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TOWARDS CIRCULAR CITIES: DIRECTIONS FOR A MATERIAL PASSPORT ONTOLOGY

Ranjith K. Soman[1,2], Firehiwot Kedir[1,2], and Daniel M. Hall[1,2]
[1]Chair of Innovative and Industrial Construction, ETH Zürich, Switzerland
[2]Circular Future Cities, Future Cities Laboratory Global, Singapore-ETH Centre, Switzerland

Abstract

Material passports have been proposed to collect, store, and share material information to promote circularity in the construction sector. However, the current recommendations for material passports focus on material information at a building scale with little attention to its implications on a city scale. To address this limitation, this paper provides directions for developing a material passport ontology that could be used to collect, store, share, and retrieve data at multiple scales of abstraction. It describes the requirements for a material passport ontology and provides recommendations for integrating existing ontologies. This paper is relevant to researchers developing information management platforms to enable a circular economy

Introduction

The construction sector accounts for 39% of CO2 emissions (Dean, B., Dulac, J., Petrichenko, K., and Graham, 2016). Prior research has identified that 82–87% of the total greenhouse gas emissions are from building materials' embodied greenhouse gas emissions (Yan *et al.*, 2010). Although the built infrastructure has increased operational energy consumption, the material consumption is estimated to grow from 40 gigatons in 2010 to 90 gigatons by 2050 (Oberle *et al.*, 2019). Planet earth cannot provide for this increased requirement in the construction sector's current linear-produce-consume-dispose model(IRP, 2018). To address this challenge, there is a strong direction from policy and an emerging research trajectory to shift to a circular economy where used materials become valuable resources for a new production cycle (Adams *et al.*, 2017; Leising, Quist and Bocken, 2018; Heinrich and Lang, 2019; Hossain *et al.*, 2020; Kovacic, Honic and Sreckovic, 2020).

Most of the circular economy research in the built environment is about recycled/reusable materials (Gálvez-Martos *et al.*, 2018), circular transition (Pomponi and Moncaster, 2017), tools and assessment to support circular buildings (Giorgi, Lavagna and Campioli, 2019; Heisel and Rau-Oberhuber, 2020), product and building design(Akinade *et al.*, 2019), and stock and flow analyses of resources and materials (Krausmann *et al.*, 2017). Although less researched, collaborative platform for material Information management has been identified as one of the critical components of enabling a circular economy in the built environment (Charef and Lu, 2021).

Material passports are a crucial component of information management in the circular economy context (Munaro and Tavares, 2021). It has been used to improve recycling potential (Honic, Kovacic and Rechberger, 2019), optimize building design (Kovacic, Honic and Rechberger, 2019), and enhance material recovery (Kovacic, Honic and Sreckovic, 2020). Although there has been an emerging research trajectory on material passports, most studies have focused on material passports at a building scale. There is little attention towards understanding the implication of material passports at a city scale.

This paper addresses this shortcoming by proposing the directions for developing a material passport ontology to enable a circular economy at a city level. The rest of the paper is divided into five sections. The following section introduces the circular future cities and describes the need for material passports at the city level. This section also explains the state-of-the-art in material passports. The following section explains the research method followed in this paper. The next section describes the directions and recommendations for developing a material passport ontology from a city perspective. This is followed by a section on the limitation of the proposed directions. Finally, the conclusions of this work are presented.

Background

Circular future cities

There is a great drive towards developing systemic innovations supporting circular economies in construction. There are several projects initiated to improve circularity at a city level and to improve the reuse of materials (*Circular Future Cities*, 2020; *Digital Twins for Circularity – Digital Twin Cities Centre*, 2021). Integrated frameworks and tools are developed based on advanced digital technology to inform circular buildings' design and deploy more effective resource solutions.

These frameworks include investigating the digital information from various scales and abstractions to support the circular economy. For example, to store the material stock information of a city, the material information must be viewed from a city scale with higher-level abstraction. Whereas a designer substituting materials with mined material needs to understand detailed material information to aid his decision process. Therefore, the material information must be represented at different levels of abstraction and scale.

Material passports

Material passports are information management records of materials used to document and track circularity potential provide accurate information for reuse and recovery(Debacker *et al.*, 2016). Prior studies have identified that material passports can enable circular economy by providing circularity potential, design guidance, creating a market differential for suppliers, providing information clarity and authentication, increasing traceability, understanding gain/loss ratio, guiding users on installation, maintenance, and disassembly, create a secondary materials market, increase supply security and reduce environmental footprint (Hansen, Braungart and Mulhall, 2013; *Building a Circular Future*, 2016; *Onze diensten - Talking Heads*, no date; Luscuere, 2017; Heinrich and Lang, 2019).

As stated, most of the work on material passports in the construction sector focused on developing material passports at a building level (Honic *et al.*, 2019; Heisel and Rau-Oberhuber, 2020; Kedir, Bucher, and Hall, 2021). However, from a circular perspective, the material passport should have additional information to support city-level activities such as urban planning (Herthogs *et al.*, 2012; Li, Quan, and Yang, 2016). This requires integrating information at city scales from geographical information systems and building scale from building information models. Although there are existing frameworks to ingrate GIS and BIM (Zhu *et al.*, 2018; Wang, Pan, and Luo, 2019), to the extent of our knowledge, there are no existing frameworks that integrate city-level information all the way to material level information to enable circular future cities.

Point of departure

Integrating material passport information for circular cities requires integrating data from heterogeneous sources at different levels of abstraction. Linked-data technologies and ontologies have been used in such cases to integrate data from multiple domains and scales (Pauwels, Zhang, and Lee, 2017; Soman, Molina-Solana, and Whyte, 2020) and modelling constraint relationships (Soman, 2019). Further linked-data technologies have also been used in the city scale for decision-making during city planning (Chadzynski *et al.*, 2021; Richthofen *et al.*, 2021). Also, ontologies have been used to develop material passports to enable circular information flow in Industrialized construction (Kedir, Bucher, and Hall, 2021).

Extending these studies, this paper aims to provide recommendations for developing a material passport ontology to enable a circular economy at a city scale.

Research Method

The main goal for this paper is to define the directions towards a material passport ontology that could enable circular future cities. There are many methodologies to develop ontologies as proposed by Grüninger and Fox (1995), Fernández-López, Gómez-Pérez and Juristo (1997), and Uschold and Gruninger (1996). Zheng, Törmä, and Seppänen (2021) have adapted and combined the concepts in these methods and established a hybrid ontology development method for the construction sector following the framework for ontology development by Zhou *et al.* (2016). It contains seven stages which are as follows.

1. Identify the scope, purpose, and intended users of the ontology.
2. Specify the requirement of the ontology.
3. Review domain knowledge, existing ontologies, data models, and other sources.
4. Enumerate higher-level classes and build up properties.
5. Construct ontology.
6. Integrate existing ontology.
7. Ontology evaluation.

Since this paper aims to define the directions for a new ontology, it considers the first three steps from the hybrid ontology development method, as shown in Figure 1.

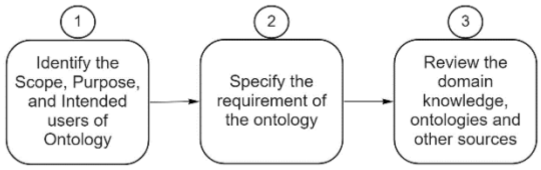

Figure 1: Research method

Towards Material Passport Ontology

This section details the different aspects of developing an ontology to enable a circular economy at a city scale.

Purpose, scope and end-users

The purpose of the material passport ontology is to conceptualize material information from different perspectives of city planning, design for reuse, operation and maintenance, and disassembly to promote the reuse of materials to enable a circular economy at a city scale.

The scope of the ontology is to represent the conceptualization of building stock information and the material information at the city scale while representing the material properties such as physical and functional properties while maintaining the provenance. A non-exhaustive list of intended users of this ontology is shown in Table 1. The users would have different levels of access and operations with some users who are the consumers of information, whereas others would be involved in creating and updating the information.

Table 1:End-users of the ontology

Abstraction	End users
City	Regulators, Planners, Operations
Building	End users, operations team, architects, engineers, contractors, demolitions team
Assembly/Module	Designer, Manufacturer, Assemblers, Supply chain
Component	Designers, Manufacturers, Supply chain
Material	Mining firm, Processing firm, Supply chain

Requirement

Based on the ontology purpose, Scope, and end-users, the ontology's functional requirements are identified using competency questions (CQs) (Grüninger, and Fox, 1995). CQs are a set of requirements represented as questions in natural language that the ontology should handle. These questions should be used to define ontology's main concepts and the concepts' modalities, attributes, relations, and axiom. The competency questions for the proposed ontology are listed in Table 2.

Table 2: Competency questions

End user	Competency Questions
Architect	Q1-When will double glazed windows with PP dimensions be available in *XX* city?
Planner	Q2 When buildings in sector YY are demolished, what different materials would be available for reuse and in how much quantity?
Engineer	Q3 Where can one obtain QQ qty of structural steel beams of load capacity RR next year?

The competency questions described in the table require the information from multiple models to be integrated as presented. For example, breaking down the competency question 1, when will *double glazed windows* with *PP dimensions* be available in XX city? Here, the information is first queried in the abstraction '*city*' for a component '*glazed windows*. The abstractions are shown in Figure 2. The query should traverse through the abstraction 'building' to get that. Further, the property of the '*glazed window*' dimension is queried from the abstraction component. Finally, suppose there is a component available. In that case, the query should fetch the end of life for the '*building*' and return the data.

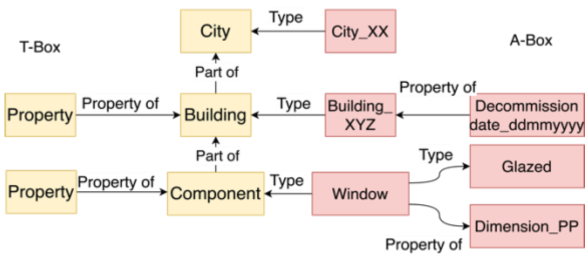

Figure 2: Query traversal for competency question Q1

Similarly, breaking down question 2, When *buildings* in *sector YY* are demolished, what *different materials* would be available for reuse and in how much *quantity?* Again, the query traversal starts from a region *YY* in the city, all the way to the abstraction *material.* Then the amount of the material is computed from the abstraction *building and component.*

The competency questions described here require the information from multiple models to be integrated as presented. The several aspects that a material passport ontology needs to handle are listed below.

1. **Topology**: The ontology should represent a city as a part of a topology that can be traversed. The material should be part of a component, which is a part of a module or assembly installed in a building, as shown in Figure 3.
2. **Actors**: The ontology should handle different actors and their functions in terms of data input and data use. The actors may be associated with the materials directly or through other abstractions, as stated in Table 1.
3. **Geometry**: The ontology should store the details about the geometry of how the material was molded. This is necessary to compute the quantity of the available material.
4. **Material properties**: The ontology should have the capability to store different properties of the materials to be queried for reuse. This aspect of

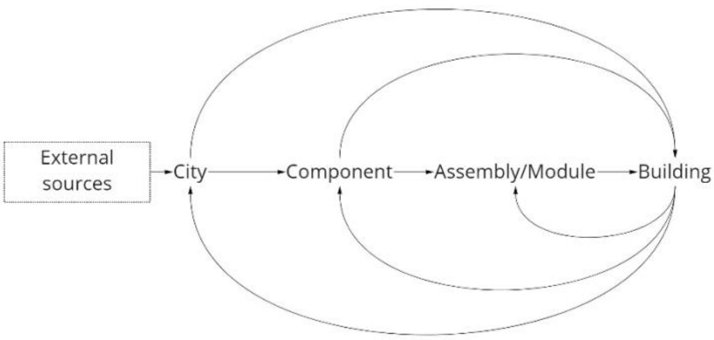

Figure 3: Construction material flow in a circular city

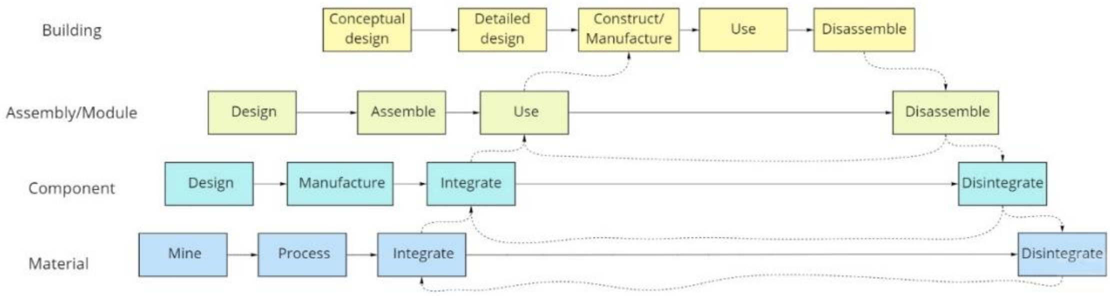

Figure 4: Interdependent lifecycles of different abstractions of material use

the ontology stores the functional properties of each topological abstraction at each stage of the lifecycle.

5. **Life cycle**: The ontology should store the information regarding the material within the different stages of its evolution at different abstraction levels, as shown in Figure 4
6. **Property evolution**: As the properties of the materials evolve over time as they are passed through different lifecycles, the ontology should store the evolution information.
7. **Semantics for circular exchange**: The ontology should support semantics for circular exchange such as creation, post-use, and reverse logistics.

In addition to handling the above, the ontology and the triple store should handle both advanced SPARQL and GeoSPARQL queries. The ontology should handle the different stages of the materials as it gets embedded into components, assemblies, and buildings, as shown in Figure 3. Further, it should also handle interdependent lifecycles of different abstractions, manage the input from different stakeholders engaged in each lifecycle stage, and provide their queries.

Reusing existing ontologies

Based on the requirements, the existing ontologies in the built environment were reviewed to investigate whether they can handle the complex queries. Since the ontology needs cover broad contents and requirements, a modular approach must be adopted to design the ontology. An ontology module may be defined as "a reusable component of a larger or more complex ontology, which is self-contained but bears a definite relationship to other ontology modules" (d'Aquin *et al.*, 2007).

Since most of the knowledge required for circular future cities is available in different existing ontologies, different ontologies based on similar upper-level ontologies can be combined to satisfy the requirements. They need to be linked together so that the complex query traversal can happen to fetch and infer information. Different ontologies required for circular future cities are identified in this study (See Table 3). Proposed ontology integration is shown in Figure 5.

Topology: Three ontologies OntoCityGML (Chadzynski *et al.*, 2021), Building topology ontology (BOT) (Rasmussen *et al.*, 2017) and Building product ontology (BPO) (Wagner *et al.*, 2022), can be used to enable topology traversal of queries. While OntoCityGML handles the city-level traversal, BOT handles the traversal inside a building. Further, product level traversal is dealt with through BPO.

Actors: Digital Construction Agents ontology (Zheng, Törmä and Seppänen, 2021) can be used to formalize the representation of the stakeholders over the construction lifecycle, to support data sharing of the social, organizational, and circular exchange relations.

Geometry: Ontology for Managing Geometry (OMG) (Wagner *et al.*, 2019) can be used to associate the geometry of the material related to a building. Further, it is possible to define the relationship and dependencies between multiple geometry representations. This aspect makes it convenient to do quantity take-off from the building information data.

Material properties: Digital Construction Information (DIC)-Materials ontology (Zheng, Törmä and Seppänen, 2021) can be used to store relationships between building elements, constructions' details, materials, and their properties. It can be used to store details related to materials, properties, values, and units.

Lifecycle: Digital Construction Information (DIC) - lifecycle ontology (Karlapudi, Valluru and Menzel, 2021) can be used to represent the life cycle stages.

Property evolution: Ontology for Property Management (OPM) (Rasmussen *et al.*, 2018) can be used to account for property changes in time or to attribute a value association with metadata such as provenance, reliability, and origin data.

Semantics for circular exchange: Circular Exchange Ontology (CEO) (Sauter, Lemmens, and Pauwels, 2018) can be used to describe the activities that enable the circulation of materials/products and information across different organizations and stakeholders to realize a circular economy.

Table 3:Existing ontologies to support circular future cities requirements

Requirement	Ontology name	Universal Resource Identifier (URI)
Topology	OntoCityGML	https://github.com/cambridge-cares/TheWorldAvatar/tree/develop/JPS_Ontology/ontology/ontocitygml/ontocitygml.owl
	Building Topology Ontology (BOT)	http://www.w3id.org/bot/bot.ttl
	Building Product Ontology (BPO)	https://w3id.org/bpo
Actors	Digital Construction Agents (DIC)	https://w3id.org/digitalconstruction/0.5/Agents
Geometry	Ontology for Managing Geometry (OMG)	http://w3id.org/omg
Material property	Digital Construction Information Materials (DICM)	https://w3id.org/digitalconstruction/0.5/Materials
Lifecycle	Digital Construction Information Lifecycle (DICL)	https://w3id.org/digitalconstruction/0.5/Lifecycle
Property evolution	Ontology for Property Management (OPM)	https://w3c-lbd-cg.github.io/opm/
Semantics for circular exchange	Circular Exchange Ontology (CEO)	http://ld-ce.com/vocab/CEO

All the ontologies described above are interoperable and based on similar upper-level ontologies and hence are interoperable. This enables querying across these ontologies to retrieve information for a circular economy.

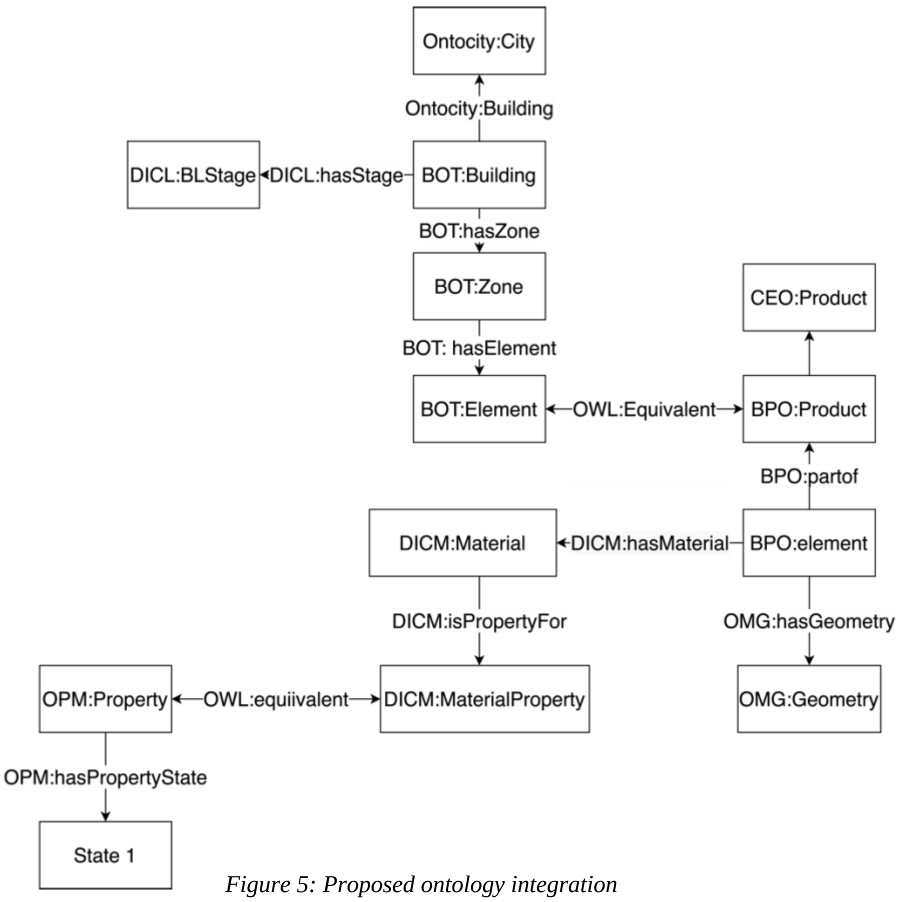

Figure 5: Proposed ontology integration

Next steps

The future work in developing this ontology is to construct the ontology. This includes connecting the equivalent classes between these ontologies and aligning them using ontology editors such as Protégé (Musen, 2015). Once built, the ontology must be evaluated for consistency using a description logic reasoner. Then it should be assessed for different criteria, such as clarity and extendibility. Then, the data assertions should be associated with the ontology, and queries based on competency questions must be run to investigate whether the query can traverse through multiple abstractions and return the desired results. As the last step, task-based evaluation should be carried out to see if the ontology can handle the integration of information across various abstraction and domains to enable circular future cities.

Limitations

This paper discussed the requirements for a material passport ontology to enable a circular economy at a city scale. There are two aspects of a material passport ontology that this paper has not mentioned. First, this paper didn't consider how material stocks could be traded in a decentralized marketplace. Although the ontology enables information storage in decentralized databases, it didn't consider the commercial information to allow decentralized marketplaces. Second, this paper didn't consider the flow parameters associated with the circular economy. However, that may be associated as a material property in the future extensions of the ontology as it is designed to be modular.

Conclusions

The main contribution of this paper is in defining the directions to develop a material passport ontology to enable a circular economy for construction materials at a city scale. It identifies the requirements for a material passport to represent the conceptualization of building stock information and the material information at the city scale. Further, the recommendation to integrate existing ontologies such as OntoCityGML, BOT, BPO, OPM, CEO, DIC, and OMG to develop a material passport has been provided in this paper. The proposed recommendations can be used to create a material passport ontology that stores material properties such as physical and functional properties while maintaining provenance. The stored information can be queried at different scales of abstraction to enable a circular economy at a city scale.

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