Bridging the gap – A database tool for BIM-based circularity assessment

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Abstract. The concept of circular economy attracts attention across sectors. Since construction materials are the single largest material stock and flow, there is a particular interest from research and policy to apply the circularity concept to buildings. Large quantities of construction and demolition waste end up in landfill, despite new EU legislation that requires a 70% recovery rate. There is a gap between this ambitious goal and the reality of the construction industry. Building Information Modelling (BIM) has the potential to improve building design and construction processes for an increased recovery of materials. However, insufficient data, inconsistent methods and interoperability issues inhibit BIM application to unfold its full potential in circularity assessments. This paper introduces the CirBIM database framework. It provides BIM users with the required robust data to improve the circularity throughout the building’s life cycle: from the design phase through renovation activities to the end-of-life stage. The paper proposes a new workflow of building circularity assessment, describe the architecture of the new database tool, and recommends relevant data sources and information models to streamline data mining processes. The new database tool is exemplified through application to a case study building in Portugal, emphasizing the need for different metrics and the need of integration of the end-of-life scenarios in the building design stage.

Keywords: building, database, BIM, LCA, circularity

1. Introduction

1.1. Digitalization for circular buildings
The concept of circular economy attracts attention across sectors as growing material scarcity and embodied impacts necessitate the recovery, reuse and recycling of materials. Since construction materials represent the single largest material stock and flow, there is a particular interest from research and policy to apply the circularity concept to buildings. The average building life span is decreasing, and large quantities of construction and demolition waste (CDW) end up in landfill, despite new EU legislation that requires a 70% recovery rate of CDW. There is a gap between this ambitious goal and...
the reality of the construction industry. This gap can be mainly attributed to, on the one hand, lack of required information, which should be stored in an adequate Building Information Modelling (BIM) platform, and on the other hand, the lack of know-how for advancing incentive schemes to promote an industrialized recovery rate of materials since design stage.

BIM allows the automatic calculation of areas, volumes and masses of used materials [1]. It has the potential to improve building design and construction processes for an increased recovery of materials. However, insufficient data, inconsistent methods and interoperability issues inhibit BIM application to unfold its full potential in circularity assessments.

In recent years, more and more scholars have been investigating how to collect and store building materials information regarding their use, location, origin, associated emissions and other characteristics. This body of research can be divided into three lines: 1) exact modeling of a building using BIM and digital twins for an improved environmental performance; 2) approximation of the building materials composition for a group of buildings, often in combination with energy demand, called urban building modeling; 3) collection of datasets, varying between specific, average and generic data, for embodied impacts of construction products, that relate to the sourcing, transport, and manufacturing (also known as life cycle stages A1, A2, A3 according to EN 15804), to be used in Life Cycle Assessment (LCA).

Within the first line, the work by Aguiar Costa et al. [2], as well as by Hollberg et al. [3] push the boundary of integrating LCA in automated building design. However, the required amount of building-specific information is significant. Within the second line, the work by Reinhart and his team is noteworthy [4,5,6]. They developed a workflow to define a geolocated building stock model using archetypes. Archetypes mirror typical characteristics of groups of buildings, in this way they help to abstract a building stock. In the characterization step, the constructive system and materials of each building archetype are defined. Therefore, archetypes are helpful to fill in knowledge gaps of material composition, particularly for existing models that lack a BIM model. Within the third line, the literature review by Martinez-Rocamora et al. [7] gives a good overview of LCA databases for construction materials. The most extensive databases that provide complete inventories for a wide range of products and processes are the GaBi database and the Ecoinvent database. The work by Resch and colleagues [8], [9] proposes a structure for the collection and comparison of embodied emission data of buildings. The emission values are taken from building LCAs and allow for transparency regarding method and system boundary. The authors propose to store information with the highest possible resolution for building elements, materials, and lifecycle stages. This recommendation is followed in this paper. However, Resch et al.’s work follows the Norwegian norm, while the present paper adopts the European framework Level(s) for the classification of building elements.

1.2. Background information about the Circular EcoBIM project
The work presented here is part of the Circular EcoBIM project, which is supported by EEA Grants. The project develops a platform that integrates BIM with LCA to promote a circular construction. The target users are architects and engineers who want to reduce the material use and waste production in the construction sector. More information about the overall project and the other platform components can be found at www.circularecobim.eu.

1.3. Objectives and scope
The purpose of this work is to propose a database tool, called “CirBIM”. The tool allows the systematic collection and storage of building data for a circularity assessment. It provides BIM users with the required robust data to improve the circularity of a building throughout its life cycle: from the original design phase throughout renovation activities to the end-of-life stage. This means that the tool enables the analysis of circularity indicators of a building or building element. The goal is to go beyond the mere data collection of type and quantity of materials, and towards the integration of life cycle environmental impacts to allow a more holistic approach to building circularity.
Section 2 describes background information on circularity indicators (2.1), the intended workflow of a circularity assessment with CirBIM (2.2), and the architecture of the database (2.3). Moreover, recommendations on relevant data sources and information models to streamline data mining processes are provided in 2.4. In section 3, a simple case study is analyzed to showcase the use of data from CirBIM. In section 4, conclusions are drawn.

2. Materials and methods

2.1. Circularity indicators

The CirBIM database tool is aimed at the circularity indicator methodology by Cottafava and Ritzen [1]. Their work, in turn, is an adaptation for buildings of the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation [10]. The Circular EcoBIM project is also advancing the methodology of the circularity assessment through a new plugin for Autodesk Revit, even though this is beyond the scope of this paper. For more information on the circularity plugin, please refer to Fernandes et al. [11].

A summary of the circularity assessment is given to enable a better understanding of the CirBIM database tool. The MCI is used, along with a disassembly index, to calculate the Product Circularity Indicator (PCI). The PCI is then used, along with the quantification of components per layer, to calculate the System Circularity Indicator (SCI). Finally, the SCI is used, along with a quantification of importance of each building layer, to calculate the Building Circularity Indicator (BCI). Building layers are defined using Brand’s sheering layers [12] according to [1].

2.2. CirBIM workflow

In this paper, the focus is on the database as a tool for circularity assessment. The envisioned workflow can be seen in Figure 1.

![Workflow of circularity assessment with the CirBIM tool.](image)

The CirBIM database stands between a BIM model and a methodology for circularity indicators (manual or automated through the plugin as referred above). The BIM model (light blue in Figure 1) provides information about the building geometry, volumes of building elements, and classifies the building systems into elements and into products according to the Uniclass classification scheme, the most common classification in BIM. As Uniclass is a non-hierarchical system, the information in the
database for product and material groups requires additional classification. This is based on the Brand shearing layers and the building tiers from the EC’s Level(s) framework for sustainable buildings, as illustrated in Figure 2.

The external database (green in Figure 1) provides information at different levels, e.g. product-specific, material type, building element. Finally, the information from the BIM model and database, using the circularity methodology, provides the output for circularity indicators in a circularity report (pink in Figure 1).

Figure 2. Hierarchical structure of the building considering the building tiers from the EU Level(s) framework and the Brand shearing layers. The tree can be extended but note that the proposed database only covers the green boxes.

2.3. Architecture of the database
CirBIM is a relational database. A relational database stores information and provides access to data points that are related to one another. To interact with the database, the user needs to use Structured Query Language (SQL). It is important to understand the following key concepts of a relational database:

- **Entity**: is a table for a real-world object that models and stores specific information;
- **Attribute**: is a characteristic of an entity. It describes the entity. It corresponds to a column in a table;
- **Relationship**: is an association between entities;
- **Primary key (PK)**: each entity (record) needs to have one attribute, or a combination of attributes, that identifies it uniquely. This is usually a unique identifier (ID) code.

Figure 3 shows the Entity-Relationship diagram of CirBIM. Colored headings indicate the coherency between tables of information types. The “heart” of the database are the tables highlighted in pink. Here, information is stored for construction products. A product can be a material, e.g. cement, or a pre-assembled system that consists of multiple materials, e.g. a window. Products is the master table of the database that connects to multiple child tables. It includes product-specific information (e.g. name, manufacturer), the declared unit relating to the impacts, density and cost. Each entry is labeled with a unique product ID and classified through a Uniclass Products code. EnvIndicators complements Products with relevant information regarding environmental impacts and circularity. It includes one entry per product and life cycle module, meaning multiple entries are required to include the information for multiple LC modules. It also stores information about the data source, e.g. EPD number, and methodology used, e.g. ILCD method. The entity DefaultReuseRecycle provides default values for reused materials (RM), recycled material (SM), components for reuse (CRU), and materials for
recycling (MFR), in case the product-specific information source, e.g. EPD, does not quantify these parameters, which are essential to the circularity assessment.

The tables highlighted in purple classify, firstly, in Layers, products into layers including their function. Secondly, in Elements, layers into typical building elements, including walls and roofs. Thirdly, in Archetypes, organize typical elements into a set of archetypes. The user can make use of the archetypes in case specific information about the constructive characteristics are missing. The Elements table needs additional information for its classification. This is stored in the group of blue tables.

**Figure 3.** Entity-relationship diagram for the CirBIM database tool.
Tier2BuildingAspect and Tier3BuildingAspect follow the Level(s) framework hierarchy, and BrandLayers is an additional layer of classification. This was already detailed in Figure 2. While the Level(s) tiers are important for the definition of default lifetimes, the Brand layers are required for the calculation of the Building Circularity indicators.

The orange tables provide additional information for Level(s) tier 3 for calculating Material Circularity indicator: IntensityOfUse quantifies the average lifetime and use intensity, which is needed for the MCI. Maintenance includes information about maintenance cycles and the associated costs. The information for products needs to be converted into raw materials. This can happen through the information stored in the yellow tables. RawMaterials provides a definition of typical construction material groups as provided in the ICE database by the University of Bath [13]. Additionally, BioMaterials identifies bio-based building materials and provides information about their carbon content, which is important when analyzing possible carbon storage, as well as their higher heating value (HHV), default end of life (EoL) treatment, and the average amount of biomass per type that can be derived from sustained production. All these parameters are required for calculating the MCI.

The green tables are closely linked to the materials and provide information about typical end of life scenarios. These values are specific to the country of analysis. Therefore, the location per defined value is denoted. MaterialRecycling and FeedstockRecycling store technology factors on the efficiency and emission intensity of the recycling preparation and the actual recycling process, respectively. They also define default EoL treatments for construction materials, that are not already defined in BioMaterials. In addition, LoW (for level of waste) categorizes waste types and can be used to link material groups to waste categories and available waste treatment facilities.

2.4. Data collection and organization

The input data is collected in spreadsheets. The collected information per product is stored in separate Excel sheets. The actual relational database is setup in MySQL, using the Excel tables as input. Excel and MySQL can exchange information in both ways (import and export is possible). The import of data from Excel into MySQL is simple and only requires that the Excel table to be imported is saved as a .CSV (comma separated) file. The main information source of the database is Environmental Product Declarations (EPD), especially the ones that follow EN 15804:2012 + A2:2019 as they include the end-of-life phase C and Module D. An overview of data types per parameter can be seen in Table 1.

| Parameter                          | Type of information | Type of data                     | Data source                        |
|------------------------------------|---------------------|----------------------------------|------------------------------------|
| General product information        | Product specific    | Product specific / qualitative   | EPD                                |
| Environmental impact indicators    | Product specific    | Product specific results         | EPD                                |
| Parameters describing resource use | Product specific    | Product specific input flows      | EPD                                |
| Parameters describing resource use | Default             | Product group input flows         | Literature                         |
| Environmental info on waste categories | Product specific | Product specific output flows     | EPD                                |
| Environmental info on output flows | Product specific    | Product specific output flows     | EPD                                |
| Material composition (reused amount) | Default            | Product group output flows        | Literature                         |
| Biogenic carbon content            | Material specific   | Material specific                 | EN 16449 and other                 |
| Material recycling                 | Default             | Material and plant specific       | Plant operators                    |
| Feedstock recycling                | Default             | Material and plant specific       | Plant operators                    |
| Energy recovery                    | Default             | Material and plant specific       | Plant operators                    |
| Type of waste                      | Default             | Material specific                 | List of wastes [14]                |
| Building element                   | Default             | Classification                    | Level(s); Brand; Uniclass          |
| Lifespan                           | Default             | Classification                    | Level(s) Tier 2                    |
| Intensity of use                   | Default             | Building element specific         | Level(s) Tier 3                    |
The database stores information about construction products that help to analyze the circularity indicators. The necessary data is organized in a product data template (PDT) as shown in Table 2. The PDT helps to collect new data in an organized and systematic way.

**Table 2.** Product data template for CirBIM.

| Macro Objective | Parameter/Indicator | Abbreviation | Relevant for CI | Unit | Data source |
|-----------------|---------------------|--------------|----------------|------|-------------|
| **Classification** | Product info | Product name | -- | -- | EPD |
| | | Manufacturer | -- | -- | EPD |
| | | Reference flow UUID | -- | -- | EPD |
| | Uniclass | Uniclass Product (Pr) code | PCI | -- | Uniclass |
| | Building aspect | Tier 2 name | SCI | -- | Level(s) |
| | Building Layer | Brand name | BCI | -- | Brand layers |
| | Functional unit | Declared unit | PCI | -- | EPD |
| | Functional unit | Density | PCI | kg/m³ | EPD |
| | | Expected lifespan | MCI | years | EPD or Level(s) |
| | Info about environmental indicator data | Type of data | -- | -- | EPD |
| | | Life cycle impact assessment method | LCA method | -- | EPD |
| | | Data source | -- | -- | EPD |
| | Environmental Impacts* | Global Warming Potential – total | GWP | MCI | MJ | EPD |
| | | Global Warming Potential – fossil | GWP-fossil | MCI | MJ | EPD |
| | | Global Warming Potential – biogenic | GWP-bio | MCI | MJ | EPD |
| | | Global Warming Potential – land use | GWP-haloc | MCI | MJ | EPD |
| | | Abiotic depletion potential fossil | ADP | MCI | MJ | EPD |
| | | Abiotic depletion potential non-fossil | ADPn | MCI | MJ | EPD |
| | | Total renewable Energy | PERT | MCI | MJ | EPD |
| | | Total non-Renewable Energy | PENRT | MCI | MJ | EPD |
| | | Acidification Potential | AP | MCI | MJ | EPD |
| | | Eutrophication Potential – total | EP | MCI | MJ | EPD |
| | | Eutrophication Potential – freshwater | EP | MCI | MJ | EPD |
| | | Eutrophication Potential – marine | EP | MCI | MJ | EPD |
| | | Eutrophication Potential – terrestrial | EP | MCI | MJ | EPD |
| | | Stratospheric ozone depletion potential | ODP | MCI | MJ | EPD |
| | | Photochemical Ozone Creation Potential | POCP | MCI | MJ | EPD |
| | | Non-renewable primary energy as energy source | PENRE | MCI | MJ | EPD |
| | | Non-renewable primary energy for material use | PENRM | MCI | MJ | EPD |
| | | Renewable primary energy as energy source | PERE | MCI | MJ | EPD |
| | | Renewable primary energy for material use | PERM | MCI | MJ | EPD |
| | | Use of secondary material (recycled) | SM | MCI | MJ | EPD |
| | | Use of reused material | RM | MCI | MJ | EPD |
| | | Use of renewable secondary fuels | RSF | -- | -- | EPD |
| | | Use of net freshwater | FW | -- | -- | EPD |
| | | Hazardous waste disposed | HW | MCI | MJ | EPD |
| | | Non-hazardous waste disposed | NW | MCI | MJ | EPD |
| | | Radioactive waste disposed | RW | MCI | MJ | EPD |
| | | Components for reuse | CRU | MCI | MJ | EPD |
| | | Materials for recycling | MFR | MCI | MJ | EPD |
| | | Materials for energy recovery | MER | MCI | MJ | EPD |
| | | Exported electrical energy | EEE | -- | -- | EPD |
| | | Exported thermal energy | EET | -- | -- | EPD |
| **Cost** | Type of material | Material | MCI | MJ | EPD |
| | Quantity per material | Material | MCI | MJ | EPD |

Note: Abbreviations used: GWP = Global Warming Potential, ADP = Abiotic depletion potential, ODP = Stratospheric ozone depletion potential, PENRE = Non-renewable primary energy as energy source, PENRM = Non-renewable primary energy for material use, PERE = Renewable primary energy as energy source, PERM = Renewable primary energy for material use, SM = Use of secondary material (recycled), RM = Use of reused material, FW = Use of net freshwater, HW = Hazardous waste disposed, NW = Non-hazardous waste disposed, RW = Radioactive waste disposed, CRU = Components for reuse, MFR = Materials for recycling, MER = Materials for energy recovery, EEE = Exported electrical energy, EET = Exported thermal energy, EPD = Environmental Product Declaration.
3. Results and discussion

3.1. Case study

The CirBIM database tool is tested with a renovation project of a historic residential building in Porto, Portugal. The executed project integrates the reuse of existing building elements. In this way, the original ceilings, as well as most interior walls were kept. Additionally, the project made use of direct material use on site: granite from exterior walls is reused for the construction of walls in the backyard, and mosaic tiles from the old bathroom are reused in the kitchen and closed balcony. The color scheme in Figure 4 highlights which elements were added and removed.

![Figure 4](image)

**Figure 4.** Floor plans of the case study house in Porto. From left to right: from first floor to floor -2. Source: Catástrofe, Lda. 2016.

3.2. Difference in circularity metrics

Figure 5 shows the amount of material in relation to their embodied carbon (in CO$_2$ eq.). The impacts refer to LC stages A1-A3. The inflowing materials (added) and outflowing materials (demolished) are illustrated. Clay bricks, glass and lime represent the highest amount of added material, yet glass, ceramic and insulation (rockwool) are responsible for the biggest amount of embodied carbon. These are examples that show the difference between metrics when analysing circularity. In this case study, the direct reuse of natural stone and ceramic tiles allows a 22% reduction of virgin material use, representing a 3% reduction of embodied carbon. It can be noted that glass, since it represents a significant share of embodied carbon, is a crucial material. This means that the reuse or recycling of windows, possibly from other building sites, can be recommended to improve the embodied carbon of buildings.
3.3. The importance of disassembly

This case study shows that a direct reuse of building materials on site is technically possible and environmentally relevant. However, the recovery of the granite blocks and ceramic tiles was only possible because these are products that allow disassembly. Disassembly can be quantified, according to [1], through connection type, connection accessibility, form containment, and crossings. Dry connections, which are freely accessible, have no inclusions and with modular zoning, are the optimum case, while chemical connections, without access, closed on all sides and fully integrated with other objects, are the worst case. While in theory, this seems sensible, in practice, buildings provide shelter and should be sturdy and longstanding. This often entails a choice of materials and construction system that make disassembly impossible. We need to re-think this and strive for an increased use of materials and systems that anticipate disassembly. This requires the consideration of a possible end of life scenario already in the early design stage. This is where the availability of data becomes crucial: quantifying circularity of building designs, even a cautious approximation, can help engineers and architects to achieve this goal.

4. Conclusion

This paper introduced a novel database tool that allows the organized storage of data for buildings circularity assessment. It enables both, a specific analysis through the storage of product-specific data, and an approximation, in case of a lack of information, thanks to the archetypes. Products data is categorized according to the new Level(s) framework, therefore, supporting the European Commission’s mission for sustainable buildings. Future research should deal with the challenge of data uncertainty related to the location, particularly for environmental impacts and end of life technology factors.
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