A PROPOSED MATERIAL PASSPORT ONTOLOGY TO ENABLE CIRCULARITY FOR INDUSTRIALIZED CONSTRUCTION

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ABSTRACT

There is a need to collect, store, and share product data to enable circularity in industrialized construction supply chains. To do this, the concept of a Material Passport (MP) has been proposed, but exactly how MPs should be created and managed is less understood, especially in consideration of industrialized construction product platforms. This paper proposes a knowledge and process representation framework called the Material Passport Ontology (MPO). The MPO outlines key components of MPs and their interrelationships. Finally, the paper discusses several implementation challenges and possibilities.

INTRODUCTION

As construction product complexity increases, it becomes more difficult to reuse and recycle materials. Products contain many types of materials that are usually joined to each other with the intention of permanent attachment (Heinrich and Lang 2019). The construction industry is one of the most energy and material-intensive industries in the world. Current construction methods and processes need to be shifted to more resource-conscious strategies (Kedir and Hall 2021).

The emerging economic model of Circular Economy (CE) aims to create circular products that maintain their highest value for as long as possible. Circular products also need to be safe, flexible, and durable (Heinrich and Lang 2019). This requires the creation, maintenance, and sharing of vast products' property data. Moreover, it requires close collaboration and common understanding between stakeholders involved in the value chain (Sauter and Witjes 2018; Luscuere 2017; Heesbeen and Prieto 2020).

One opportunity for the application of CE is industrialized construction (IC). IC companies often create product platforms for longitudinal continuity (Hall, Whyte, and Lessing 2020). These platforms promote long-term relations and an integrated supply chain (Lessing 2006). Therefore, they are well suited for the creation of circular products and management of circular information flows.

IC uses many manufacturing industry concepts, including standardization of elements, high-quality achievement through a factory-controlled environment, and enhanced predictability of time and cost of construction activities. These unique characteristics could allow IC to increase resource efficiency that leads to diminished environmental impacts. However, the application of CE in IC today is limited. The implementation of circular IC products is still not widely spread. One barrier is the lack of structure in capturing and sharing information across products' value chain.

Capturing and analyzing information on IC products, their processes, and stakeholders is crucial to understand and enhance the synergy between IC and CE. A proposed solution for the gap is the generation of so-called building/product/material passports (MPs). Although a few attempts exist to implement MP for construction products, there is still an insufficient understanding of MPs. Furthermore, a MP approach has not yet been applied to IC products. It is questionable if existing MP approaches provide description of an entire industrialized supply chain, including consideration of manufacturing, transportation, and assembly.

When complexities of products and stakeholders increase, it is essential to conceptualize and create a common vocabulary in which shared knowledge can be represented (Gruber, 1993; Sun *et al.*, 2012). The construction industry is moving away from a model-centric approach to a more distributed semantic approach. Semantic web technologies and linked data allow for efficient integration and accessibility of different domain data (Pauwels, Zhang, and Lee 2017). Moreover, a vital part of linked data is ontologies that use logic-based language – Web Ontology Language (OWL) (Pauwels and Terkaj 2016). Ontologies can represent knowledge, integrate information, and reason (Sun et al. 2012; Pandit and Zhu 2007). Although there have been several ongoing developments of ontologies for building products, there are few primary intentions of ontologies for CE, MP, and IC. To that end, the paper identifies key information requirements of MP and proposes a preliminary Material Passport Ontology (MPO).

DEPARTURE

Material passport as a tool for a circular economy

Material passports (MP) are a key tool at the center of the conversation of CE. Eichstädt (1982) explains the need to record product information such as product's location and state of use phase. Eichstädt explains having building passports aids in documenting relevant information. Turbull (1993) introduced a product control matrix as a means to update each stakeholder on product development. Other industries, such as the shipping industry, have adopted so-called resource passports to monitor the use of products, including during the end-of-life (EOL) phase (Brito, van der Lann, and Irion 2007). MPs can act as facilitators for quantitative and qualitative documentation of CE-related data of materials, products, and buildings (Honic et al. 2019a; Luscuere and Mulhall 2018). Specific benefits of MP include the ability to:

- Keep or increase the value of materials, products, components over time (L. M. Luscuere 2017).
- Facilitate reversed logistics and reclaim of products, materials, components (BAMB 2017).
- Link and make relevant data available for impact assessments(M. Honic, Kovacic, and Rechberger 2019).

The value of MP increases when it is created and updated during all of the buildings' lifecycle phases, leading to a dynamic tool instead of a static one. However, these benefits are not fully harnessed in the current construction value chain. One of the main issues is the lack of a framework to collect, store, and distribute MPs. Nevertheless, several institutions have defined MP and identified what constitutes an MP. Three examples are described in greater detail below.

The first example comes from 3XN architects that provide guidelines to formulate MP. Figure 1 shows an illustration by 3XN architects explaining that MP should be collected during all building lifecycle phases. The collected data should be merged into one database that allows accessibility and identification of products and their characteristic (Figure 2) (3XN Architects and GXN Innovation 2019).

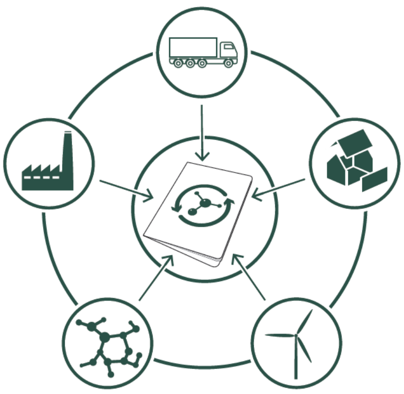

Figure 1: Material Passport data collection along building lifecycles (3XN Architects and GXN Innovation 2019)

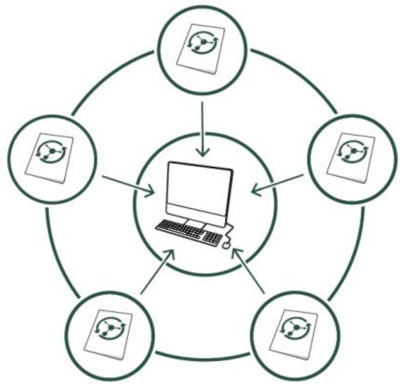

Figure 2: Database for Material Passports (3XN Architects and GXN Innovation 2019)

The second example is from the European project Buildings as Material Bank (BAMB). *BAMB* lays out a MP-implementation strategy. It *describes* relevant MP data categories such as physical, chemical, and production data collected in different composition levels *(*i.e., system, product, component, ingredients*)*. The project also discusses the importance of identifying and assigning stakeholders in the formulation of MP (BAMB 2017). The four-building composition levels of BAMB are:

- *System* refers to a product in its complex form. This includes a product that constitutes multiple components and parts from different manufacturers. Examples include a wall system that contains a range of other materials and mechanical, electrical, and plumbing (MEP) systems.
- *Product* represents an item that is manufactured and sold. A product generally constitutes a commercial name, producer ID, or similar designation. Examples include walls, floor tiles, gypsum wall panels, and wall paint.
- *Components* are the parts that make a product. It also includes raw materials such as wood, earth, clay, stone are at this level.
- *Ingredients (materials)* include the chemicals that make up a product.

The third example comes from Madaster. Madaster provides a platform to create MP using different building layers. Using the building layers originally outlined by (Brand 1995) (Figure 3), the Madaster circularity indicator calculates 1) the amount of virgin, recycled, reused, and renewable materials used in a given building. 2) compares the lifespan of materials and products used in a project with the average lifetimes of similar ones. 3) evaluates the intended downstream destination of materials and products.

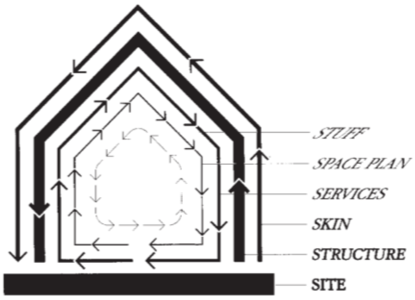

Figure 3: Building layers (Brand 1995)

Industrialized construction and potential for MP

The opportunities of IC to provide better-performing buildings is documented by several scholars (Lessing and Brege 2018; Kedir and Hall, 2021). Industrialized building companies are known for their product approach, which contrasts the existing construction industry's project approach. The product platform includes both technical and process platforms. Product platforms can take different forms, but the most common approaches are two-dimensional panelization, three-dimensional volumetric modules, and the kit-of-parts approach (Lessing and Brege 2018). Compared to conventional buildings, volumetric modular buildings offer great assembly and disassembly attributes (Rausch et al. 2020). The product architecture in IC might help to better understand IC products and their relationship with CE.

Platforms for Industrialized Construction

The standardized product and process platforms are the foundations of IC products and are responsible for decreasing conventional construction complexities (Viana et al. 2017; Lennartsson and Elgh 2018; Larsson et al., 2014). Product modeling experts and domain knowledge experts on the product and its lifecycle processes develop IC product platforms (Malmgren, Jensen, and Olofsson 2011). The *technical platform* (TP) identifies product families and house models to show product structures (Lennartsson and Elgh 2018). The TP also decomposes building parts, which help with mass customization. The research of Lennartsson and Elgh, 2018 shows an example of a TP of an IC company (Figure 4).

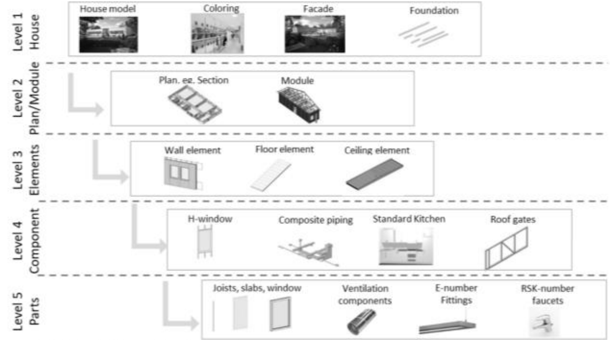

Figure 4: Building Levels in IC technical platform (Lennartsson and Elgh 2018).

Parallel to the TP, the process platform (PP) is also planned in detail. A standardized and controlled process platform allows monitoring and gathering of data in all life cycle phases (mostly from design to assembly). The PP also gives clear instructions to stakeholders (Andersson and Lessing 2017).

RESEARCH APPROACH

This work applies the concept of knowledge representation – and specifically the use of an ontology – to propose a knowledge representation framework that can give stakeholders a common foundation for collecting MP information. The methodological approach taken in this research consists of three main tasks adapted from the NeOn Methodology, which guides the most common scenarios during the development of ontologies (Suárez-Figueroa, Gómez-Pérez, and Fernández-López 2012).

Determine ontology's domain and scope.

As discussed above, a comprehensive framework to gather MP-related data in IC is not available. For that reason, this research begins with identification of MP data requirements from existing literature. From this review, four key requirements are identified:

1) The MP should describe buildings using functional layers.
2) MP-relevant properties should be collected on all functional layers.
3) The MP should assoicate properties and functional layers with building lifecycle phases (LCP).
4) The MP should identify the actors that generate and consume MP data across the LCP.

With the four requirements, we use existing literature on MP and IC products to:

Review, Reuse and Merge Ontological Resources

Building from this literature, we formulate our initial *MP-centered ontology classes and relationships.* For our specific ontology development, we focused on the reuse and merging of ontological resources (scenario 5) (Suárez-Figueroa, Gómez-Pérez, and Fernández-López 2012). In other words, our approach attempts to review, reuse, and merge existing ontological resources that are in the same or similar domains.

Particular focus is given to several recent works on ontology-based research for construction products and their links to CE. First, the Building Topology Ontology (BOT) is a minimal expression of building components and their relationship. The seven classes identified by the BOT ontology include site, building, storey, space, interface, zone, and element (Figure 5):

- Site: an area containing one more building.
- Building: an independent unit of the built environment.
- Storey: distinguishes levels of a building.
- Space: a limited three-dimensional extent defined physically or notionally.

- Interface: area where two buildings or two zones or a building element and zone meet.
- Zone: are areas with spatial 3D volumes and include buildings, storey, and spaces.
- Elements: these are parts of modules such as walls, doors, and heaters.

The relationships between classes are described using object properties such as bot:hasStorey or bot:adjacentZone, and bot:containsElement. BOT is well suited for MP requirement 1 and can describe building using functional layers, but does not encompass the additional requirements for an MP.

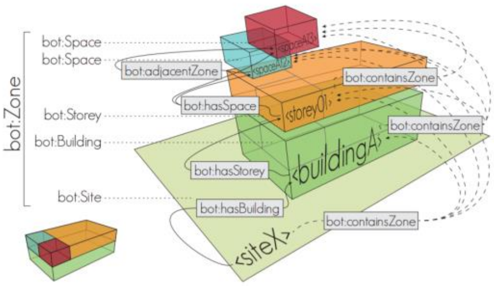

Figure 5: The BOT ontology (Rasmussen et al. 2017)

Another recent ontology, the building product ontology (BPO), describes product structures and properties (MP requirements 1 and 2). BPO is not focused on mass-produced products that have little design variance. Building components can be dissected into bpo:Element and bpo:Assembly. Manufacturers that are willing to dissect their product description can use bpo:Assembly, whereas others can use bpo:Element. Furthermore, the BPO does not specify classes for materials' level descriptions of products (Wagner and Rüppel 2019).

Additional ontologies reviewed include the Digital Construction Building Material Ontology (DICBM), which defines building layers using dicbm:LayerSet and associates them with their properties (Valluru et al. 2020) (MP requirements 1 and 2). The ontology for property management (OPM) offers the possibility to keep track of property changes in building elements. Using opm:PropertyState, property value and metadata of a specific property are described. OPM reuses provenance ontology (PROV-O) to describe the property metadata with prov:generatedAtTime referring to time of data entry and prov:wasAttributedTo referring to the agent(actor) (Rasmussen et al. 2018)(MP requirements 2 and 4).

The research of Sauter et al. (2018) through circular exchange ontology (CEO) and circular materials and activities ontology (CAMO) show three key components for circular data flow in the construction industry. The three main classes in CEO/CAMO are 1) *agent* refereeing to actors in the industry. 2) *Activity* that indicates the lifecycle phases in construction, including creation, use, and post-use. 3) *Referents* refer to requirements to execute the activity, such as resources and tools (MP requirements 2, 3, and 4). However, the research is not very specific to construction products' life cycle phases, actors, functional levels of a building, and their properties. Building circularity assessment ontology (BCAO) is another example of MP for CE. BCAO covers product descriptions, properties, and actors. The BCAO is mainly focused on assessing the circularity of products for early design optimization. (Al Naber and Morkunaite 2021).

Develop the Material Passport Ontology

Through merging domain-related existing ontologies, we propose a new Material Passport Ontology (MPO) for MPs in IC. The MPO is described using class hierarchy and their properties prototyped in Protégé. We derived specific concepts from the existing BOT, OPM, CEO/CAMO, DICBM and BCAO ontologies. The basic topological concepts of a building defined in the BOT are partially adapted as well as reused in the application for this paper. Considering the product breakdown of a MP, BOT:Building and BOT:Storey were reused for the high-level breakdown. MPO:Module, MPO:Component and MPO:Product are native functional classes of the ontology. Finally, DICBM:Material is mapping corresponding material used in a MP as they are a core component Furthermore, the assignment of properties to products or components applied in OPM is reused during application. By the refinement of the CEO/CAMO ontology, specific activity classes were defined. They are named as lifecycle phases (LCP) and the subclasses are also extended and refined to IC LCP. Similarly, the class agent/actor is reused and the subclasses were expanded to constitute IC-specific actors (Figure 6). From BCAO, some circularity assessment classes and object properties were adopted.

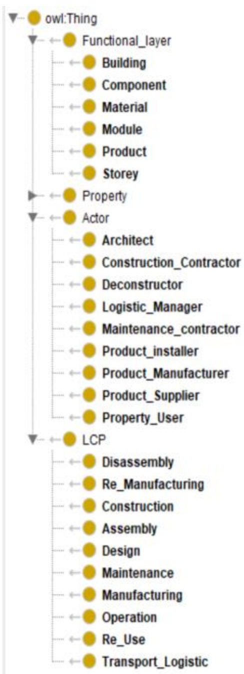

Figure 6: MPO classes

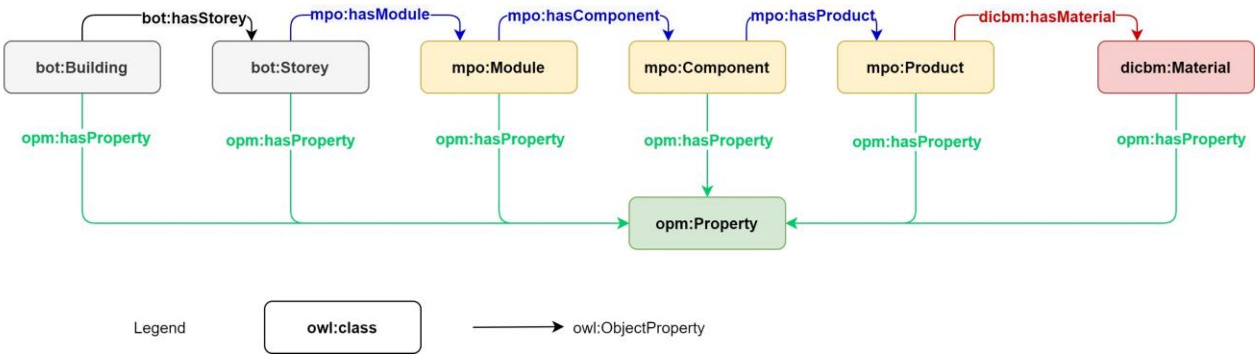

Figure 7: MPO – Functional levels and object properties

When developing an ontology, the description of properties consists of two different concepts. On the one hand, object properties are used to create a connection between objects of different classes and are used to map constraints as well as aggregation of information on the objects (Cao and Hall 2020). OPM:hasProperty was reused to connect functional and property classes. Secondly, data properties are used to set specific values for class objects. From OPM, prov:generatedAtTime is reused to indicate a timestamp of data entry and prov:wasAttributedTo is adapted to mpo:filledby to indicate stakeholder responsible for the data entry (Figure 8). Due to space limitations, the full list of classes, object properties, and data properties is not presented.

RESULTS

One of the challenges in creating an MP is to make it formally consistent and easy to use. This requires a detailed description of the product composition breakdown and their inherent information to understand the stakeholders' processes. To show the usage of the MPO, we demonstrate in the following section the conceptual use by instantiating class objects and their aggregation of information by object and data properties.

In the first step, modules, their associated products, and the underlying materials are instantiated and connected by the object properties such as *mpo:hasProduct and dicbm:hasMaterial*. All these instances are informed by the objectProperty hasProperty (Figure7).

Conceptually, having opm:hasProperty means that individual information is inserted at all functional levels such as modules or product. These properties are used in this paper as data requirements to create an MP. They include physical information, such as weight and porosity as well as unique identifies such as GTIN/ EAN numbers of products.

Next, objects from the actors' class are instantiated. As different stakeholders involved in a specific product or project input or consume MP related data, they should be mapped as well. This structure allows stakeholders to identify different data inputs from relevant actors. Furthermore, the MPO defines and links building lifecycle phases. Building lifecycle phases are integrated to accommodate for any changes that occur in the property sets. As shown in Figure 8, this structure distinguishes functional classes' properties in different building lifecycle phases.

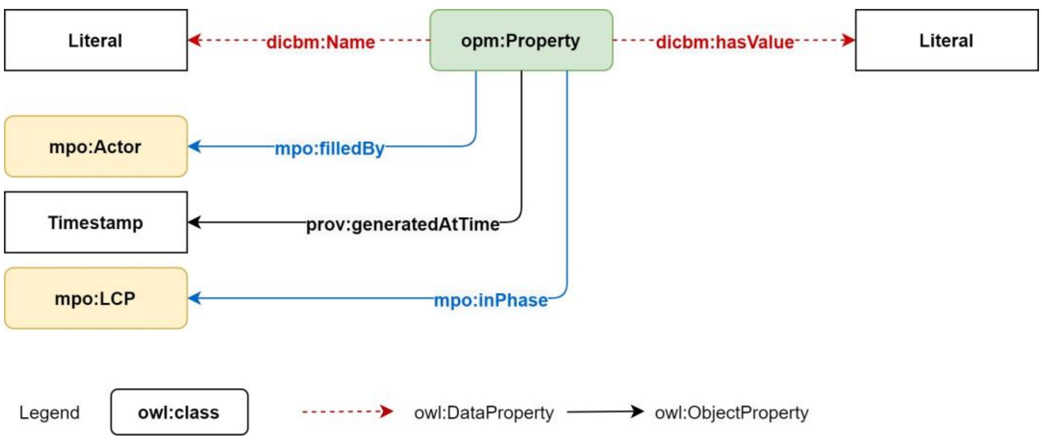

Figure 8: MPO – Actors, property data, and building lifecycle phases

In summary, the MPO shows a structure to create a working MP for IC. Figure 9 outlines the different elements in the MPO. The framework connects different functional classes, actors, data properties, and building lifecycle phases. Each functional class identified are associated with different data properties. These properties are filled-in by different actors. The lifecycle classes direct actors to fill in data properties that might be different across lifecycle phases. Actors can also give temporal data, such as when that data entry was made. The data entered in the ontology is designed to accommodate different data types.

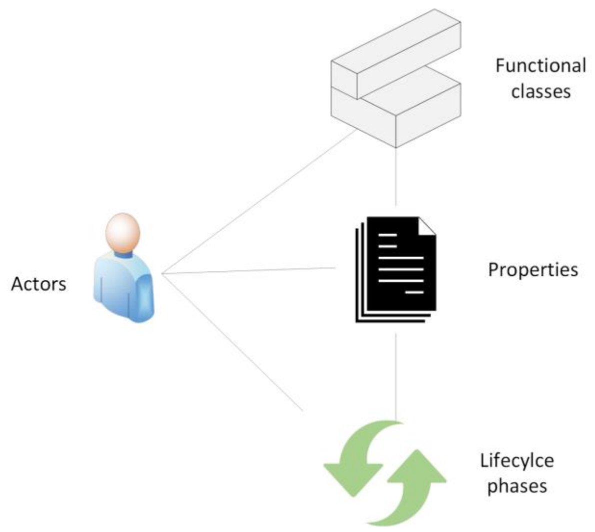

Figure 9: Material Passport Structure

PRELIMINARY VALIDATION

The full refinement and validation of the ontology will be conducted in future research**.** However, a preliminary validation is done by using the five main characteristics an MP should have as listed by (3XN Architects and GXN Innovation 2019) (Table 1).

The current structure of the MPO allows 1) for all relevant data to be collected across all lifecycle phases and functional classes. It is also accessible to relevant actors. As an example, a product manufacturer can provide disassembly instructions at a product or module level. 2) with the data property classes, actors can also include any unique identification elements such as GTIN or EAN numbers to trace specific objects. 3) The MPO structure is designed in a way that actors can enter property data across different building lifecycle phases. For example, an assembly instruction can be registered in the assembly class, and a maintenance guideline can be entered in the disassembly class. The MPO also allows for upkeep of data. 4) the MPO property class can be expanded to include any relevant data such as safety. 5) using the actor class, the MPO facilitates the assignment of responsibilities and ownership.

Table 1: Five principles to follow when creating Material Passport (3XN Architects and GXN Innovation 2019)

1 Documentation.	All relevant information is documented in all building phases
	The MP is all-inclusive from Material level to building level.
	The MP is accessible to relevant actors during the whole process.
2 Identification.	Include physical identification of elements.
	Materials should have unique labels.
	A database containing all relevant information should exist.
3 Maintenance.	Maintenance and restorations guidelines of physical assets should be incorporated.
	The MP has to be updated with any physical modifications.
4 Safety.	All safety procedures should be documented for all building lifecycle phases.
5 Interim.	Document ownership and responsibilities of elements in all phases.

DISCUSSION

There are pressing challenges in the industry regarding sharing data from heterogeneous data sources and stakeholders (Valluru et al. 2020). Collecting MP-related data can be technically and socially challenging. Collecting MP-related data is not mandatory and is mainly filled based on stakeholders' willingness, making data collection and coordination difficult (BAMB 2017). MP relevant data are collected using different file formats and, at times, in written forms. Generally, design and manufacturing-related object data are stored as CAD files. Next, in the value chain, logistics-related data is stored in materials resource planning (MRP) and enterprise resource planning (ERP) systems. Construction-related information is reported using paper-based daily field reports (Babič, Podbreznik, and Rebolj 2010). Since these tools are not often used in conjunction, researchers have found that nomenclature and geometrical data definition used to describe elements is not consistent and is difficult to structure information (Andersson and Lessing, 2017; Malmgren *et al.*, 2011; Babič et al. 2010). The implementation of MP can also depend on the different business models of IC companies. Vertically integrated industries such as the automotive industry could have an easier structure to collect relevant data (L. Luscuere and Mulhall 2018). This business model is also seen with IC companies. Detailed design, prefabrication, and construction activities are often done or managed by the same company. There is also a long-term relationship between stakeholders, which can create an easier pathway to a standardized MP data collection throughout the supply chain (Babič, Podbreznik, and Rebolj 2010).

Another issue is that MP-related data are not sufficiently created or collected. During the value creation processes of products (e.g. design and manufacturing), most MP-relevant data is often created through digital design and manufacturing tools. Nevertheless, during value retention phases such as maintenance, the process becomes complicated (3XN Architects and GXN Innovation 2019). Although there are recent movements to tackle this challenge, such as BIM for facility management or AIM (asset information model), their use is quite rare (BAMB 2017). Also, most recent collaboratives tools are proprietary and lack sufficient integration (Valluru et al. 2020). Experts also argue whether BIM-based softwares are the best platform for MP. This is due to the sheer amount of data it needs to store, which makes models heavy to handle(M. Honic, Kovacic, and Rechberger 2019).

For these reasons, semantic web technologies are considered as the efficient way to host different domain data and to create interoperability (Pauwels, Zhang, and Lee 2017). The MPO framework for circular IC products outlines a means to achieve circular MP collection in next-generation products and processes. By formulating a fundamental understanding of knowledge in the form of an ontology, it is possible to define an MP's structure in the smallest possible detail. This should make it possible that even though heterogeneous sets of information are formed, they can be represented in an agreed mapping. Therefore, this contribution should be considered as a common starting point to perform further detailed research on the structure, requirements, and related processes of creating an MP.

In this paper, the MPO created a preliminary framework to show the basic components of MP and their interrelationship. Nevertheless, we acknowledge some limitations. The current MPO classes and relationships are simplified and not exhaustive. Additionally, the MPO is at an early conceptual level and has not fully considered elements that would need to be in place. Different accessibility levels of data and restrictions on property values are a few examples. Issues that could arise from duplication of data and integration of different file sources are also not explored. The MPO also needs to be refined and validated. Further work by the authors will refine and expand the ontology framework using an IC case company.

CONCLUSIONS

The product platform used in IC creates a better control of products and close collaboration with stakeholders. These attributes make a potential fit to applying the principles of CE and create MP. Considering that notion, the paper identifies key components of MP and proposes an ontology-based framework to collect MP-relevant data for IC products. Findings show that 1) functional levels of buildings should be identified and their property attributes collected at each level. 2) Property attributes can have different values in different building lifecycle phases. Hence each value should be filled with the corresponding lifecycle. 3) actors are a vital component of MP. They fill in and consume MP related data. Hence actors should be identified and assigned responsibilities. The fundamental structure in the MPO gives basic MP pointers to IC firms that are willing to design, produce, and manage circular IC products. Finally, the paper discusses the technical, social, and business-related challenges and possibilities to implement the MPO in the current construction sector.

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