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An Open Data Platform for Early-Stage Building Circularity Assessment

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Abstract
The construction industry is a significant source of pollution and consumer of natural resources. As the damage to the environment is rapidly growing, the criticism towards the linear economy model is increasing. Circular Economy is perceived as an environmentally friendly alternative. However, Circular Economy implementation in the industry is still in its infancy. Researchers agree that the early design phase plays a significant role in building circularity, but early-stage circularity assessment is not a common practice. Therefore, this paper investigates the technical needs for early circularity assessment and proposes a novel assessment framework relying on Semantic Web and Linked Building Data technologies. A new Building Circularity Assessment Ontology (BCAO) is proposed to structure the scattered heterogenous manufacturer product data needed for the assessment. The ontology and the application framework are evaluated in a use case that reveals the potential in guiding the design decisions to more circular alternatives.

Keywords: Circular Economy, Linked Building Data, Semantic Web, Ontologies

1 Introduction

The damage industries have caused to the environment is undeniable at present (European Commission, 2020). Unfortunately, the Architecture, Engineering and Construction (AEC) industry is not an exception. It is found to be a significant source of pollution and the largest consumer of natural resources (Benachio et al., 2020; Cottafava & Ritzen, 2020; Heisel & Rau-Oberhuber, 2020). The linear economy model traditionally relies on the "take-make-dispose" principle where raw materials are collected, transformed into products and finally discarded as waste at the end of the products' life, thereby encouraging further resource consumption. Circular Economy (CE), on the other hand, aims for decoupling economic activities from resource consumption and eliminating waste (European Commission, 2020).

Despite their undeniable potential, CE implementations in the built environment are still in their infancy and research acknowledges that many factors influence the transition to the circular model (Pomponi & Moncaster, 2017). Many scholars agree that the early design phase is the best time to evaluate the decisions made for the future building in terms of circularity. In this phase of design development, changes targeting circularity can be done with the least effort and at the lowest cost (Munaro et al., 2020). Unfortunately, designers are currently not equipped with the necessary tools to carry out early-stage building circularity assessments.

Early building circularity assessment will enable practitioners (architects, engineers, designers, etc.) to quantify their progress towards sustainable development (Saidani et al., 2019).

That being said, transparent and reliable CE related data is essential for providing the necessary input for a successful assessment (Akbarieh et al., 2020). However, the fragmented nature of the construction supply chain hinders CE data exchange (Adams et al., 2017).

Therefore, this study first investigates existing assessment tools, models, strategies and possibilities to retrieve required data for the circularity assessment. A new Building Circularity Assessment Ontology (BCAO) and a novel early design CE assessment application framework are proposed based on the findings. The framework leverages Semantic Web and Linked Open Data (LOD) technologies to structure the heterogeneous and scattered manufacturer data necessary for the assessment. Furthermore, the proof of concept is demonstrated with a prototype that utilizes the BCAO ontology to perform the CE assessment following a defined mathematical model that employs technical CE indicators.

The remainder of the paper is organized as follows. Section 2 highlights the related works in the area of building circularity assessment. Section 3 introduces the main methodological approach adopted in the study. Sections 4 and 5 present the results and their evaluation. Finally, Sections 6 and 7 discus the results and present concluding remarks.

2 Circularity Assessment in Architecture, Engineering and Construction

A robust circularity assessment calculation model is one of the main pillars towards CE implementation in the AEC industry. Currently, there are several authors investigating assessment models and criteria. Saidani et al. (2019) have identified 55 sets of circularity indicators and classified them into ten categories, thereby creating an extensive database to assist in decision making. Similarly, European Commission (2020) proposed indicators focusing on climate neutrality and zero pollution. EASAC (2016) also provided a variety of indicators with relevance to CE, gathered into six categories: (1) Sustainable development; (2) Environmental; (3) Material flow; (4) Societal behaviour; (5) Organizational behaviour; (6) Economy performance. While the indicators provided by EASAC are exhaustive, they are more inclined towards the implementation of CE at the macro and meso levels. As a result, consideration of product performance circularity indicators is lacking (Saidani et al., 2017).

The Material Circularity Indicator (MCI) calculation method proposed by Ellen MacArthur Foundation & Granta Design (2015) can be considered as a foundation for circularity assessment. It is based on three primary parameters: (1) Amount of virgin material; (2) Product utility; (3) Amount of unrecoverable waste. However, Verberne (2016) noticed the necessity to supplement this model with other important variables to assess building circularity. Therefore, the author introduced product, system, and building circularity indicators showing the material circularity and materials as a single product and systems. Later, Cottafava & Ritzen, (2021) utilized the work by Verberne (2016) and proposed a Predictive Building Circularity Indicator (PBCI) while implementing Design for Disassembly (DfD) factors directly into the MCI calculation method.

As CE aims at eliminating the waste, reusability of building elements is essential. Several authors have researched various design strategies such as Design for Disassembly, Design for Adaptability or Design for Material Recovery while stressing the importance of their implementation in the early design stages (Benachio et al., 2020). Elma Durmisevic & Brouwer (2002) introduced a pyramid model reflecting the three dimensions for the transformation capacity of buildings, indicating DfD as a top strategy. They also suggested eight main DfD aspects with respective sub aspects for evaluation of elements disassembly.

Knowing what type of data is necessary for the assessment is only the first step. Manufacturer data inputs play a significant role. However, the current research shows a substantial issue regarding relevant data retrieval, as data is usually heterogeneous and scattered among multiple sources (Kebede et al., 2020). A great deal of currently proposed assessment tools are BIM-based and rely on manual or spreadsheet-based data input (Akanbi et al., 2018; Akinade et al., 2015; Guerra et al., 2020).

Semantic Web technologies and Linked Open Data (LOD) can flip current practices of storing product data in various databases and file formats (e.g., PDFs or tabular data) by bringing a common vocabulary to define and retrieve information in a common data environment (Kebede et al., 2020; Pauwels et al., 2017). To achieve the latter, a shared vocabulary and structure are of essence. Currently, there are several ontologies proposed, e.g., Building Product Ontology (BPO) (Wagner & Ruppel, 2019), Digital Construction Building Materials (DICBM) (Karlapudi et al., 2020), Circular Exchange Ontology (CEO) and Circular Materials and Activities Ontology (CAMO) (Sauter et al., 2018), but they contain only some of the relevant classes and properties necessary for the technical early-stage building circularity assessment.

Thus, this study attempts to bridge the above-identified gaps by combining a mathematical model for technical circularity assessment with ontology engineering and web technologies.

3 Methodology

This study aims to identify the latest contributions relevant to the early-stage building circularity assessment and propose technical solutions to bridge the current gaps. Therefore, this research is exploratory by nature. For that purpose, dedicated Research Design was combined and divided into three phases with respective methods (Figure 1). Phase 1 is based on qualitative data collection from desk research, which, together with the outcomes of the interviews with four industry professionals, acts as the process input for a Systems Engineering process (Lightsey, 2001) in Phase 2. During Phase 2, a novel assessment framework was combined and based on Ontology Engineering guidelines (Suárez-Figueroa et al., 2012) to develop a new ontology for building circularity assessment. Finally, the usability of the prototype is evaluated in Phase 3.

4 Results

This section presents a novel system framework for early-stage technical building circularity assessment. Figure 2 shows the framework, which consists of three main layers: *User Layer, Application Layer* and *Data Layer*. The layers are interconnected by intermediate data exchange, thereby creating a coherent system. The purpose of the system is to enable the users to assess their early design based on technical circularity indicators while incorporating the manufacturer data. Manufacturers play a critical role by providing the necessary data regarding the materials and products for circularity calculations and an exact circularity calculation method creates the requirements for the needed manufacturer data input.

The following subsections present each layer in detail. Section 4.1. explains the role of the users. Section 4.2 defines the purpose of the application, including the chosen circularity calculation method. Finally, section 4.3 proposes a new Building Circularity Assessment Ontology (BCAO) for structuring the heterogeneous and scattered manufacturer data, which later can be stored and made accessible by the use of Semantic Web and Linked Open Data technologies.

4.1 User layer

The *User Layer* combines two types of actors. On one side is the main end user (architect, consultant, project manager, etc.) who aims at evaluating the project's circularity (top left in Figure 2), and on the other - the manufacturers who provide the material/product data (top right in Figure 2). To assess the circularity of the project, the main user exports an Industry Foundation Classes (IFC) file of the preliminary design and converts it to Linked Building Data (LBD) by the use of the IFC to RDF converter tool[1]. This intermediate step is necessary to match the schema of the knowledge base. Furthermore, the LBD exporter uses the buildingSMART Data Dictionary

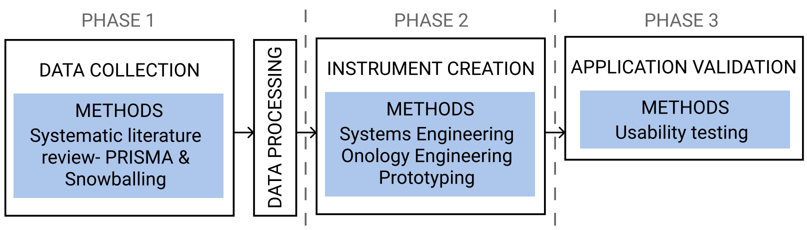

Figure 1. Research design

[1] https://github.com/jyrkioraskari/IFCtoLBD

(bSDD) definition so that the project elements later can be easier recognized in the database. The resulting LBD is later used by the building circularity assessment application to retrieve the building elements.

Manufacturers provide the data for the knowledge base required to assess the design. As identified during the literature review, there are many different sources of manufacturer data and data is provided in various structures and formats (Kebede et al., 2020). Therefore, a separate manufacturer data input application is proposed, allowing the manufacturers to enter the data in a homogenous manner.

4.2 Application layer

The *Application Layer* incorporates two applications: (1) the building circularity assessment application and (2) the manufacturer data input application. This layer acts as a bridge between the users and the knowledge base, i.e., it utilizes the input data provided by the users and retrieves the data from the knowledge base needed for the assessment. The purpose of the application is to evaluate the early design for circularity based on the selected assessment model. The main functionalities of the application are:

- *Grouping elements by layer and type*. The imported LBD model elements are represented in separate groups based on Brand's (1995) layers and element type. For example, the structure layer would include load-bearing constructions like walls, beams or columns.
- *Refined element search*. Using the circularity assessment application, the knowledge base is accessed based on the user needs. The user can define the required utility factor, connection type or the percentage of non-virgin material input for a specific element like a wall, thereby retrieving all walls from the database meeting the requirements.
- *Calculate circularity indicators*. Two main assessment models were considered in relation to the necessary indicators required to conduct circularity assessment for buildings. First, Material Circularity Indicator (MCI) (Ellen MacArthur & Granta Design, 2015) considers the technical cycle and is based on three characteristics: (1) mass of virgin material used; (2) mass of unrecoverable waste; and (3) utility factor measuring life span and intensity of product use. This assessment model measures the circularity of materials and products by calculating the linear flow index (LFI) and the modified utility factor (X), which is

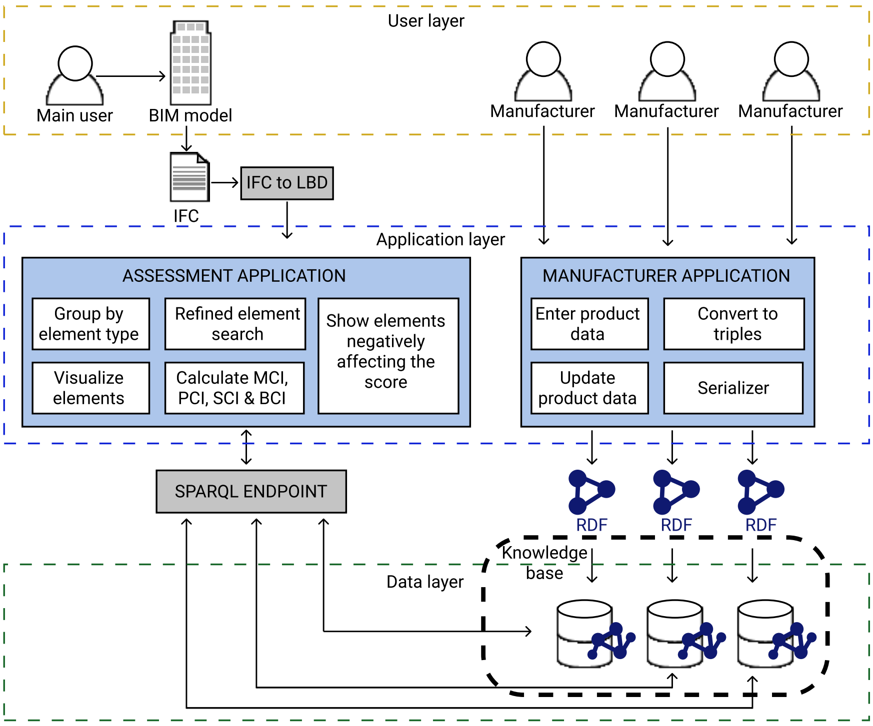

Figure 2. The proposed early design building circularity assessment framework

calculated by evaluating the life span of the product and use intensity. Additionally, a scoring between “0” and “1” demonstrates the degree of circularity based on equation (1):

$$MCI\text{=max }(0, (1-LFI\cdot F(X)) \qquad (1)$$

Second, the Building Circularity Indicator (BCI) developed by (Verberne, 2016) measuring the building level of circularity was also considered. BCI is based on the MCI developed by Ellen MacArthur Foundation & Granta Design, (2015). According to Verberne (2016), BCI is calculated in a progressive manner, i.e., first calculating the MCI, then the Product Circularity Indicator (PCI) and the System Circularity Indicator (SCI). PCI utilizes the results of MCI and the Design for Disassembly factors (F_i) developed by (Elma Durmisevic & Brouwer, 2002), which are important for showing the degree of attachment between different building elements. PCI is calculated based on equation (2):

$$PCI\frac{1}{Fd}\sum_{i=1}^{n} MCI \cdot Fi \qquad (2)$$

Moreover, building elements are aggregated in relation to Brand's (1995) building layers into systems and multiplied by each system products’ mass (W_i), while a total system products’ mass is used as a normalizing factor (W_s). SCI is calculated based on equation (3):

$$SCI=\frac{1}{Ws}\sum_{i=1}^{n} PCI \cdot Wi \qquad (3)$$

Finally, the circularity score for a building is calculated by summing up the circularity of each building system according to its level of importance (L_k), and a score between “0” being fully linear and “1” being fully circular is provided, based on equation (4):

$$BCI=\frac{1}{Lk}\sum_{i=1}^{n} SCI \cdot L_{Ki} \qquad (4)$$

- *Show elements negatively affecting the score and give suggestions*. When the circularity indicators are calculated, the products decreasing the circularity score most significantly are indicated, and more circular recommendations for similar products are given.

The second application completing the *Application Layer* is the manufacturer data input application. This application aims to provide means for the homogenous manufacturer data input, which can later be appropriately structured and stored in the knowledge base. Therefore, the manufacturer application is intended to assist the manufacturers to load, manage and transfer their data to triple stores. It is important to note that data ownership should always remain with the manufacturer and focus should be placed on decentralised data management and appropriate access control mechanisms similarly to the proposed by Werbrouck et al. (2020). The main manufacturer application functionalities are represented in Figure 2.

4.3 Data layer

The *Data Layer* accommodates the knowledge base, which is combined from different manufacturer data Resource Description Framework (RDF) triple stores. The triple stores are populated by the data parsed from the manufacturer application and can be accessed by the circularity assessment application through a SPARQL endpoint. However, to make sure that the data in the triple stores are structured and correctly linked, a dedicated ontology is essential.

The literature review has shown that no existing ontology can currently provide the necessary full vocabulary for structuring technical circularity assessment data needed to perform the calculations according to selected model. Therefore, this paper proposes a new Building Circularity Assessment Ontology (BCAO) devoted to filling this gap.

4.3.1 Ontology definition for building product circularity

In this sub-section we propose a novel Building Circularity Assessment Ontology following Ontology Engineering guidelines presented by Suárez-Figueroa et al. (2012) and the Linked Open Terms (LOT)[2] methodology. The purpose of the ontology, as well as the scope, implementation language and functional requirements have been defined during the ontology requirement specification stage. The functional requirements were derived in the form of competency questions (Grüninger & Fox, 1995). The outcome of ontology requirement specification stage is the Ontology Requirements Specification Document (ORSD).

The ontology implementation stage comprises three phases: conceptualization, encoding and evaluation. Conceptualization refers to organizing and structuring the information obtained during the acquisition process into meaningful models at knowledge level according to the ontology requirements specification document (Suárez-Figueroa et al., 2012).

Encoding is a process of transforming the concept into an ontology expressed in the chosen ontology implementation language (Espinoza-Arias et al., 2020). During the encoding process, it is highly recommended to search for existing ontologies to be reused. In this study the potentially reusable ontologies were identified during the desk research. Figure 3 illustrates the conceptualization of BCAO while utilizing the classes and properties of reusable ontologies.

The conceptualization of BCAO was implemented using the *Protégé* software. Necessary classes and sub-classes, as well as object and data properties for the BCAO ontology in *Protégé* are presented in Figure 3. Figure 4 shows an extract of implemented BCAO class taxonomy. Furthermore, necessary restrictions were set according to the assessment model to ensure that the building product will have the data assigned correctly. For example, while defining the DfD factors regarding the wall fixings, only one type of the fixings, such as *accessible* or *accessible with causing damage*, etc., can be assigned.

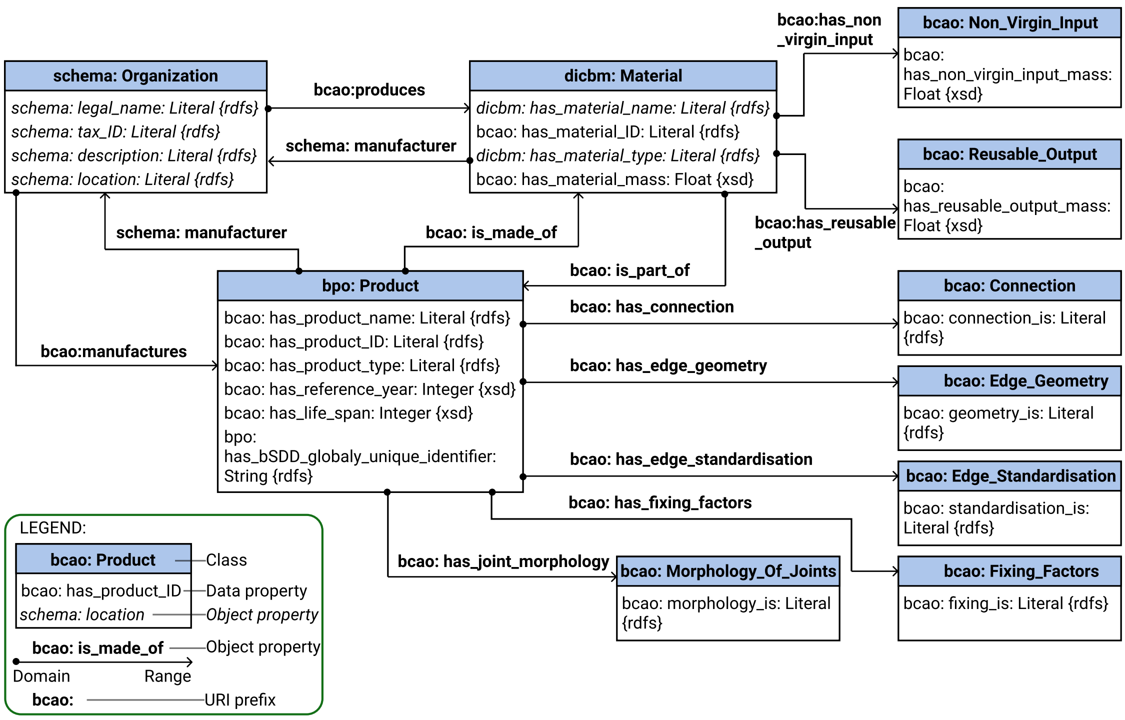

Figure 3. Building Circularity Assessment Ontology conceptualization

[2] https://lot.linkeddata.es/

5 Evaluation

An initial evaluation was performed with an early design stage BIM model of a residential house to evaluate the BCAO structure and vocabulary while assessing the circularity according to the proposed assessment model. Two building layers were selected: (1) the structural layer including external concrete and sandwich walls; (2) the space layer including partition concrete walls, doors and windows. Respectfully to the chosen layer elements, mock-up manufacturer data was created in a spreadsheet format providing required data for the circularity calculations.

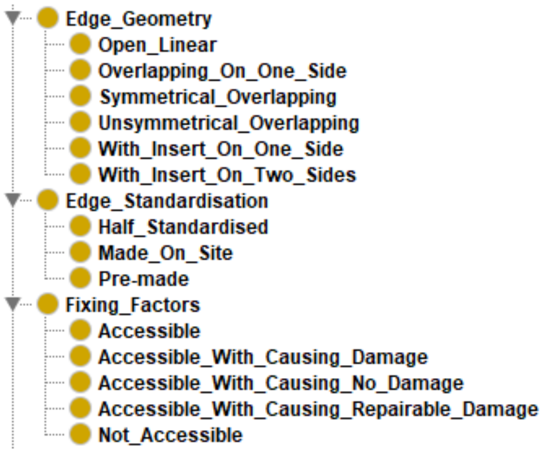

Figure 4. Extract of BCO taxonomy in Protégé

```
SELECT
        *
WHERE

{

  ?External_Walls      bcao:has_life_span  "75";
                       bcao:has_product_name  ?P_Name;
                       bcao:has_product_ID   ?P_ID;
                       bcao:is_made_of      ?M_ID.
  ?M_Subject           bcao:has_material_ID   ?M_ID;
                       bcao:has_material_name ?M_Name
```

Figure 5. SPARQL query to retrieve all external walls with the utility factor of 75 years

5.1 Employing manufacturer data

As manufacturer data is commonly represented in a type of spreadsheet, similar mock-up data was combined to test the usability of BCAO. The data includes basic manufacturer company information (e.g., company name, type, location), product data (ID, name, location), product utility factor, material composition (including total mass, the mass of non-virgin input and the mass of reusable output) as well as DfD factors (edge standardization, edge geometry, morphology of joints, fixing factors and connection type). *OpenRefine*[3] was used to align the records with the proposed otology while importing it into the software and assigning respective classes and object properties. The resulting RDF graph was exported in *Turtle* file format and imported to *Apache Jena Fuseki*[4] triple store together with the BCAO.

5.2 Querying the data

According to the system framework, the users should be able to refine their search by selecting the necessary element properties using dropdown menus in the assessment application. For this use case, the database was queried to find all external walls with a utility factor of 75 years. To achieve that, a SPARQL SELECT query was employed (Figure 5). Having all the available walls listed, the user is able to select a specific one and retrieve further assessment data.

5.3 Model assessment

The proposed assessment application utilizes two types of data input: (1) data from the BIM model in IFC format and (2) manufacturer product data. In the first prototype, only the quantities, materials and dimensions were extracted from the BIM model. Therefore, the remaining assessment data should be provided by the manufacturer. Five model elements from two building layers used for this case study were queried and selected from the database. Four circularity indicators were calculated for the material (MCI), product (PCI), system (SCI) and building (BCI)

[3] https://openrefine.org/

[4] https://jena.apache.org/

according to the previously described assessment model. To check the possibility for altering the results by choosing alternative elements, a gypsum partition wall is selected from the database to replace the concrete partition walls. As a result, the circularity indicators are recalculated. The calculation results are represented in **Table 1**.

Table 1. Results for structural and space layers MCI, PCI, SCI and BCI calculations

	Structural layer		Space layer			
	External concrete wall	External sandwich wall	Partition concrete wall	Doors	Windows	Partition gypsum wall
MCI	0.78	0.80	0.68	1.00	0.88	0.91
PCI	0.61	0.65	0.34	0.84	0.72	0.69
SCI	0.63		0.36			0.75
BCI	0.41					0.73

6 Discussion

The lack of an open data approach is among the main gaps preventing building circularity assessment implementation. Linked data technologies show a great potential to bridge this gap. However, none of the existing ontologies alone can provide the necessary structure and vocabulary to satisfy the assessment model requirements for storing data containing technical circularity indicators. Therefore, a novel BCAO ontology was proposed and utilized together with other LBD ontologies. The use case results showed that BCAO can be employed when converting manufacturer spreadsheet data to RDF triples. However, this method is not considered user friendly and, in the future, should be replaced by a dedicated application as proposed in the main framework. Furthermore, since manufacturers are currently not providing all the needed product information for the assessment (especially DfD factors), mock-up data was combined for the purposes of the use case. Nevertheless, this data was semi-structured and intended to fit the assessment model's requirements; thus, during further stages of ontology evolution, the proposed structure and vocabulary should be extended to fit additional data structuring needs.

The aligned manufacturer data was exported in TTL serialization and imported together with BCAO in the Apache Jena Triple store. Even though this method served well for the proof of concept, in reality it would raise data ownership questions. In the future, this issue could be solved by creating a decentralised common data environment and access to data can be controlled as proposed by Werbrouck (2019) and Werbrouck et al. (2020) respectively. Furthermore, the necessary assessment data was retrieved through SPARQL queries. In the future, the querying process should be automated as well. This can be done by predefining SPARQL queries, which the building circularity assessment application should send on user request. Finally, the usability of the retrieved data and the assessment model was tested by performing manual MCI, PCI, SCI and BCI calculations.

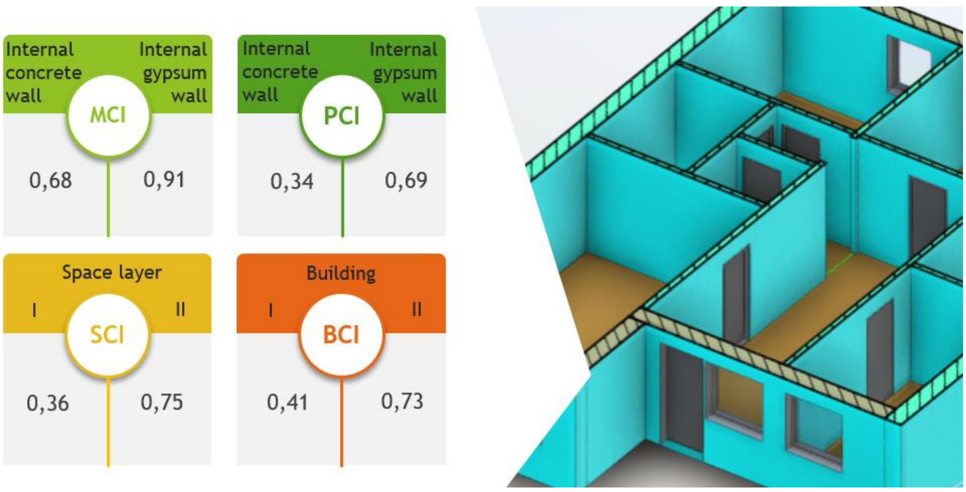

Figure 6. Circularity indicators calculation results comparison and case study model

The results show that the DfD factors, as well as the amount of non-virgin material input and reusable output highly alter the circularity indicator results. This can be a strong competitive point for manufacturer industries in the future. Using the mock-up manufacturer data, it was possible to fulfil the assessment needs and all the necessary information was retrieved from the knowledge base.

To check if the calculations could affect the design decisions, an alternative product (partition gypsum wall), was also assessed for circularity. The calculations show that the alternative decision would increase the circularity of the whole building. Figure 6 indicates the result comparison between the two options while using internal: (I) concrete walls and (II) gypsum walls. It can be observed that a change in even one type of element alters all the indicators, as the model calculations are progressively interconnected. Therefore, it can be concluded that early design assessment could assist the designers in making more circular design decisions.

7 Conclusion

As the environmental issues become more evident, industries must take action in adjusting to current circumstances. This study identified that early-stage building circularity assessment could aid a more sustainable future for the AEC industry. Even though many variables influence such a shift, technology applications play a significant role in the process. However, initial research shows that not many applications evaluate building circularity in the early design stages, especially DfD factors, which are crucial for products' reusability. Furthermore, most of the current contributions utilise IFC export data together with additional spreadsheets representing manufacturer product data. Such an approach often locks the user in a proprietary environment and leads to issues with reusing available manufacturer data.

This study attempts to bridge the technical gaps for early-stage building circularity assessment and proposes a system framework connecting various stakeholders (e.g., architects, consultants or manufacturers). The initial circularity assessment model suggested in this paper sets the requirements for the product/material data that needs to be provided by manufacturers. However, in the future, additional variables could be involved for more detailed evaluation. The recently released ISO/CEN 23386 and ISO/CEN 23387 standards provide guidelines for quality data exchange between industry stakeholders and could also be applied in the proposed framework.

One of the most significant challenges to early circularity assessment is the lack of open data approaches providing structured and reliable manufacturer data. Therefore, a novel Building Circularity Assessment Ontology was proposed. The BCAO was technically implemented in the Protégé software and evaluated in a use case. The results show that the proposed BCAO structure and vocabulary are consistent with the assessment model, and the data can be retrieved from the knowledge base using SPARQL queries. However, in the future, the ontology has to be adjusted reflecting further data structuring needs.

Finally, the circularity assessment calculations reveal that the proposed framework can lead the designers towards more circular decisions by allowing them to choose from a variety of products in the knowledge base. Nevertheless, there are still many challenges to overcome when creating and maintaining this kind of platform.

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