Estimating the Circularity of Building Elements using Building Information Modelling

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Abstract. The circular economy (CE) aims at a transformation towards a sustainable economic system whose growth is decoupled from the availability of finite resources. Due to the resource intensity of the construction sector, it is one of the main sectors where the CE concept is being applied. Central to the concept of circular buildings (CB) is to close the technical use-cycle of building components, which is influenced by their detachability. Building detachability is the extent to which building components can be deconstructed without damage. The scope of this research addresses the integration of its assessment using Building Information Modelling (BIM). This study includes an analysis of existing building circularity assessments (BCA) and their integration potential using BIM. Next, we propose a framework to automate the evaluation of building detachability using BIM. This framework entails the utilization of business process models and notations (BPMN) for delineating the detachability assessment procedure and deriving the model information requirements for the assessment by developing attribute matrices. The research process evidences that an accurate interpretation of established detachability assessment requisites facilitates enhanced integration and automation within the BIM method. Nevertheless, the need for better standardization of the conventional assessment requirements emerges as a pertinent concern. However, by leveraging project-specific 'employer's information requirements (EIR) and BIM execution plan (BEP), the outlined workflow can be integrated into BIM-based projects.

1. Introduction

Circular economy (CE) is a sustainable economic system in which today's products serve as resources for future products, resulting in an economy whose growth is not dependent on the availability of new resources [1]. CE deals with the shift from the contemporary linear consumption approach, based on the take-make-use-dispose model, to a closed-loop approach, which, among other applications, replaces disposal with reuse and recycling in the linear consumption model [2]. Due to the significant resource consumption and overall environmental impact of the built environment, the European Commission listed it among the major sectors in which the CE concept would be implemented within the CE action plan [3, 4]. The application of the CE concept to the built environment resulted in the conception of the circular building (CB) model and the building circularity assessment (BCA) methodologies used for analyzing the degree of building circularity. Similarly, the adoption of BIM is on the rise within these frameworks (CB and BCA) [5].

This paper aims to support the automation of the building detachability assessment process, within the current BCA framework, using a BIM-based framework. To achieve this, first, currently available BCA methodologies were reviewed to identify key assessment factors and the significance of detachability assessment (DA) within these BCA methodologies. Thereafter, the existing DA methodologies were analyzed for their level of detail and integration within the BIM-based framework. The possibility of further integrating the DA methodologies within the BIM-based framework was assessed, after which a methodology for automating the BIM-based DA process was proposed and prototypically tested.

2. Background and related works

There are currently different approaches for carrying out BCA, focusing on different aspects of the CB framework, such as the environmental, technological, or economic aspects [6]. Some BCA workflows employ building sustainability frameworks such as lifecycle assessment (LCA) and costing (LCC), while others are built on the material circularity index (MCI) model, a CE assessment framework developed by the Ellen MacArthur Foundation (EMF) [7, 8]. In their research, Zhang et al. [7] identified the MCI-based BCA approach as the key BCA methodology applied to the technical dimension of the CB framework [7]. As this research is based on the detachability of buildings, which falls within the technological aspect of BCA, MCI-based BCA methodologies were reviewed to identify key assessment factors and the significance of detachability assessment within them.

2.1. Material Circularity Index (MCI) Research Trend

Over the years, circularity assessment based on the MCI model developed by the EMF has been adopted, and its implementation in the built environment has been increasingly improved [9]. Examples of BCA methodologies that build on the MCI approach, arranged in order of incremental improvement, are those from Verberne Jeroen [10], van Vliet [11], Alba Concept, and Madaster [12]. The BCA methodologies employed by these works are called Building Circularity Indicators (BCI) because they are based on the assessment of set parameters using indicators.

The BCI developed by Verberne [10] builds on the MCI methodology from EMF [13], applied to the built environment by employing Elma's [14] concept of the „design for transformable structures“, and based on the building material hierarchy introduced by [14]. Building circularity is assessed beginning at the material level with the MCI, progressing to the product (component) level with the product circularity indicator (PCI), and to the building-system (sub-system) level with the system circularity indicator (SCI). Finally, the BCI (the system level) is calculated by aggregating the SCI values.

Van Vliet [11] adopted the same BCI structure as Verberne [10] but modified the building detachability assessment approach within its PCI, SCI, and BCI calculation methods (**Table 1**). Contrary to the seven indicators used by Verberne [10], Van [11] considers twelve indicators grouped into technical, process-based, and financial-based indicators. These indicators decision was made based on the work of Durmisevic [14], Verberne [10], and van Oppen [15]; however, the technical indicators used build on the work of Durmisevic [14] and Verberne [10]. Alba Concept, in line with the developmental trend of the MCI-based BCA, similarly modified their detachability indicator, cutting down the number of indicators used to two. The only factors considered are the connection types and their accessibility. [12]

The most recent development in the detachability assessment research trend was ascribed to Madaster [16] as it is currently being applied in the Madaster material passport platform (MPP). However, other organizations, such as the Alba concept, were also involved in the research process [17]. In this methodology, four indicators are considered, namely the connection type, connection accessibility, edge confinement, and enclosure form, which all belong to the physical decomposition category of Durmisevic ￼ DfD framework. It is key to note that, though the name used for the indicators tends to change from research to research, each indicator written on the same horizontal row in **Table 1** has the same meaning across the methodologies in which it is being considered and the empty cells denote indicators that are not considered within the respective methodology.

Table 1. Overview of the detachability assessment indicators within the MCI-Model

Decomposition categories	DfD factors by Durmisevic (2006)	Technical Indicator			
		Verberne (2016)	van Vliet (2018)	Alba Concept (2018)	Madaster (2021)
Functional	Functional Separation	Functional Separation	Independence	-	-
	Functional Dependence	Functional Dependence	Method of fabrication	-	-
	Structure of Material Level	-	-	-	-
	Clustering	-	-	-	-
Technical	Base element specification	-	-	-	-
	Use of Life cycle	-	-	-	-
	Technical Lifecycle	Technical Lifecycle	-	-	-
	Component and element Lifecycle in relation to size	-	-	-	-
	Type of relational pattern	-	Type of relational pattern	-	-
Physical	Assembly direction based on assembly type	-	-	-	-
	Assembly sequence	-	Assembly Sequence	-	Enclosure form
	Geometry of product edge	Geometry of product edge	Assembly Shape	-	Edge Confinement
	Standardization of product edge	Standardization of product edge	-	-	-
	Connection type	Connection type	Connection type	Connection type	Connection type
	Connector Accessibility	Connector Accessibility	Connector Accessibility	Connector Accessibility	Connector Accessibility
	Tolerance	-	-	-	-
	Morphology of Joints	-	-	-	-

From the MCI research trend, three main observations were drawn. Firstly, the BCA methodology adopted by each research is based on the MCI assessment framework developed by EMF [13]. Secondly, the assessment categories (MCI, PCI, SCI or ECI, and BCI) used in these BCA methodologies are based on the building material hierarchy introduced by Durmisevic [14]. MCI is assessed on the material level, PCI on the component level, SCI on the (sub-) system level, and BCI on the whole building level. Thirdly, building disassembly (i.e., detachability) plays a vital role in these BCA methodologies, as its evaluation was the main factor modified by each research.

2.2. *BIM-based Building Circularity Assessments (BCA)*

Five main studies related to the integration of BIM in building sustainability assessment and automation processes were evaluated to devise a workflow for the BIM-based DA process[30–34]. Some examples of BIM-based BCA approaches include the „BIM-based Whole-life Performance Estimator“ (BWPE) [18], „Building Information Modelling based Deconstructability Assessment Score“ (BIM-DAS) [19], and steel structure deconstructability assessment scoring (SS-DAS) [20]. Generally, these studies conducted their circularity assessments by enriching the building model with additional parameters required by their tools to evaluate the building and ran the circularity analysis in the Revit Dynamo environment or using MATLAB (BWPE). In the case of the BIM-DAS tool, examples of additional parameters included are the building elements’ recyclability, toxicity, reusability, lifespan, etc. The BWPE used MATLAB for its calculations by using the material quantities derived from the Revit-generated bill of quantities as input.

On the other hand, from the MCI research trend discussed in section 2.1 above, Madaster is the only solution that uses open BIM in its workflow. Similarly, the Madaster BIM-based BCA approach is currently the most used in the industry-practise in several countries and thereby the most matured approach [21]. Madaster has also been identified as the only BCA tool that supports open-BIM workflow

[22]. With respect to these, the DA approach within Madaster was adopted and further evaluated by this research.

The Madaster platform stores building material and product information, which can be updated and evaluated throughout the building's lifecycle. With this information, building circularity, potential salvage value, and environmental impact can be assessed [23]. Its BCA methodology builds on the MCI research trend that originated from Verberne [10] and the DA method developed by van Vliet [17]. Building detachability is evaluated at the material and element level, and the indicators used are grouped as connection detachability index and composition detachability index as shown in **Figure 1** below. The connection detachability index assesses the ability of components to be deconstructed based on the connector types used and their accessibility. Whereas, the composition detachability index assesses detachability based on component arrangement.

Figure 1. Madaster Detachability Indicators [17]

On the Madaster platform, building information can be inputted either through Information Foundation Class (IFC) format or Microsoft Excel file format. Following the information input, building elements are matched with their corresponding products on the platform. Thereafter, the circularity and detachability of the building elements are computed. For computing the degree of building detachability, Madaster expanded its existing custom property set, „Pset_Madaster“, to contain the fields required for assessing components' disassembly potential, as shown in **Table 2** below. [16, 17]

Table 2. Madaster detachability Pset data field, adapted from [16]

DETACHABILITY INDICATOR	PSET_MADASTER DATA FIELD
CONNECTION TYPE	DetachabilityConnectionType
	DetachabilityConnectionTypeDetails
CONNECTION ACCESSIBILITY	DetachabilityAccessibiliity
DEGREE INTERSECTION	DetachabilityIntersection
ENCLOSURE FORM	DetachabilityProductEdge

However, research into the application of Madaster has shown some limitations [5, 22]. Theißen et al. [22] observed in their research on the application of Madaster for assessing the circularity of ventilation and air-conditioning (VAC) system, a high level of subjectivity in the tool's output. This subjectivity arises from the need for planners to fill out the detachability assessment data field in the Pset-Madaster. Through this, the credibility of the detachability assessment depends on the information the planner provides, which depends on the planner's expert knowledge of the installation and disassembly of the VAC system, which can vary from person to person. A similar research conducted on building elements also points to a similar drawback [5]. This research is targeted at reducing this high level of subjectivity, by deriving the DA indicators value using readily available BIM model information.

3. Analysis of building detachability indicators for BIM integration

To derive a detachability assessment workflow that relies less on assessors' input and consequently reduces the subjectivity in BIM-based projects, analysis was conducted on both a native BIM format using Revit and an open BIM data format using IFC4. This analysis evaluates the extent to which geometric and semantic properties required for building detachability assessment can be derived from a BIM model.

Table 3 represents the four indicators employed in the DA methodology by van Vliet [17]. It specifies the building level at which they are assessed and outlines the type of information needed for their evaluation, categorized into semantic and geometric information.

Table 3. Information required for analysing each indicator.

INDICATORS	ASSESSED ON		INFORMATION NEEDED	
	Element Level	**Material level**	**Semantic Information**	**Geometric Information**
Connection Type	🟩	🟩	Examples Screw, Bolt, Nail, Cements-sand mix	
Connection Accessibility	🟩	🟩		* Component Arrangement * Connection points *distance surrounding connection points (m, mm, m²)
Degree Intersection	🟩		* Element Life span (years) * Building Layer (Structure, Skin, Space …)	* Component Arrangement
Enclosure Form		🟩	* Material life span (years)	* Component Arrangement

3.1. Assessment of Autodesk Revit model structure for Detachability Analysis

In this subsection, we assess the Autodesk Revit ontology for the availability of required information for deriving each of the four detachability indicators. To aid in this assessment, a 3D model of two connected walls with level of development (LOD) 350, detailing the wall materials, was created in Revit. The available geometric and semantic information in this model was analysed in relation to the indicators' requirements. Additionally, BIMForum's [24] specification on information requirements in model elements, according to their LOD 350, was reviewed to determine the design phase in which the required information should be included in the model during the design process.

Table 4 summarizes the output of the analysis. The second column (titled hierarchy) points to the different levels at which the indicators are being assessed. The third column shows the design phase in which the indicator information can more easily be extracted, varying between the early and detailed design phases. Lastly, the fourth column states the availability of the indicator information within the Revit model structure. While there is no universal definition for the content of early and detailed design models, in this study, we consider the detailed design phase to start from LOD 300. This decision aligns with the insights provided by research from Schneider-Marin et al. and DEGES [25, 26], wherein the model LOD is correlated with design phases across various countries.

Table 4. Indicator information availability check in Revit-model structure

Indicator	Hierarchy	Design Phase	Indicator Information
Connection Type	Element level	Detailed Design	Directly implemented
	Material level	Detailed Design	Not available
Connection Accessibility	Element level	Early phase design	Needs to be processed from model information
	Material level	Detailed Design	Not available
Degree Intersection	Element level	Early phase design	Needs to be processed from model information
Edge Confinement	Material level	Detailed Design	Not available

3.2. Assessment of the IFC Schema for Detachability Indicators Analysis

We analyzed the IFC documentation by buildingSMART for the availability of IFC schemas containing the information required for deriving each detachability indicator. Subsequently, to gain a better understanding of these schemas and check the availability of their values in an IFC model, the wall model, **Figure 3** from section 3.1 above, was exported to IFC format using the IFC4 „Design Transfer View„ model view definition (MVD). IFC 4 „Design transfer view" was used as it supports advanced geometric and relational representation of the model components [27]. However, it is key to note that this MVD is currently in a draft developmental state and is not particularly focused on model-based sustainability assessment, which may result in some inadequacy in its use for DA [27].

The evaluation process was executed utilizing Blender software in conjunction with „IfcOpenShell„ [28]. Blender is an open-source 3D computer software that allows for 3D manipulation and includes a scripting interface that supports Python programming language [29]. IfcOpenShell helps parse IFC files from their implicit geometry to explicit geometry, allowing for the viewing, editing or modification of IFC model schema using Python programming language [28]. Using BlenderBIM and IfcOpenShell, a better understanding of the IFC schema could be achieved, and the identified schemas in the IFC documentation could be checked within the IFC models. **Table 5** summarizes the outcome of the examination.

Table 5. Indicator information availability check in IFC Schema & IFC Model

Indicator	Information Needed	Available in IFC Schema	in IFC Model
Connection Type	Element Level	Available	
	Material Level	Not Available	
Connection Accessibility	Element Level	Not Available	Processable
	Material Level	Not available	
Degree Intersection	Element Level	Available	
Enclosure Form	Material Level	Not Available	

3.3. *Evaluation and current limitations*

The evaluation of the detachability indicators in the Revit ecosystem (section 3.1) and IFC schema (section 3.2) identified three assessable indicators: connection type, connection accessibility, and degree intersection, with their accessibility limited to the element level of their respective application. Furthermore, we observed that the complete assessment of the detachability indicators using solely the readily available BIM semantic and geometric information is currently not feasible within the current Revit and IFC ecosystem. Model semantic enrichment would be required, as both the IFC schema and Revit ecosystem do not completely capture all the required information.

Deriving the required information for the „enclosure form“ indicator, however, proved more challenging. This indicator is based on the material level of buildings and requires elaborate material representation detailing the edge shape of the individual material. In **Figure 3**, for instance, the indicator considers the shape of each material to assess the ease of removing the central „orange material” from the construction, without deconstructing its surrounding materials. Meanwhile, in the IFC schema, aside from the *IfcRelAssociatesMaterial* class and its related subclass *IfcMaterialLayerSetUsage* and *IfcMaterialProfileSetUsage*, there are no further entities or classes that represent the shape or relationship of the *IfcMaterial* class. Therefore, deriving more complex material arrangements and shapes required by this indicator proved challenging. A similar challenge was observed in Autodesk Revit. In Revit, materials are mainly represented in layers (**Figure 4**); however, the enclosure form indicator requires a more detailed material representation detailing the edge shape of the individual materials (**Figure 3**). While this level of material representation can be visually presented in Revit, its geometric representation is not practical. Furthermore, it was observed that the availability of a schema, entity, or class in the IFC documentation does not guarantee the availability of the entity information in the IFC model.

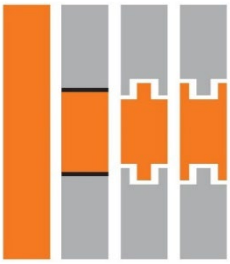


Figure 2. Exemplary material representation required for „Enclosure form“ indicator assessment [17]

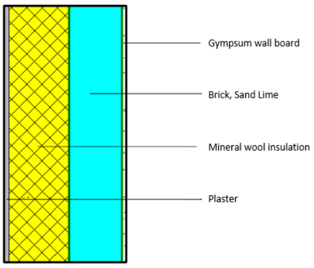


Figure 3. Material arrangement with an exemplary wall visualized with Autodesk Revit

4. Framework of a BIM-based Building Detachability Assessment

4.1. General Framework

Although the reviewed studies follow a similar BIM implementation and automation procedure, the ONIB approach was adopted as it gives more detailed information on how these steps (**Figure 5**) can be implemented. Firstly, using business process models and notations (BPMN), the conventional process model for deriving each indicator value is represented. Secondly, a matrix of all required attributes for deriving each indicator is created based on their process model. Thirdly, these attributes are represented in a BIM model. This is achievable in projects through the creation of Employer's Information Requirements (EIR) and BIM Execution Plan (BEP). Lastly, the analysis is conducted using the assessment tool.

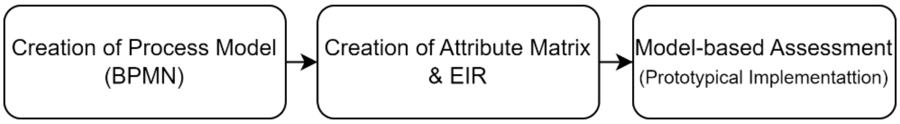


Figure 4. Proposed framework of a BIM-based Building Detachability Assessment

4.2. Process model (BPMN)

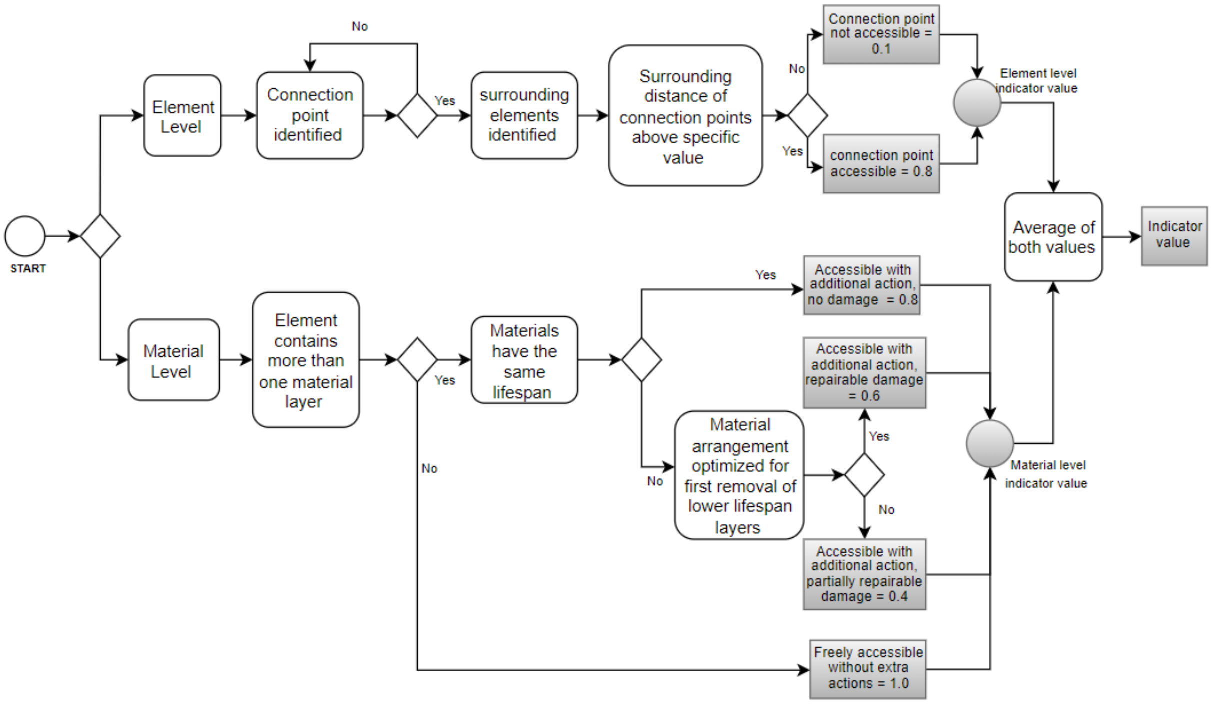


Figure 5: Connection accessibility process model

The process models form the basis of this workflow as it leads to the identification of model properties and rulesets needed for deriving each 'indicator's value. Conventionally, the derivation of these values depends on expert knowledge. However, the process diagram helps represent this expert knowledge and outlines the decision-making process for choosing each indicator value. This makes the assessment process transparent and allows for incremental improvements as knowledge grows or assessment requirements change. **Figure 6** shows the process model for the connection accessibility indicator from the prototypical implementation conducted for this research. Additionally, as the BIM ecosystem does not contain all the required information for deriving each indicator (as outlined in section 3), the process model highlights the additional required model properties.

4.3. *Creation of Attribute matrices*

The attribute matrices serve as a tool for translating the conventional expert knowledge represented by the process model to a data structure that can be represented by the BIM model, such that all the information required for deriving each indicator value can be taken directly from the model. They outline the geometric and semantic properties required by the BIM model for the complete assessment of the indicators. They also form the basis for defining the EIR and BEP required for the implementation of the DA workflow in BIM-based projects.

For the successful implementation DA workflow within a project, the use case of the BIM model for building detachability assessment, as well as the model information requirements for its complete execution, must be clearly stated and defined within the EIR and BEP. This is essential as a high level of information standardization is required for this assessment process. Nevertheless, in the prototypical testing of the workflow in this research, the BIM model was developed to contain all the information outlined by the attribute matrix.

To ensure creating clear, consistent and understandable matrices, the specific structure and primary information content of the matrices need to be defined. This will prevent ambiguity and serve as a template for incremental improvement of the assessment workflow. **Table 6** below outlines the structure and exemplary content for the attribute matrices created for the connection accessibility indicator.

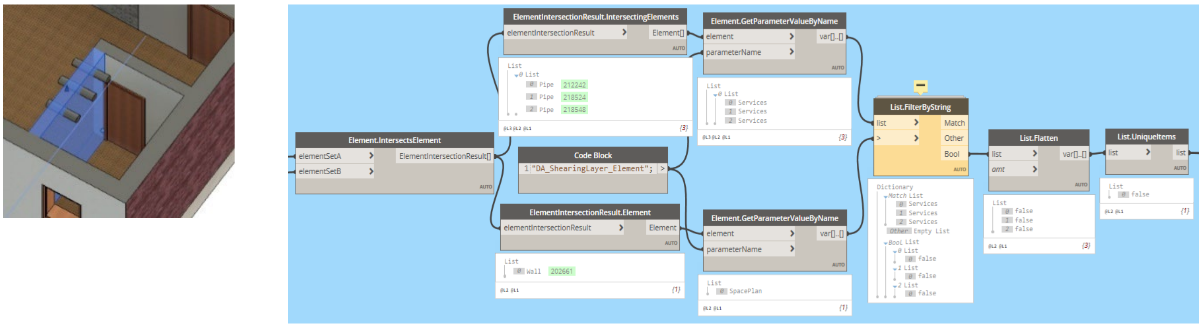
Table 6. Information content requirement for the attribute matrices, based on [34]

Information Requirement	**Range of values**	**Example**
Indicator	Name of the indicator	Connection accessibility
Assessment level	The building level in which the indicator assessment is being carried out [Element level or Material level]	Material level
Attribute Documentation	Decribes the form of the attribute documentation with the BIM model [component geometry or component attribute]	component attribute
Type of check	describes the attributes checked within the model [geometric check or attribute check]	logical check of component attribute
Logical check	Logical question used to assess the indicators criteria requirement using the BIM-model	check 2: Do all the materials in the material layer have the same lifespan
Need for additional parameter	Is an additional parameter needed to be added to the model to complete this assessment? [Yes or No]	yes
parameter type	The type of attribute parameter [IFC parameter OR custom-shared paramter]	Custom-shared parameter
Attribute name	Attribute name; provided a new custom parameter was added to the model	DA_Lifespan_Material
Attribute explanation	Explanation of what the custom parameter defines	defines expected material lifespan
Attribute datatype	the data type of the attribute [string, int, boolean etc.]	int
Unit	the attribute unit [m, years, etc.]	year

Similarly, to ensure clarity and uniformity when defining the custom parameters required for the assessment process, defining a standard naming convention is essential. This makes it easier to identify parameters that are particular to the detachability assessment workflow within the BIM model (**Figure 7**). **Figure 8** below shows the chosen naming convention.

4.4. *Prototypical implementation and Case study*

To validate the introduced BIM-based detachability assessment workflow, a case study was conducted using the Revit ecosystem (a Closed-BIM approach). Using Revit, the model was created to meet the requirement for deriving each indicator's value according to their respective process model and attribute matrices, and the assessment calculations were conducted using Revit Dynamo. A Closed-BIM approach was chosen due to the interoperability challenge faced in the Open-BIM ecosystem. For instance, custom parameters added to the building materials, in the authoring software (Revit) were not exporting to IFC. Also, parameters added to the building materials of the already exported IFC model were only visible in some BIM software. Dynamo, on the other hand, has good integration with Revit, ensuring easy and seamless access to the assessed model's geometric and semantic information within the dynamo scripting environment. **Figure 9** shows an exemplary indicator assessment using Dynamo.



```
1 "DA_ShearingLayer_Element";
```

```
List
  0 List
    0 Pipe 212242
    1 Pipe 218524
    2 Pipe 218548
```

```
List
  0 List
    0 Services
    1 Services
    2 Services
```

```
List
  0 Wall 202661
```

```
List
  0 SpacePlan
```

```
Dictionary
  Match List
    0 Services
    1 Services
    2 Services
  Other Empty List
  Bool List
    0 List
      0 false
    1 List
      0 false
    2 List
      0 false
```

```
List
  0 false
  1 false
  2 false
```

```
List
  0 false
```

Figure 6. „Degree Intersection“ indicator assessment implementation in Dynamo

Figure 10 below shows the model used for this case study, created using Autodesk Revit 2021. The model was created to meet the basic requirements of the indicators to be assessed according to section 3.1 (**Table 4**), which resulted in the creation of a multi-LOD model. The prototypical assessment is primarily based on the wall elements, and they were modelled to a LOD of 350. This is because the „connection type“ and „connection accessibility“ indicators involve material level assessment, and the required material information is modelled in LOD 350 according to the BIMForum [24] specification. Also, four different wall construction types (two exterior and two interior wall types) are represented in the model, differing mainly in their material arrangement, particularly because of the „connection type“ and „connection accessibility“ indicators, as they involve the material level assessment of the wall elements**.**

For the other model elements (e.g., pipes), LOD 200 suffices, as only their approximate representation is required for this case study. The pipes in the model were specifically included for the assessment of the „degree intersection“ indicator and as pointed out in section 3.1(**Table 4**), early phases model elements are sufficient for this indicator's assessment. The use of a multi-LOD model for this case study was practical, as different elements require different level of information and geometry for the completion of this assessment, which is a common practice in the interdisciplinary decision-making phase of a BIM project [35]. **Figure 13** shows the result visualization of the model in Revit following its analysis by Dynamo, wherein the walls are colour-graded based on their detachability.

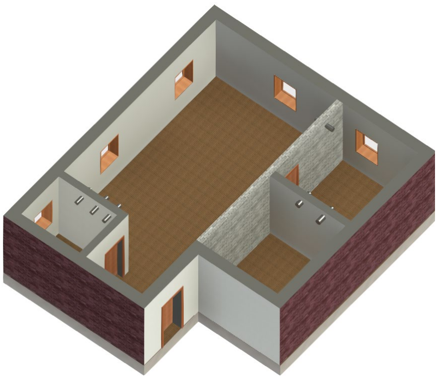
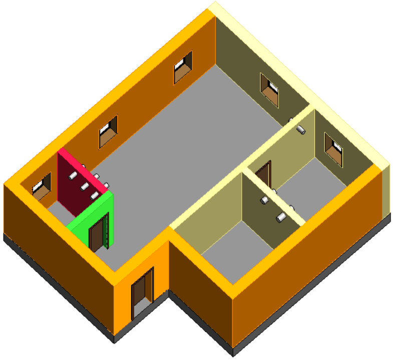


Figure 7. Case study model



Detachability	Detachability Index	Colour
Very High	0.8 - 1.0	🟩
High	0.6 - 0.8	🟩
Medium	0.4 - 0.6	🟨
Low	0.2 - 0.4	🟧
Very Low	0.0 - 0.2	🟥

Figure 8. Detachability index result visualization

4.5. Limitations

The methodology proposed in this research shows the possibility of automating and better integrating building detachability assessment process into BIM. However, both the proposed workflow and its prototypical implementation have some limitations.

Firstly, due to the non-standardized format of the detachability indicators assessment requirements and procedure, their complete representation using a process model proved challenging. Their assessment rules are not explicitly specified and are generalized across all building components, making it difficult to effectively represent their requirements for specific building components. Similarly, as the indicators were not originally intended for BIM implementation, their representation with BIM ontology proved challenging.

Secondly, in the prototypical implementation of the proposed workflow, high dependence on the use of custom parameters to meet the model requirements for automating the detachability assessment process was observed. According to the analysis from section 3, this is because some semantic information required to completely assess the indicators is not readily available in the model and needs to be added as property sets. An example is the model elements' shearing layer (according to [36]), which is required for assessing the degree intersection indicator. The required geometric information, however, could be derived from the model.

Also, both the IFC schema and Autodesk Revit are limited in their possible representation of the materials within building elements. This prevents the detailed geometric representation of the materials as required by the indicator and the simplification of the indicators' process model to the level that can be accommodated by the possible material representation. Another limitation observed with working on building materials is the inability to export the custom parameters added to the building materials from Revit to IFC. In aid of resolving this challenge, the custom parameters were added to the materials in the already exported IFC model through Python scripting using IfcOpenShell. However, while the added properties were visible in some BIM software, such as BIMcollab ZOOM, they were not visible in others, such as Solibri and DesiteBIM. This contributed to the use of a closed BIM approach for implementing the proposed workflow.

5. Conclusion and Outlook

This research contributes to the knowledge of BIM-based building detachability assessment and building circularity assessment in the following ways. Firstly, the review conducted on current BCA methodologies identified building detachability as a key assessment factor within the current BCA framework (section 2.1). Secondly, in the process of addressing the limitation of the currently most adopted BIM-based BCA methodology, implemented by Madaster, its detachability indicators were evaluated for the degree to which their value can be entirely derived from a BIM-model. From this evaluation, we observed that the current closed and open-BIM framework (Revit ecosystem and IFC schema) are limited in completely representing all required information for DA without model enrichment.

However, contrary to the current implementation by Madaster, which takes the final DA indicators' values as input, the proposed workflow takes generally available and easily verifiable information as input (e.g., material lifespan, elements shearing layer, etc.), outputting the final indicators values. Through the creation of the detachability indicators’ process models and attribute matrices, the BIM-model requirement for analysing each indicator can be derived. The process models represent the expert knowledge for conducting this assessment, it clearly outlines the decision-making process for deriving its values, which can be peer-reviewed, accepted, or updated as required. Thereby promoting the transparency and objectivity of the assessment process. Furthermore, through the creation of attribute matrices and thereby the use of EIR and BEP, the proposed workflow shows how the detachability assessment process, and the entire BCA process can be successfully incorporated into a BIM-based building design project.

With respect to the research findings and limitations, a key step towards the complete automatization of the detachability assessment process is the development of a more standardized and explicitly rulebased detachability indicator assessment criteria by circularity specialists. In developing these requirements, hands-on research on the deconstruction of selected building components (such as walls, roofs etc.) should be conducted, and through this, element-specific assessment criteria should be developed. This will improve the accuracy and clarity of the assessment process and make it easier for BIM integration.

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