly, Scholten (2015) identifies the need for 'intelligent agents' to source used materials: "The material passport can for example be linked to a 'used' material database in an *intelligent* material pool". Even though the references to intelligent computer agents or search engines are vaguely defined, the need for them is clearly stated.

At the time of writing, separate material passport platforms created by third-parties are emerging. Also, product databases in construction industry tend to arise from third-party vendors, rather than from the owner of the product data (the manufacturer). For example, coBuilder (third-party vendor) is the creator of the goBIM repository[1] which contains product databases, often as Revit families; the manufacturer relies on this third party to spread building product data. However, these platforms are more closed, and disconnected from the actual material or product owners. These platforms do not respond to the need for a data ecosystem that: 1) is open and connected, all over the web, and managed in a decentralized manner 2) where everyone is participating, interacting dynamically with information and exchanging materials. Such a decentral data ecosystem can be realized using Linked Data and Semantic Web technologies, which is the topic of the next sections.

2.3 *Linked Data and the Semantic Web*

The Semantic Web is a vision for the World Wide Web put forth by its creator, Sir Tim Berners Lee (Berners-Lee, Hendler, & Lassila, 2001). The Semantic Web is involved with the mission of creating a 'web of meaning', where not only humans, but also machines and software agents can understand and interpret the information published on the web. In this Web, individual pieces of data are connected via '*smart*' relationships enabled by the Resource Description Framework (RDF) standard, that allows for machines to read, and interpret the information.

RDF is a graph data model where data is published as triples (Cyganiak, Wood, & Markus, 2014). Triples are statements containing the parts *subject*, *predicate*, and *object*: Iron*(s)*- is a*(p)*- metal*(o)*. In this way, triples clearly express the connection and meaning between the pieces of information.

To weave the Semantic Web, Linked Data best practices are introduced by Berners Lee (2009), to connect and publish structured information in the web. This yields a web of data, a collection of interlinked datasets known as Linked Data.

A key component of semantic technologies are the ontologies. They are vocabularies that provide an explicit and formal description of a domain of discourse (Noy & Mcguinness, 2001) in a shareable, machine-readable format and encoded using the Web Ontology Language (OWL) (W3C, 2012). Additionally, the SPARQL Protocol and RDF Query Language (SPARQL), provides the specifications with which applications interact, query and draw inferences from the information stored as RDF graphs (W3C, 2013). The next section explains how semantic technologies are applied to the CE use case.

3 APPROACH

The approach taken in this research is comprised by four steps:

1. Gathering material passports as data sources
2. Ontology creation
3. Conversion to RDF
4. Querying via SPARQL

[1] https://cobuilder.com/en/gobim/

3.1 *Gathering Material Passports as Data Sources*

The upsurge of material passport initiatives in the construction sector provides a rich data source for the materials to be circulated. Madaster, BAMB, and 3XN/GXN are initiatives that are considered as input sources for material passports for buildings.

At the time of writing, the BAMB platform is not yet launched, 3XN/GXN establishes guidelines for a passport for buildings but does not translate these into a platform. Consequently, only a demo dataset is obtained from Madaster for the building named "The ARC". The different data fields included in the passport are analyzed to see which are relevant to extract for the purposes of this research. Relevant information for this passport is: the material, product, the NL-SfB classification[2] and the volume.

3.2 *Ontology Creation*

Next, an ontology design process is followed to create a common language for material circulation in the CE. The NeOn Methodology (Suárez-Figueroa et al., 2012) provides a theoretical basis for ontology engineering by proposing nine scenarios dealing with situations such as reengineering, alignment or modularizing. From this methodology, Scenarios 4 and 7 are utilized for the extension of an existing ontology. When applicable, extension of ontologies is preferred over creating a new one, because sharing and reuse is one of the major principles behind the Semantic Web. However, some concepts are not suitable for handling with the extended ontology, thus Scenario 1 is used for the creation of a new ontology.

The steps for the extension and creation of ontologies are detailed as follows. First a conceptual model is created, following the NeOn step *ontology conceptualization activity (Scenario 1)*. Then a detailed exploration of the available ontologies evaluates if the concepts are part of existing ontologies, *ontology search, comparison and assessment (Scenario 4)*.

Next, competency questions are drafted to define the scope of the ontologies, *ontology requirements specification activity (Scenario 1)*. This is followed by the *ontology formalization activity (Scenario 1)* where a 'semi-computable' ontology model is performed. Some concepts in this model are present in existing ontologies, so suitable classes and properties are extracted during *ontology selection (Scenario 4).* Other concepts are not present; thus, they are included when extending existing ontologies or when creating a new ontology.

Then the *ontology implementation activity* is performed. The ontology that is to be extended (PRT see Section 3.2.1) is imported in Protégé, a common ontology editor tool. Existing classes, properties from PRT are added, and subsequently new classes and properties are created under the new extended Circular Exchange Ontology (CEO) during *ontological resource restructuring/re-conceptualization (Scenario 4).* Furthermore, a new Circular Activities and Materials Ontology (CAMO) is created to capture specific material data. Both ontologies are documented in the next two sections.

3.2.1 *Circular Exchange Ontology (CEO):*

This research first extends the Place Reference Theory (PRT) ontology, (Scheider et al., 2014) with the Circular Exchange Ontology (CEO) (http://ld-ce.com/vocab/CEO). CEO describes the elements necessary to undergo a material exchange between different actors of the CE.

The existing PRT ontology establishes in a generic manner (Figure 1): what is an `agent`, what `activity` does the agent perform, what are the `referents` of this activity (namely `resources`, `tools` and `products`). A `tool` is something that helps performing an activity, but is not consumed, contrary to a `resource`. CEO adopts the PRT semantics and thus benefits from the design logic embedded in the existing PRT ontology. As PRT is not created to address the CE context, extensions are made in CEO to include terms such as `waste`. Some of the extended classes and properties are shown below:

Activity sub-classes:
`Creation, PostUse` and `ReverseLogistics`
Referent sub-classes:
`Tool, Waste, Product` and `Resource`
Object Properties:
`input, output, waste/wasteOf`

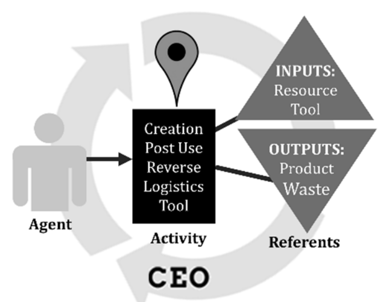

Figure 1. The CEO Ontology Main Elements. Agents perform activities, activities have an associated location and specific input and output referents. **Adapted from:** (Scheider et al., 2014)

Using the CEO semantics, a material passport can be translated to a series of activities undergone by an agent, with specific inputs and outputs. These semantics will serve to find and connect the output of one

[2] A standard used in the construction sector for classification of the buildings parts and installations (BIM Loket, n.d.).

industry to the input of another, thereby enabling material circulation.

3.2.2 *Circular Activities and Materials Ontology (CAMO):*

This research also creates a new ontology: CAMO (http://ld-ce.com/vocab/CAMO - Figure 2). It provides a CE classification system for the different materials, products and activities, which is based on EPEA, an institution recognized for its Cradle-to-Cradle certification. CAMO distinguishes for example i.e. biological and technological materials.

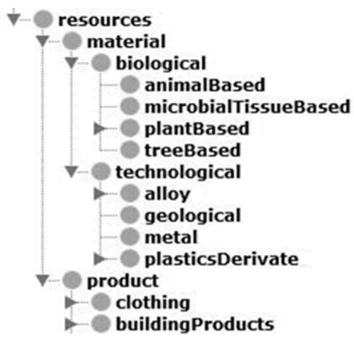

Figure 2. Hierarchical representation CAMO Ontology Elements. CE Classification shows biological and technological material categories.

The CAMO ontology is modular, first containing the generic Circular Economy classification scheme. This basis can then be extended by industry members when developing their own use cases with their field-specific classes and properties. It would be useful to extend this ontology in the direction of the existing efforts in the building products context. For example, the ontology could be directly linked to the Building Product ontology[3].

3.3 *Conversion to RDF*

This step comprises building the RDF resources from the demo Madaster passport. Not all data fields are used in this investigation (see Section 3.1).

The material passport data is triplified to RDF (converted to triples), with a Turtle serialization, thereby relying on CEO and CAMO. Listing 1 contains the prefixes for these vocabularies.

```
ce: <http://ld-ce.com/vocab/CEO#>
camo: <http://ld-ce.com/vocab/CAMO#>
prt:     <http://www.geographicknowledge.de/vo-
cab/PlaceReferenceTheory#>
rdf:  <http://www.w3.org/1999/02/22-rdf-syntax-
ns#>
rdfs: <http://www.w3.org/2000/01/rdf-schema#>
owl: <http://www.w3.org/2002/07/owl#>
xsd: <http://www.w3.org/2001/XMLSchema#>
```

Listing 1. RDF vocabulary prefixes

[3] https://github.com/w3c-lbd-cg/product

Listing 2 shows part of the triplified data for the ARC building; the full file can be found online (http://ld-ce.com/data).

```
inst:PabloVDBosch prt:agentOf inst:ownBuilding.
inst:TheARC a camo:building .
inst:TheARC camo:parcelNumber "1095"^^xsd:int .
inst:TheARC camo:composedOf inst:beamM8 .
inst:beamM8 a camo:beam .
inst:beamM8 camo:NLSfB "28"^^xsd:string .
inst:beamM8 camo:volume "0.15"^^xsd:string .
inst:beamM8 camo:composedOf camo:steel .
camo:steel camo:hasHardness "120"^^xsd:int .
inst:ownBuilding prt:tool inst:beamM8 .
inst:ownBuilding rdf:type prt:Activity .
```

Listing 2. ARC Building Material Passport in RDF

The Madaster passport provides general information, and more specificity is necessary to derive decisions about materials. The CAMO ontology allows to add such information (e.g. last 6 lines in Listing 2). These statements indicate that one of the beams is an `M8` type beam, composed of `steel` with hardness `120HB`. It is also stated that beamM8 functions as a `tool` for the activity `ownBuilding` as it is one of the elements that is also owned within the building.

3.4 *Querying via SPARQL*

This phase deals with the selection of the SPARQL triple store and endpoint. The preference is that the triple store is able to handle the GeoSPARQL query language to process geospatial queries. Two software platforms are considered and tested for their triple store and GeoSPARQL processing capabilities: Parliament and GraphDB. Queries are constructed from use cases mentioned in Section 4.1 to test the functioning of the newly created ontologies within the Circular Economy context. The queries are created in the editor interface of each triple store using the SPARQL/GeoSPARQL query language.

4 EVALUATION

4.1 *Use Case SPARQL Query Evaluation*

This section first provides sample questions for different use cases. These questions indicate how this proposition can be used in real-life situations where materials in the building context need to be circulated.

1. John (Krane Marine Engineering) is looking for buildings to be demolished that are 70km

away, to get waste steel beams with hardness greater than 100 HB for building ships?
2. Which buildings in the region of Gelderland have more than 150 m^2 in waste stone roof tiles which can be used as input by a construction company for the roof of a new building?
3. Which companies have collection activities that take back waste carpets from buildings to be processed into asphalt by an asphalt-processing-plant within a 50 km radius?

Note that even though construction is the primary domain, other disciplines such as the shipping industry can benefit as well. For the CE to be realized, all disciplines should be interacting amongst each other, hence some of the queries highlight this potential.

A SPARQL query is documented here for use case #1 (Listing 3); other queries can be found in http://ld-ce.com/query. This query serves as an initial proof that the ontologies created/extended in this research achieve the desired capabilities for material circulation.

The query showcases how two agents, ship company and building owner, are connected via the desired material, a steel beam which would act as a `resource` for making ships. Thus, the owner of this building and material parts can be matched with the ship constructor. This building will then function as a deposit or asset bank where steel parts will be obtained for ship construction. Through the FILTER clause towards the end of the query, it is specified that the beam should be made of steel and that its hardness should be greater than 100 HB. The query also handles the distance requirements, in this case less than 70km, which are fundamental in any logistics transaction in the supply chain field.

```
?shipCompany prt:agentOf ?shipBuildActivity.
?shipBuildActivity prt:resource camo:steel.

?buildOwner prt:agentOf ?ownBuildingActivity.
{{?ownBuildingActivity ceo:waste ?xyBeam}
union {?ownBuildingActivity prt:tool ?xyBeam}}

?xyBeam a camo:beam.
?xyBeam camo:composedOf camo:steel.
camo:steel camo:hasHardness ?hardness.
                [. . .]
FILTER (?dist < 70000 && ?hardness >100)
```

Listing 3. Selected query parts of use case #1

Note that there is a `union` clause between two triples: one specifying waste beams and the other specifying tool beams. Whenever a building is demolished the beams become `waste`. However, when the building is standing, the beams are `tools` enabling the building to stand. The query searches and contemplates for both cases.

4.2 *Wide Scale Evaluation*

The above query, RDF data and OWL ontologies show an initial proof for using Linked Data technology in the CE. This concept will have to be evaluated on a broader scale, thus requiring appropriate server infrastructures, business plans and workflows to not only gather and connect the data, but also to have it running as a wide decentralized self-sustainable system. Such systems can be implemented as part of the existing platforms such as Madaster. However, in a decentralized approach, all data would have to be made available by the individual users and building owners themselves. Using the CEO, CAMO and PRT ontologies, a common language is at least available to make sure that the data published by individual users ('the material passports') can be combined and reused appropriately. An example system architecture is proposed in Figure 3, allowing more wide-scale implementation of the proposed CE data for buildings. This diagram shows how individuals (building owners) as well as organizations (Madaster) should be able to publish information about their products (material passports). End-user applications can query this data through platforms that can send federated queries over the available repositories.

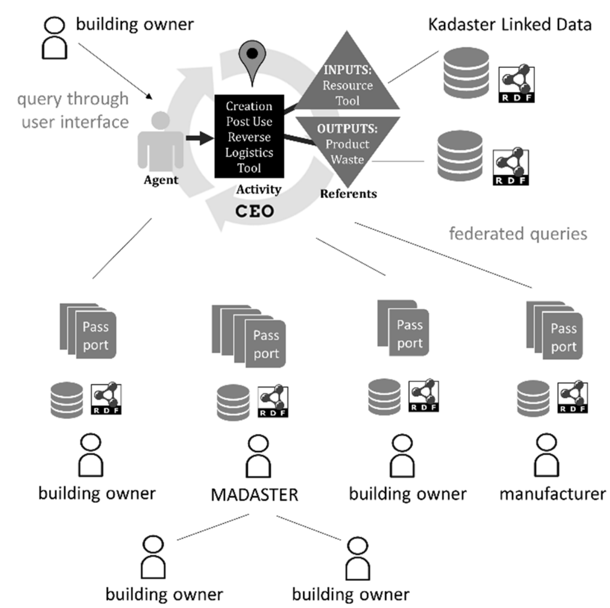

Figure 3. Wide Scale Infrastructure and Workflow. Architecture showing Linked Data repositories published by building owners and organizations following CEO/CAMO ontologies and querying by end user applications.

Moreover, an advantage of converting material passports to Linked Data, thereby using the CEO/CAMO vocabularies, is that they can further be linked to external data, including official cadastral data. The Dutch Kadaster publishes Linked Data such as the "Base Registrations for Addresses and Buildings" (BAG) dataset, which contains information about all buildings and addresses in The Netherlands. With the BAG data included, one can easily infer that a building has 'permission to be demolished'[4] or that the building is 'out of use'[5]. If the BAG data is considered in the proposed setup, these data fields will make sure that only these building types are selected, therefore indicating that all the materials in the passport can be considered as *waste* instead of a *tool*. This exemplifies the use of authoritative data services provided by official institutions to enhance and enrich internal datasets such as those of material passports.

Material passports can be enriched with other data as well, such as, product data sheets built following Linked Data standards. Later, relevant circular properties such as its characterization as a biological or technological material are added via the CAMO ontology, and then the exchange mechanics are added via CEO. Finally, the materials can be circulated in a circular marketplace that can make use of the openly available ontologies and data.

A systematic approach as displayed in Figure 3 could in the future enable to answer situations like: when should the municipality of Eindhoven build a new building, when 50% of the products need to come from local demolitions in an area of 50 kilometers? These interactions of heterogeneous datasets, complex queries and reasoning over large volumes of data are made possible by using Linked Data technologies and the proposed wide scale setup.

There are also some limitations to this wide scale set-up that need to be addressed. A first endeavor is the technical standardization accompanied by the policy and law changes that need to be agreed upon within the construction community before implementing this set-up. Privacy is also an issue that becomes relevant in a context where confidentiality of information is imperative. Similarly, controllability of the data takes precedence, as data needs to be reliable and trustworthy. In that regard, versioning and data duplication need to be correctly managed for proper system functioning. Finally, determining the cost to institutionalize this wide scale setup and the parties responsible for this investment is necessary.

5 DISCUSSION

The approach explored in this paper attempts to prove that with the *same* material passport data, when converted to a Linked Data ecosystem, people and products can now be found and connected using queries. Computer agents can derive answers out of the same information that is already collected by material passport developers. With the adequate semantics, material passports can serve to provide transparency and information to actors, so that material circulation is enabled.

This paper aims to also put some indication of what a wide-scale implementation and publication mechanism would be like, using a web technology approach. This wide-scale decentralized scenario contemplates not only the publication of data as Linked Data (RDF). Also, data has to be made discoverable, which requires that addresses of servers with this data must be discoverable too; perhaps via a community-driven website that publishes the different server addresses that host building information. In this way, developers of central applications such as marketplaces, can find the servers hosting relevant information and then enable these platforms to derive answers posed by users through (federated) queries.

For this context to work, it is proposed that manufacturers and platform developers such as Madaster, BAMB and others be on board as well. They could play the role of 'resellers', considering that they are now involved in DBFM constructions, and adopt the performance model to keep track of their materials throughout their different use cycles.

6 CONCLUSIONS

In this work, we have presented a number of proposals regarding the realization of the Circular Economy in our built environment.

- A common ontology is developed to align the product descriptions and increase material circulation in the construction sector within the CE.
- A procedure for publishing CE data in RDF from existing material passport data sources is proposed. This approach contemplates linking and enriching independently owned and maintained material passports.

These proposals have been evaluated using proof-of-concept implementations. A number of conclusions can be drawn from this work:

- Individual users as well as organizations and manufacturers should publish their material data as Linked Data, following the CEO/CAMO/PRT ontologies.
- The proposed Linked Data approach for CE proves advantageous over third-party data storage in silos separate from product data owners. This approach can be implemented as a layer on existing databases (e.g. D2RQ[6]), so that existing infrastructures, if they are there, do not need to be adapted.
- Wide-scale adoption necessitates: openly published data following Linked Data standards; a decentralized architecture where both

[4] `stat:SloopvergunningVerleend`

[5] `stat:PandBuitenGebruik`

[6] http://d2rq.org/

data and servers are discoverable and connected; end-user platforms that handle incoming queries and federate them across available material passport repositories in a desired area.

Future work contemplates not only validation of the created ontologies with construction companies from the Benelux area, but also product alignment and matching with the existing ontologies in the community. An agreement within the construction community must be reached in order for integration to occur. While there are technical means to do this integration, this is a matter that necessitates further community discussion and negotiation (European and international standards). Moreover, the limitations mentioned in Section 4.2 should also be part of this discussion. Devising a business model that allows for the formal implementation of this proposition should be addressed in future investigations. Finally, the purpose of making the CEO and CAMO ontologies available on the web is to let computer scientists assess the concepts for their applications. Further study is needed to evaluate such usage.

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