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Chair of Computational Modelling and Simulation

Estimating Circularity of Building Elements Using BIM

Master's Thesis

Of the Master of Science program Civil Engineering

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Abstract

The circular economy (CE) concept aims at developing a sustainable economic system whose growth is independent of the availability of new resources. Due to the resource intensity of the construction sector (among other factors), it is one of the main sectors where the CE concept is being applied, resulting in the circular building (CB) concept. The CB concept entails the ability for building components and materials to be kept in a closed use-cycle; however, due to the complexity of buildings, a significant factor that can ensure building circularity is its detachability. Building detachability is the extent to which building components can be deconstructed without damage, and this master thesis targets the optimization of its assessment process using Building Information Modelling (BIM). To achieve this, the detachability assessment processes from currently available building circularity assessment (BCA) methodologies and their integration with BIM were analysed. Followed by the research into a workflow for automating building detachability assessment using BIM. The adopted workflow for this thesis entails representing the detachability assessment process using business process models and notations (BPMN), deriving the model information requirements for the assessment through the creation of attribute matrices and developing a dynamo script to conduct the assessment process. It was discovered that effectively interpreting the conventional detachability assessment requirements will result in better BIM integration and automation. However, there is a need for better standardization of the conventional assessment requirements. Likewise, through the use of projects' employer's information requirements (EIR) and BIM execution plan (BEP), the adopted workflow can be integrated into BIM-based projects.

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List of Abbreviations

AEC	Architecture, Engineering, and Construction
AIA	American Institute of Architects
BAMB	Building as a Material Bank
BCA	Building Circularity Assessment
BCAS	Building Circularity Assessment Scoring
BCI	Building Circularity Index
BEAM	Building Environmental Assessment Methods
BEP	BIM Execution Plan
BIM	Building Information Modelling
BIM-DAS	Building Information Modelling based Deconstructability Assessment Score
BPMN	Business Process Model and Notation
BPS	Building Performance Simulation
BWPE	BIM-based Whole-life Performance Estimator
CB	Circular Building
CDW	Construction and Demolition Waste
CE	Circular Economy
DfD	Design for Disassemble
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)
DI	Detachability Index
DIN	Deutsche Institut für Normung (German Institute for Standardization)
ECI	Element Circularity Index
EE	Embodied Energy
EIR	Employer's Information Requirements

EMF	Ellen MacArthur Foundation
EoL	End-of-Life
EU	European Union
GBI	Green Building Index
HOAI	Honorarordnung für Architekten und Ingenieure
IDM	Information Delivery Manual
IFC	Industrial Foundation Classes
ISO	International Organization for Standardization
LCA	Lifecycle Assessment
LOD	Level of Development
LoD	Level of Detail
LOG	Level of Geometry
LOI	Level of Information
LOIN	Level of Information Need
LP	Leistungsphasen (Service phases)
MCI	Material Circularity Index
MP	Material Passport
MPP	Material Passport Platform
MVD	Model View Definition
ONIB	Optimierung der Nachhaltigkeit von Bauwerken durch die Integration von Nachhaltig- keitsanforderungen in die digitale Methode Building Information Modeling (Optimizing the sustainability of buildings by integrating sustainability requirements into the digital method Building Information Modeling)
PBCI	Predictive Building Circularity Index
PCI	Product Circularity Indicator
QL	Quantity Level
SBC	Standard Building Components

SCI	System Circularity Indicator
SS-DAS	Steel Structure Deconstructability Assessment Scoring
UMI	Urban Mining Index
VAC	Ventilation and Air-conditioning

1 Introduction

Circular economy (CE) can be described as a sustainable economic system in which today's products serve as resources for tomorrow's products, resulting in an economy whose growth is independent on the availability of new resources (Ellen MacArthur Foundation, 2013, p. 2). 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, in the linear consumption model, with reuse and recycle (Arup, 2016, p. 9). The initial abundance of cheap natural resources has funded the linear consumption approach; however, due to the increased scarcity of natural resources to fulfil the ever-increasing demand of the growing population, the switch to a CE is essential. For instance, there is a projected increase in population to about 9 billion by 2050 and a projected increase in purchasing power of over 3 billion people by 2030 (Cheshire, 2019, p. 13; UN DESA, 2022). These projections back the need for a changed resource consumption approach and the adoption of the CE concept.

In Europe, the CE concept gained increased popularity following the establishment of the Ellen MacArthur Foundation (EMF) and the release of the CE action plan by the European Commission in 2015 (K. Rahla et al., 2021, p. 3). Due to the significant resource consumption and overall environmental impact of the built environment, it was listed by the European Commission among the major sectors requiring the implementation of the CE concept. The built environment accounts for about 40% of the global energy consumption, 50% of overall resource extraction, and over 35% of waste generated in the EU. Meanwhile, the effective management of construction materials can result in about an 80% reduction in these impacts. (European Commission, 2020b, p. 11; Maggie et al., 2012)

The CE concept applied to the built environment led to the conception of the circular building (CB) concept, aimed at closing the resource consumption loop of the built environment. CB adopts existing building sustainability methods such as building lifecycle assessment (LCA) and applies other tools such as material passport (MP) and design for disassemble (DfD) to design for the circularity of buildings, influencing the entire life cycle phases of the building. For instance, DfD is based on the design of buildings, such that their materials and components can be easily deconstructed at the end of their useful life. Therefore, its application spans from the early design phases of buildings to their end-of-life phases. Likewise, the MP intends to make information on materials and components within the building readily available whenever needed. Through this information, materials and components in old buildings can be planned into new ones, further promoting the circularity concept.

1.1 Motivation

Building Information Modelling (BIM) is increasingly being applied to various areas in the construction industry, all through the building's lifecycle, right from the early design phase of the building till its end-of-life (EoL) phase. BIM offers numerous advantages to the Architecture, Engineering, and Construction (AEC) sector, such as the increased cost-effectiveness of BIM-implemented projects, improved interaction between parties involved in projects, increased construction planning efficiency etc. (Talebi, 2014). However, the BIM methodology is more established in some construction applications than others. One of the BIM applications still in its infancy is its application to the EoL phase of buildings (Akbarieh et al., 2020).

The building EoL phase plays a significant role in the overall sustainability of the built environment, as some of the built environment's adverse effects are related to this phase. Example of which is the vast amount of waste generated by the construction sector. In 2014, the European Union (EU) reported an estimated 333 million tonnes of waste generated from construction and demolition waste, with Germany topping the list with approximately 85 million tonnes (Kabirifar et al., 2020, p. 3). Similar to this, the increased significance of construction materials' embodied energy (EE) in relation to the overall building emission and energy consumption, from 5% in 1996 to over 40% in 2016, is another reason for the increased attention in building EoL phase (Ness & Xing, 2017).

The CB concept can, however, be applied to help tackle these challenges by closing the use cycle, thereby reducing construction waste and limiting dependency on new resources. In light of this, similar to building LCA, which measures the environmental impact of building with the aim of reducing their adverse effects, building circularity assessments (BCA) are also being conducted to measure the conformity of buildings to the circularity concept, and BIM can be applied to boost the effectiveness of this assessment process. Therefore, BIM has been recommended and is increasingly implemented, right from the conceptual stages of the building design phases to its EoL phase, to help promote building circularity. (Honic et al., 2019)

1.2 Research Objectives

The main aim of this research is to automate the building detachability assessment process, carried out within the current building circularity assessment framework, using a BIM workflow. To achieve this aim, this research is framed by several research objectives, which will be investigated throughout this thesis.

The first research objective is to determine the currently available building circularity assessment methodology, the assessment factors considered in these methodologies, the significance of detachability assessment within these methodologies, and the current existing detachability calculation methods within these BCA methodologies. This objective helps create the basis for this thesis by establishing the relevance of building detachability assessments and the current methods with which they are being carried out.

The second objective builds on the output of the first. Here the existing detachability assessment methods are evaluated for their level of detail and quantitativeness. Similarly, their current integration into the BIM framework will be evaluated. Here the most suitable and quantitative detachability assessment method will be selected for further investigation.

The third objective will assess the possibility of further integrating the selected detachability assessment methodology with the BIM framework. Firstly, all required information to carry out this assessment will be gathered; thereafter, the availability of this information in the BIM model will be analysed. The availability of this information will be checked for a Revit-based workflow. Additionally, the industry foundation class (IFC) schema by buildingSMART will be analysed for the availability of this information.

The fourth objective is to research and implement the methodology that allows for the automatic reading of the needed geometric and semantic information from a BIM model and analyse the detachability of its component. Finally, the fifth objective implements and validates the developed framework using a prototypical BIM model.

To summarize all these five objectives, the following research questions serve as a guide for this thesis:

1. What are the existing detachability assessment methods in the current BCA methodologies?
2. Is BIM currently being used by these methods? If yes, are there limitations to be improved?
3. How detailed are these detachability assessment models, and how quantifiable are they such that they can be quantitatively assessed?
4. What information would be needed for them to be assessed, and is it readily available in BIM models?
5. How can the detachability assessment BIM-based process be automated?

1.3 Outline and Structure

This thesis is structured into five main parts based progressively on its research objective. In chapter 2, the background knowledge is presented. This includes the definition and explanation of terms and concepts such as circular economy, circular building, building information modelling and their related concept. Also, in this chapter, the second research objective of understanding the current BCA methodologies and their detachability assessment models was fulfilled.

Chapter 3 is focused on the second and third research objectives. Here the available detachability assessment methodologies are evaluated in detail, along with the possibility of integrating them better into the BIM system. Thereafter, the possibility of automating the BIM-based detachability assessment method was researched in chapter 4, fulfilling the fourth objective of this thesis.

In Chapter 5, the developed workflow from chapter 4 was tested on a case study to verify its feasibility and effectiveness, and chapters 6 and 7 discuss the research limitations and provide an outlook for future work.

2 State of the Art

2.1 BIM

BIM is commonly interpreted both as a process (Building Information Modeling) and a product (Building Information Model), and is defined by Borrmann, König, et al. (2018, p. 4) as follows:

"**A Building Information Model** is a comprehensive digital representation of a built facility with great information depth. It typically includes the three-dimensional geometry of the building components at a defined level of detail. In addition, it also comprises non-physical objects, such as spaces and zones, a hierarchical project structure, or schedules. Objects are typically associated with a well-defined set of semantic information, such as the component type, materials, technical properties, or costs, as well as the relationships between the components and other physical or logical entities […]. **The term Building Information Modeling (BIM)** consequently describes both the process of creating such digital building models as well as the process of maintaining, using and exchanging them throughout the entire lifetime of the built facility […]". (Borrmann, König, et al., 2018, p. 4)

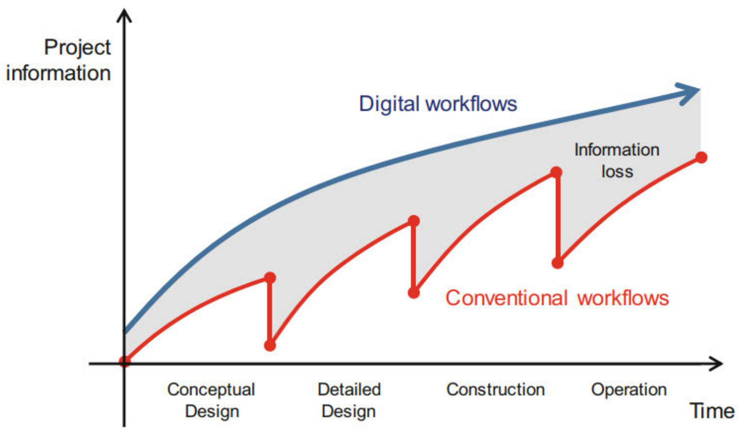


Figure 2-1: Information loss along conventional workflow vs BIM workflow (Borrmann, König, et al., 2018, p. 3)

Building Information Modeling is a business process that allows stakeholders in the AEC sector to work together, giving them access to the same information and preventing data loss during handovers that occur at different phases of construction designs, as illustrated by Figure 2-1. The planning and realisation of a construction project is a complex process, and to successfully create a high-performing building, there is a need for constant interaction between the people involved in the project throughout the design process (WBDG, 2022). This access to information is one of the advantages offered by the BIM process.

Though known for its more realistic visual representation, the BIM model is not limited to the three dimensions (3D). It gains additional dimension when specific types of information are added to it according to the purpose the model is to serve (BibLus, 2018). In addition to the 3D model, the generally accepted dimensions of BIM continue until 7D with each dimension meant for a particular use case (Figure 2-2), such as for project time management, construction cost calculation, etc. (UnitedBIM, 2019b). As summarized by Figure 2-2, the 4D BIM is used for project time scheduling and planning, 5D BIM for project cost calculation, 6D BIM involves sustainability simulations, and the 7D BIM contains information used for facility management.

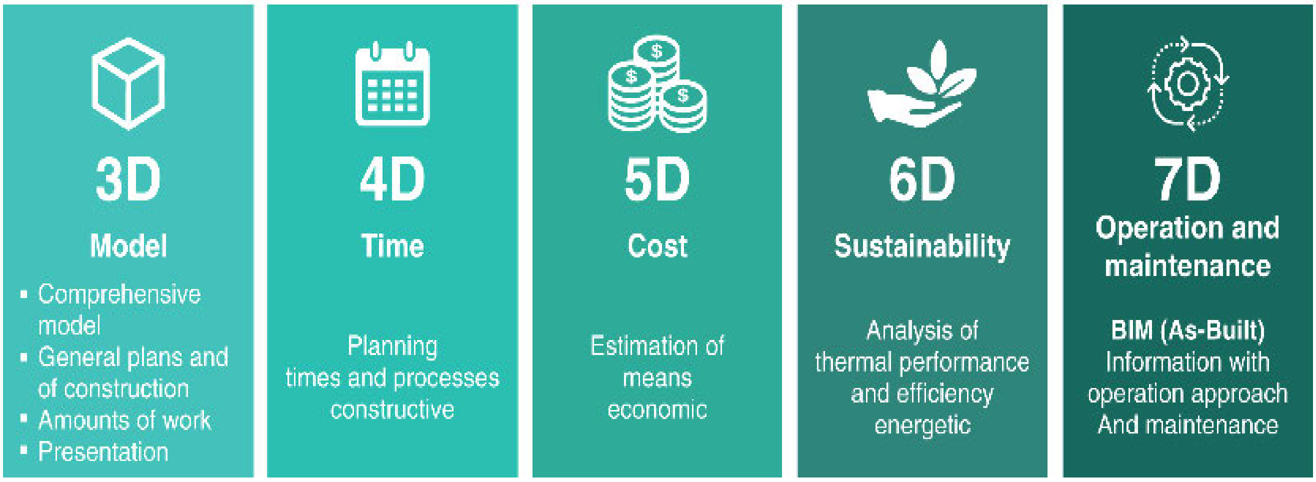
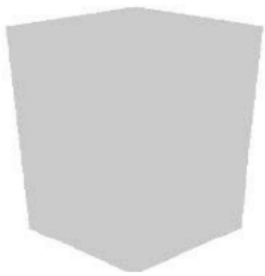
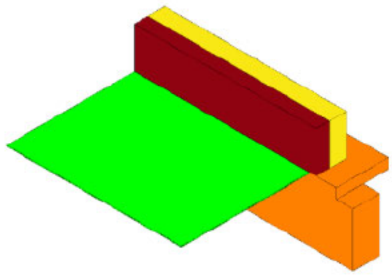
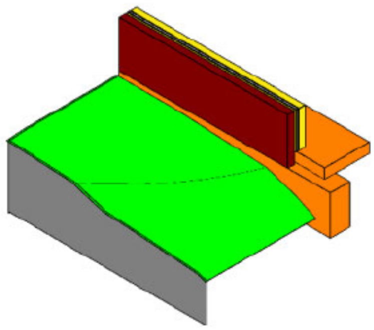
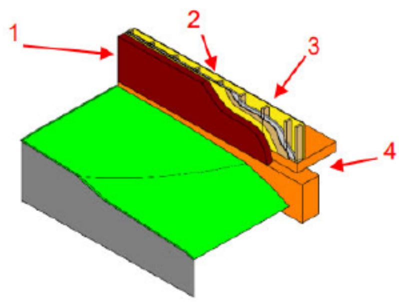


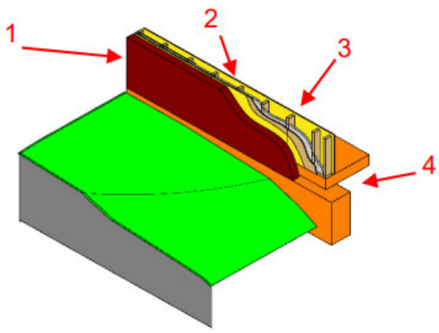
Figure 2-2: BIM Dimensions (CalyMyor, 2022)

2.1.1 BIM Model Information

According to the BIMForum (2021, p. 5), the level of development (LOD) specification was developed to improve the quality of information transmitted among the stakeholders involved in a BIM project. LOD gives the stakeholders an understanding of the model element information progression from the conceptual phase to the more detailed phases, by providing the basic information requirements for each design stage. The American Institute of Architects (AIA) introduced LODs in 2008, and it ranges from LOD 100 to LOD 500, with an increase in model information from LOD 100 to LOD 500 as shown in Table 2-1. Thereafter, LOD 350 was introduced by the BIMForum working group, in 2013, to provide the information needed for adequate trade coordination (BIMForum, 2021, p. 5; Cathi, 2013)

Table 2-1: LOD description, example of an exterior wall veneer, based on data from BIM Forum 2021 (BIMForum, 2021)

LOD	Description (BIMForum, 2021, p. 16)	Images (BIMForum, 2021, p. 77)
LOD 100	"LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate"	
LOD 200	"At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LOD 200 elements must be considered approximate."	
LOD 300	"The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs. The project origin is defined and the element is located accurately with respect to the project origin."	
LOD 350	" Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs." 1. "Wall veneer element 2. Skin layers … 3. Core framing 4. Concrete sleb edge"	

LOD 400	"An LOD 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs." 1. "Individual masonary units 2. Skin layer including Moisture barrier, sheathing and insulation 3. Core framing 4. Bolt 5. Concrete slab edge 6. Weep holes"	
LOD 500	"The Model Element is a field verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements."	

Each LOD is made up of geometric and non-geometric information (semantic information), referred to as the level of geometry (LOG) and level of information (LOI) of the BIM model, respectively. LOD has had different interpretations over the years, it often holds different meanings in different regions and is often used interchangeably as level of detail (LoD) (Abualdenien & Borrmann, 2022, p. 372). However, BIMForum (2021, p. 16) gave the distinction between LOD and LoD as follows:

"Level of *Detail* is essentially how *much* detail is included in the model element. Level of *Development* is the *degree to which the element's geometry has been thought through* – the degree to which project team members may rely on the information when using the model". (BIMForum, 2021, p. 16)

Therefore, LoD is simply the amount of information in a model, while LOD is the amount of relevant information in a BIM model. Figure 2-3 gives an exemplary distinction of the two using an inverted T-beam.

Figure 2-3: Difference between LOD and LoD (Abualdenien & Borrmann, 2022, p. 373)

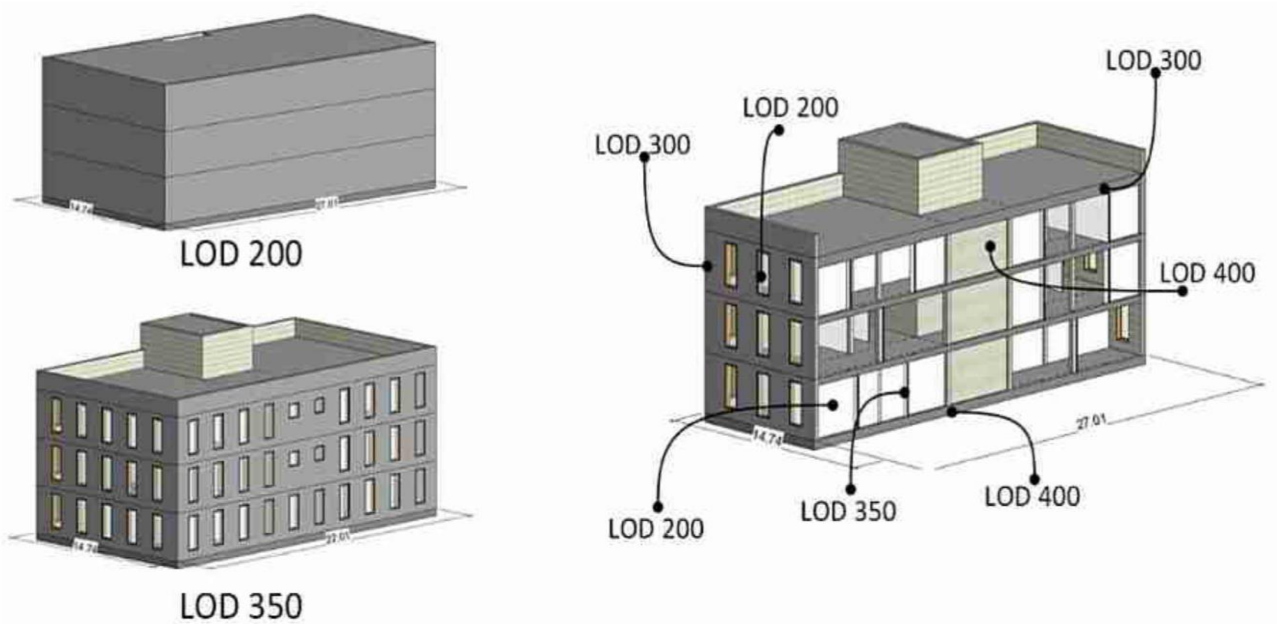


Figure 2-4: Model-based LOD vs Element-based LOD (Abualdenien & Borrmann, 2022, p. 375)

As illustrated by Figure 2-4 above, it is essential to note that LODs are ascribed per building element (such as doors, walls, roofs, etc.) in a BIM model and not to the entire model (BIMForum, 2021, p. 266). Therefore ascribing a particular LOD to an entire model, for instance, LOD 350, as shown in Figure 2-4, will be incorrect as different elements in the model may have varying LOD (DEGES, 2020, p. 6). In the same context, BIMForum (2021, p. 266) pointed out that design phases do not define the LODs of elements in a model, as the models are prone to contain different parts with different LODs, as seen in Figure 2-4. However, LOD requirements can be used as guidance for deliverables expected in different design phases. In light of this, DEGES (2020, p. 7) gave a correlation between LOD and project phases, “leistungsphasen” (LP 1-9), according to “Honorarabrechnung für Architekten und Ingenieure” (HOAI) as shown in Table 2-2.

Table 2-2: Comparison of HOAI project phase and LOD, adapted from (DEGES, 2020, p. 7)

HOAI Project Phase (LP)		LOD
LP 1	Conceptual planning	100
LP 2	Preliminary design	
LP 3	Design planning	200
LP 4	Approval planning	
LP 5	Implementation planning	300
LP 6	Tender	
LP 7	Contract award	400
LP 8	Construction work	
LP 9	Project management	500

Another similarly important concept or term governing information transfer in BIM projects is the recently introduced European standard called the level of information need (LOIN). LOIN specifies the specific geometric and semantic information needed by a particular stakeholder involved in BIM project design at a particular phase to complete a particular task. The LOIN is independent of the design LOD, it focuses mainly on communicating the information needed to complete a particular task during a project design phase. Unlike LOD, it does not represent the design maturity; therefore, a project still in an early design phase might be required by the LOIN to provide a building envelope with high LOG and LOI to ensure adequate energy simulation, which might be used for better decision-making. (Abualdenien & Borrmann, 2022, p. 374)

2.1.2 BIM Documents

To ensure the successful execution of a BIM project, legally binding documents are needed to guide the information requirements and workflows throughout the project phase, particularly the model's handover to the owner. As shown in Figure 2-5, these documents contain but not limited to: the organisation information requirement (OIR), BIM execution plan (BEP), project information requirements (PIR) etc. However, in particular, the BEP and the employer's information requirements (EIR) play a significant role. Both documents are part of the project contract and are particularly tailored for the project. (Borrmann, König, et al., 2018, p. 15; Scheffer et al., 2018, p. 239).

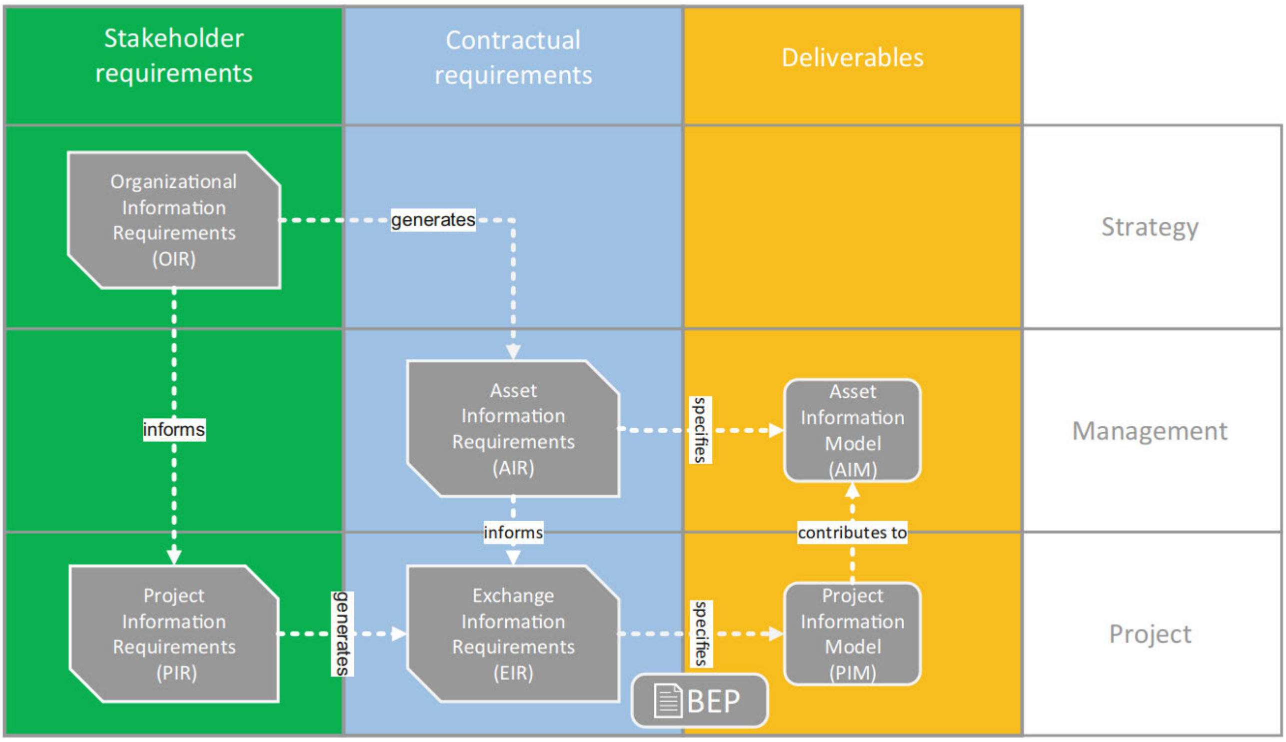


Figure 2-5: BIM Information Management documents (Scheffer et al., 2018, p. 239)

The EIR outlines the project owner's expectation concerning the implementation of BIM in the project, and the BEP serves as a response from the design team or contractor to the EIR, on how the owner's requirements will be met (UnitedBIM, 2019a). The EIR specifies requirements such as the LOI and LOG to be delivered for each element at different project stages, it specifies the different responsibilities, expected handover dates and data exchange formats (Borrmann, König, et al., 2018, p. 15). The BEP, in addition to fulfilling the requirements of the EIR, contains information such as the project implementation plan, the project collaboration goals, major project milestones specification, model deliverables, as well as software solutions to be used for the project (Scheffer et al., 2018, p. 242).

Understanding these information transfer documents such as LOD, LOIN, EIR and BEP are essential for this thesis as it gives the understanding of how the information needed for our methodology implementation can be required from the contractors or the design team.

2.1.3 Early Design Phases

As depicted by Figure 2-6 below, there is a higher opportunity to influence a project at the early design stages, with lesser cost than in the more mature stages of a project. As shown in Figure 2-6, the early stages of the design process are also the stages with the highest BIM workload, as they provide the highest opportunity for making changes and safe costs that may occur in the later stages of a traditional workflow. At the early design stages, clash detections can be carried out to resolve design conflicts between different design disciplines, which potentially would have been observed at the later stages in the traditional workflow (Borrmann, König, et al., 2018, p. 6). Therefore, since the goal of the building design is to create a high-performing building, all the stakeholders involved need to apply an integrated design approach starting from the early stages of the design process (WBDG, 2022).

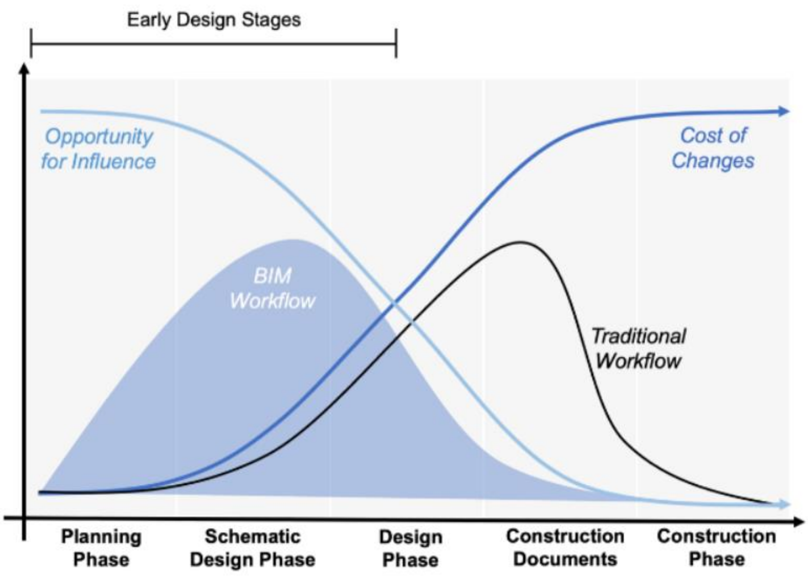


Figure 2-6: BIM design phases (Drewes & Kasimir, 2021)

There is no general definition of what the early design phases should entail. However, in their research, Schneider-Marin and Jimmy (2019) gave an overview of early design stages according to different countries. According to them, the early design phase in Germany spans through the first three HOAI phases, which similarly corresponds to the early design phases according to the AIA. Therefore, for this thesis, the early design phases will be defined as ranging from LP1 to LP3. Which, according to Table 2-2, correlates with LOD 200.

2.1.4 BIM Implementation

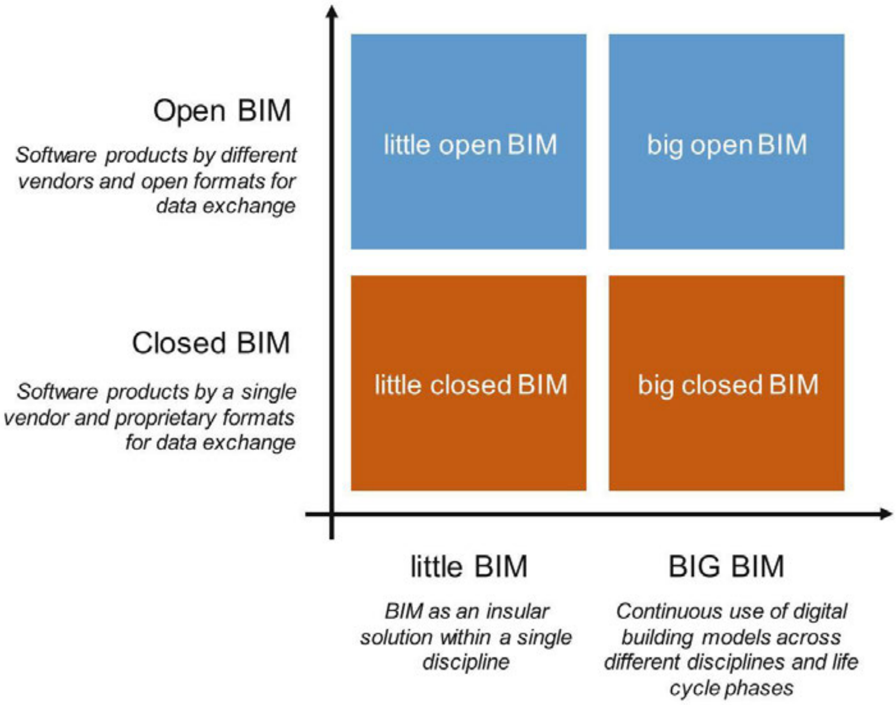


Figure 2-7: BIM implementation levels (Borrmann, König, et al., 2018, p. 12)

Figure 2-7 shows the different BIM implementation levels we have, which are: the little BIM, big BIM, closed BIM and open BIM. Little BIM can be referred to as the opposite of Big BIM, as closed BIM is the opposite of open BIM. Little and big BIM differ mainly based on the communication method employed by the stakeholders involved in a design process, using the BIM methodology. Little BIM occurs when a specific BIM software is used by an individual AEC specialist to carry out a discipline-specific task (Borrmann, König, et al., 2018, p. 11). The little BIM process is similar to the conventional workflow, where all the communication exists using plans, therefore not maximizing the full potential of the BIM process (drivecon, 2022). Contrary to little BIM, Big BIM involves model-based communication, between different stakeholders involved in a project design, all through the project lifecycle.

On the other hand, open BIM and closed BIM differ mainly based on the software range used for a project and how project files are being exchanged. Closed BIM involves the use of software from a single manufacturer, limiting the data exchange to the vendorspecific exchange format, whereas in an open BIM process, a vendor-neutral data transfer format is used, which ensures the use of project data and files between different BIM-software packages without information loss. Eventually, the aim is to tend towards the use of big open BIM, a combination of both open and big BIM workflow, thereby maximizing the full potential of the BIM process. An example of a vendor-independent data format that can support a big open BIM workflow is the Industry Foundation Class (.ifc) exchange format.

2.1.5 Industrial Foundation Classes (IFC)

BuildingSMART (2022) defines IFC as a vendor-neutral, standardized (ISO 16739-1:2018) digital description of the built environment that can be used for different use cases across many software platforms and hardware devices to promote the open BIM methodology. IFC uses an object-oriented approach to represent the geometry and semantic structure of a building model, its composing components, their spaces and the interrelationship between them (Borrmann, Beetz, et al., 2018, p. 84).

The IFC data schema was developed by buildingSMART International (bSI) to enable information loss-free data transfer between software packages from different manufacturers in the AEC sector, promoting an open BIM workflow. It provides a generic data schema that supports the model exchange needs of the different specializations in the construction industry throughout the building lifecycle, facilitating different software interoperability, and aiding a big open BIM workflow (Rafael, 2010). As there are currently a number of different modelling tools particular to different use cases, such as in the different BIM dimensions explained in section 2.1, the development of the IFC schema and ".ifc" exchange format significantly facilitates the smooth information exchange between these tools and use cases. Nevertheless, the realization of absolute interoperability still remains a challenge in the BIM ecosystem (Shirowzhan et al., 2020).

The IFC schema is defined using a data specification language called EXPRESS (ISO 10303-11, 2016). Though influenced by several programming languages such as Ada and C++, EXPRESS is not a programming language but a data modelling language created mainly for product data representation through schemas and constraints (Library of Congress, 2016). It employs an object-oriented modelling approach in which entities are taken as classes in the objected-oriented framework, and each entity can be assigned attributes and have relationships to other entity types (Borrmann, Beetz, et al., 2018, p. 87). Additionally, EXPRESS have qualities such as the ability to define inverse relationships between entities, the ability to create relationship with object groups using datatypes such as Lists, arrays, sets etc., and the possibility to use optional WHERE functions to define algorithmic conditions.

Due to its complexity and to ensure it could be maintained and extended, the IFC schema is structured into four main hierarchical layers, designed such that the upper layers can refer to the lower layer, but impossible vice versa. These layers are the resource, core, interoperability and domain layers, arranged from the bottom up (Borrmann, Beetz, et al., 2018, p. 88). The core layer forms the basis of the schema as all identifiable entities are derived from the IfcRoot class, which is contained in this layer. IfcRoot is an abstract and a root class for all entities defined in the core layer and the layers above it (BuildingSMART, 2020). IfcRoot has the Global Unique Identifier (GUID) attribute, therefore, all entities that inherit from the IfcRoot can be used independently. Figure 2-8 below shows an exemplary inheritance structure from the IfcRoot class.

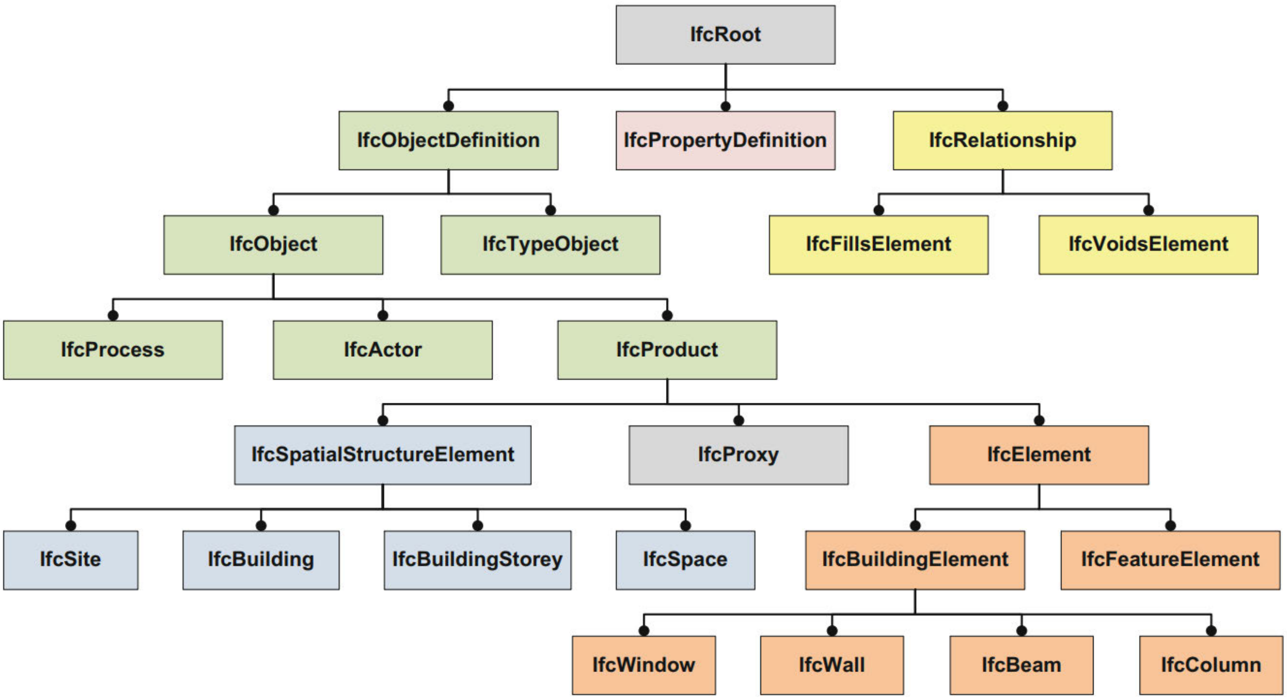


Figure 2-8: IfcRoot inheritance hierarchy (Borrmann, Beetz, et al., 2018, p. 91)

2.1.5.1 IDM & MVD

The IFC data model is extensive and mainly concerned with the data structure for describing the digital built environment; therefore, a generic IFC model might contain too much or too little information needed for a specific task or use case. The information delivery manual (IDM) and the model view definition (MVD) concepts were developed to tackle this issue (Beetz et al., 2018, p. 128). IDMs define the what, the when, the “by whom” and the “for who” details of the information transferred throughout the design process. The technical implementation of the IDM forms the MVD. Therefore MVDs are subsets of the IFC data schema (Figure 2-9), defined to support one or more workflow in the built environment sector by specifying properties, entities and attributes required by the workflow (bSI, 2020). It allows for the simplification of the IFC schema by sharing only information required for the specific workflow. Examples of currently available MVDs in the IFC 4 schema are:

- The “reference view”, optimized for coordination between the architectural, structural and building services domains
- The “design transfer view”, optimized mainly for one-way data and responsibility transfer
- The “Quantity take-off view” meant for construction cost estimation (buildingSMART Technical, 2021)

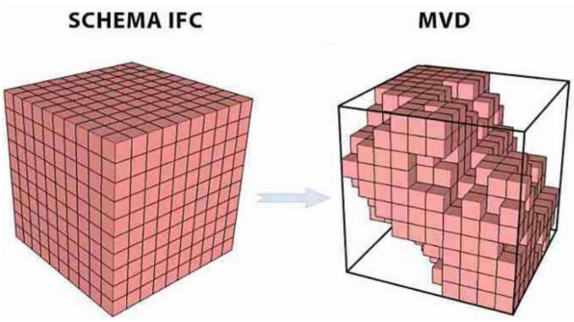


Figure 2-9: Illustration of MVD in IFC (BibLus, 2020)

2.2 Circular Building

Circular building (CB) can be explained as the application of the circular economy (CE) framework to the built environment. Therefore, in this section, as an introduction to the CB concept, circular economy will first be introduced. CE can be defined as follows:

“A circular economy is an industrial system that is restorative or regenerative by intention and design […]. It replaces the ‘end-of-life’ concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models.” (Ellen MacArthur Foundation, 2013, p. 7)

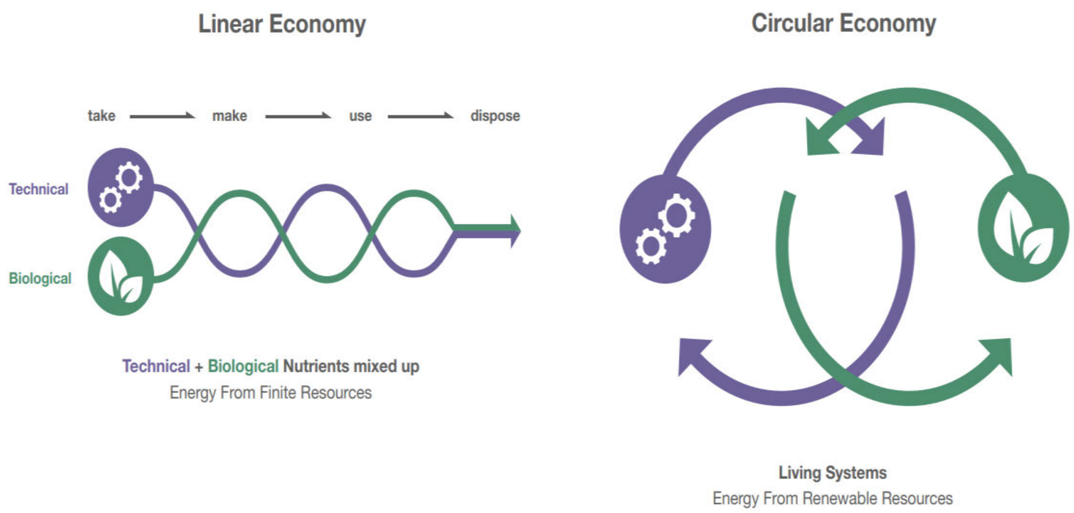


Figure 2-10: Linear to Circular Economy Approach (Arup, 2016)

Simply put, CE is the shift from the linear consumption approach, based on the take-make-use-dispose model, to a closed-loop system fashioned to eliminate disposal from the model (Figure 2-10) (Arup, 2016). To close the consumption loop, the 9R framework was introduced, which is based on the recovery, recycle, repurpose, remanufacture, refurbish, repair, reuse, reduce, rethink, and refuse (9R) of products and materials; arranged from the least to the most preferred option as shown in Figure 2-11 (José et al., 2017). However, from the 9R framework, recycling, reuse and reduce (the 3R framework) is the most applied approach in the CE concept, according to research conducted by Kirchherr et al. (2017, p. 226).

Circular economy ↑ Increasing circularity ↓ Linear economy		Strategies	
	Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
		R1 Rethink	Make product use more intensive (e.g. by sharing product)
		R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
	Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
		R4 Repair	Repair and maintenance of defective product so it can be used with its original function
		R5 Refurbish	Restore an old product and bring it up to date
		R6 Remanufacture	Use parts of discarded product in a new product with the same function
		R7 Repurpose	Use discarded product or its parts in a new product with a different function
	Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
		R9 Recover	Incineration of material with energy recovery

Figure 2-11: The 9R Framework Framework (Kirchherr et al., 2017, p. 224)

In line with EMF's definition and explanation of the CE concept, its advantages are not based solely on its environmental impact but also on its economic impacts (EMF, 2013). According to Kirchherr et al. (2017, p. 227), the anticipated financial benefit of adopting the CE business model fuelled its popularity in the industrial sector, while CE's environmental advantages led to its popularity in the academic sector. Similarly, the CE concept is encouraged by governmental bodies. This, for instance, is evidenced by the development of the European Union's CE action plan aimed at transforming Europe's economy from a linear to a circular model. In the developed action plan, the construction sector is one of the seven targeted sectors for achieving circularity in Europe by 2050, and CE applied to the built environment resulted in the CB concept (European Commission, 2020a).

The CB concept can be considered as an extension of already existing sustainability concepts in the built environment, encompassing the six sectors (environmental, technological, economic, societal, governmental and behavioural) considered in the CE framework, as shown in Figure 2-12 (Pomponi & Moncaster, 2017). Similar to the CE concept, the waste-saving and resource management potential (economic and environmental impact) of the CB concept are some of the primary reasons for its implementation. It seeks to eliminate construction waste by rethinking building materials as valuable resources to be reserved rather than disposed of after use, therefore, incorporating the circularity concept into the building design and management process (Kabirifar et al., 2020).

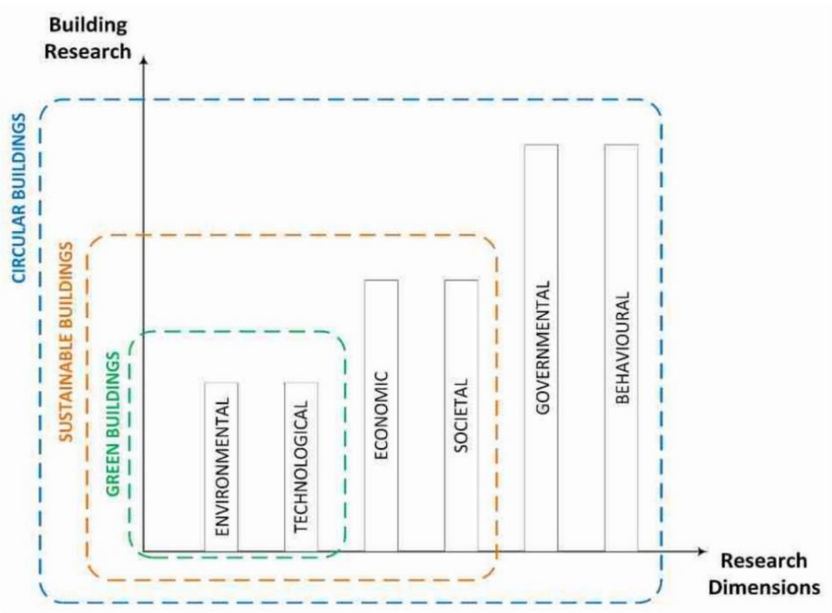


Figure 2-12: Built environment sustainability framework (Pomponi & Moncaster, 2017, p. 14)

The increased significance of construction materials' embodied energy (EE) in relation to the overall building emission and energy consumption, is another reason for the adoption of the CB concept. Buildings’ energy efficiency has improved over time, resulting in lower energy consumption during the building's use phase. This has, however, resulted in the increased contribution of building EE to the overall building emission and resource consumption. According to Ness and Xing (2017, p. 574), this proportion increased from 5% in 1996 to over 40% in 2016. In this regard, through the adoption of the CB concept, the EU has estimated a potential 80% reduction in the built environment emission (European Commission, 2020b, p. 11).

Nevertheless, according to Pomponi and Moncaster (2017, p. 4), CE solutions applied in other sectors are unlikely to be functional in the built environment due to the complexity of buildings and their extended life span. However, this challenge can be tackled through the adoption of the design for disassemble (DfD) and material passport (MP) concept (sections 2.2.1 and 2.2.3, respectively).

2.2.1 Design for Disassemble (DfD)

Design for disassemble (DfD) allows for the easy adaptation, renovation, reuse and recycling of building materials and components during the building use and EoL phase (Kanters, 2018, p. 1). It is applied from the early design phase of buildings to device construction approaches that will aid in the optimum removal and recovery of building components and materials without causing damage to them or their surrounding objects (ISO 20887, 2020). The DfD concept is not new, and its implementation can be observed as far back as the 19th century. Examples of which are: London’s crystal palace from 1851, Jean Prouvé's work from 1949 and the works of Archigram in the United Kingdom and Metabolist in Japan in the 1960s (Crowther, 2005; Kanters, 2018, p. 2). Archigram's "The Walking City" design, for instance, was created to highlight the possibility of entirely disassembling and transferring a 40-story building from one location to another and Metabolist's "Move" design allows for changing any building component, within the building, without affecting any other structural part (Elma, 2006, p. 86). However, this design method, DfD, was phased out in modern architecture due to the need for unique expertise and the high investment cost associated with it (Elma, 2006, p. 91).

To achieve circularity in the built environment, the DfD concept is currently being reintroduced into the design process of buildings. According to Elma (2006, p. 93), the concept of DfD is applied to the built environment on three main dimensions: structural, spatial, and material (Figure 2-13). On the spatial dimension, buildings are designed such that their spaces can be easily adapted for various uses, and this serves as the basis for the "Design for Adaptability (DfA)" concept. The structural dimension deals with the ease with which building components can be disassembled without causing damage to themselves or their surrounding components. This is the concept of building detachability and is referred to as the backbone of the DfD concept, as it influences the other two dimensions. Finally, the material dimension addresses the need for extended use of material through reuse and recycling.

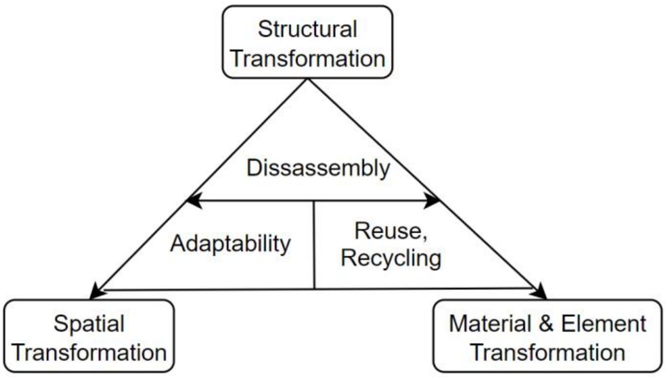


Figure 2-13: Three dimensions of Design for Disassemble (Elma, 2006, p. 93)

2.2.2 Building Detachability

The detachability of building components plays a vital role in building disassembly and forms the basis for DfD and DfA. "Detachability of a building is the extent to which objects can be dismantled at all scale levels, without compromising the function of the object or surrounding objects in order to protect the existing value" (Vliet et al., 2021, p. 7). Similar to DfD, the detachability concept is not new and has long been implemented in other industrial sectors (Shalaby & Saitou, 2008). However, in the research by Elma (2006) on the “design for transformable structures”, it was named as one of the key factors for DfD and has further been built on by researchers adopting the DfD framework or assessing the circularity of buildings (Zhai, 2020, p. 42).

The detachability of building materials, components, and systems adopt the “Theory of level” concept. “Theory of level” regards buildings as complex entities composed of smaller entities that can be classified into levels based on their structural or functional lifespan. A popular example of this model was developed by Brand (1995), and subdivides buildings into site, structure, skin, services, space plan, and stuff, as illustrated in Figure 2-14. In its application, the DfD concept seeks to separate building levels with longer lifespans, called the slow-changing levels, from those with shorter lifespans, called the fast-changing levels. Therefore, ensuring that the disassembly of elements in the fast-changing level will not affect those in the slow-changing level.

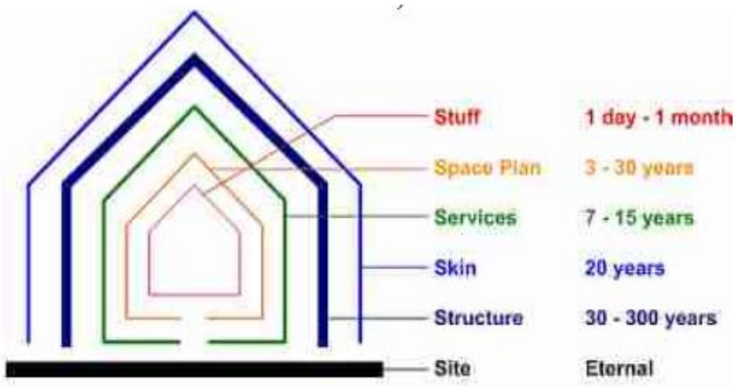


Figure 2-14: Shearing layers of buildings and their lifespan (Farouk &. Abdelsabour, 2019, p. 885)

The process of assessing building detachability is simply a method of evaluating the conformity of building design with the DfD concept, which according to Elma's (2006, p. 99) framework, is based on the ability to functionally, technically and physically decompose or separate building parts. In this framework, functional decomposition involves how functions are assigned to building elements. It encourages assigning different functions to elements with no structural connection to each other. This way, in the case of functional obsoleteness, elements can be disassembled with no structural implications to the building. Technical decomposition, on the other hand, is related to the construction method used. It encourages the specification of a base element, to which other elements are attached and allows for a reverse construction method when deconstructing. By this, the building is constructed such that building parts with shorter lifespans can be deconstructed first. Lastly, physical decomposition deals with the geometry of the building elements and how they are connected to one another. Some factors considered include the types of connections between elements and the ability to access these connection points.

As this thesis focuses on building detachability, more details on the detachability assessment methods considered in different circular building assessment methodologies will be further discussed in section 2.3.

2.2.3 Material Passport (MP)

Douglas et al. (2017) defined material passports as a "(digital) set of data describing defined characteristics of materials and components in products and system that give them value for present use, recovery, and reuse" (Douglas et al., 2017, p. 3). In another definition, Heinrich and Lang (2019) described MP as a digital report that is stored and retrievable from a centralized database, called the Material Passport Platform (MPP), and contains relevant data for assessing building circularity.

MP intend to help tackle the challenge of information availability, which is one of the main challenges of the DfD and CB design concept. Though DfD is implemented in the design phase of buildings, it serves its purpose during the building's renovation (i.e. use phase) or at the building's EoL phase. MP makes information such as the detachability of components and their physical, chemical, and biological properties available whenever they are needed throughout the building lifecycle (Figure 2-15) (Heinrich & Lang, 2019). In light of its importance, the development of MPPs is among the strategies adopted by the EU for attaining circularity in the construction sector, evidenced by the EU Horizon 2020 project, Building as a Material Bank (BAMB), an example of a digital logbook implementation project, embarked on by the EU (Cordis, 2022).

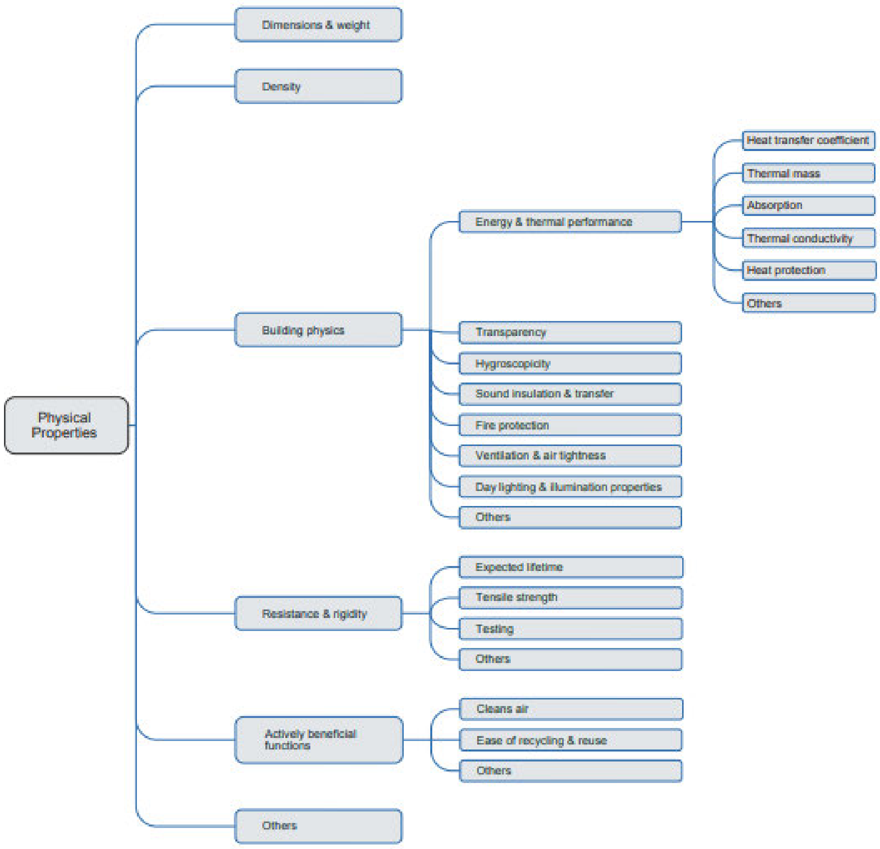


Figure 2-15: Example of physical properties stored in an MP (Heinrich & Lang, 2019)

Another significant advantage of MP is that it serves as an information source for the availability and location of reusable and recycled materials and components. This is significant because DfD and CB are measured not only on the material outflow from buildings, but also on the reuse of recycled and old materials and components from deconstructed buildings, in new buildings. This necessitates knowledge of the availability of reusable and recycled materials or components that can be designed into new structures. MPP provides this information, thereby aiding circularity. As defined, MPs are digital sets of data saved on digital platforms called MPP; therefore, this concept is associated with digitalization in the AEC sector. To facilitate the effective implementation of the MPs, DfD and, therefore CB design, MPPs are advised to be implemented in conjunction with BIM (Atta et al., 2021; Honic et al., 2019).

2.3 Building Circularity Assessment

Building Circularity Assessment (BCA) can be explained as a method for measuring the conformity of building design and management with the circular economy principles throughout the building lifecycle. BCA provide a medium for stakeholders involved in the building planning, design, and management processes, such as sustainability experts, architects, structural engineers, and others, to evaluate their work based on the CB and CE framework. It similarly provides an evaluation process for grading building circularity in green building rating systems such as the Leadership in Energy and Environmental Design (LEED) and the "Deutsche Gesellschaft für Nachhaltiges Bauen" (DGNB) rating systems. Furthermore, based on its output, governmental bodies can assess their progress in integrating circularity into the economy with respect to the built environment. (Zhai, 2020, p. 35)

There is currently no generally accepted approach for carrying out BCA, as different approaches tend to focus on different aspects of the CB framework, such as the environmental aspects, technological aspects, etc. While some BCA workflow employs already matured methods in the sustainable building framework such as LCA, others are built on the material circularity index (MCI) (section 2.3.1), a CE assessment framework developed by the Ellen MacArthur Foundation (Zhang et al., 2021).

From the review of 96 papers related to the evaluation method of CE in the built environment, Lovrenčić Butković et al. (2021, p. 5) identified LCA as the most commonly used method for BCA. In their observation, LCA is mostly used in conjunction with lifecycle costing (LCC), material flow analysis (MFA), and cost-benefit analysis (CBA), focusing mainly on BCA's environmental and economic dimensions. This buttresses the observation drawn by K. M. Rahla et al. (2019, p. 5), stating that the current BCA methodologies focus mainly on the environmental and economic aspects of Circular buildings. However, the scientific review by Zhang et al. (2021, p. 3) identified the MCI-based approaches as the key BCA methodology applied to the technical dimension of the CB framework. Therefore, since this thesis is based on the technological aspect, more focused will be placed on the MCI-based BCA methodologies and others related to it.

2.3.1 Material Circularity Index (MCI) Research Trend

Over the years, circularity assessment based on the MCI model developed by the Ellen MacArthur Foundation (EMF) has been widely adopted, and its implementation in the built environment has been increasingly improved (Cottafava & Ritzen, 2021, p. 3). The EMF (2015a) CE model seeks to keep materials in a closed biological or technical cycle. Decomposable organic materials are kept in a biological cycle, while non-decomposable components and products are kept functional in the technical cycle for as long as possible. The model is based on three main principles: (i) eliminating waste and pollution, (ii) keeping products and materials in a closed use-cycle through reuse and recycling, and (iii) regenerating the natural system through the avoidance of non-renewable materials and the preservation of renewable ones (EMF, 2015a, p. 7).

MCI is designed to measure the degree to which the circular flow of products has been maximized and its linear flow minimized in comparison to similar products in the industry. It evaluates three main product characteristics: the amount of virgin raw materials used in product manufacture, the amount of unrecoverable waste associated with the product, and the product's life span, as illustrated in Figure 2-16. (EMF, 2015a)

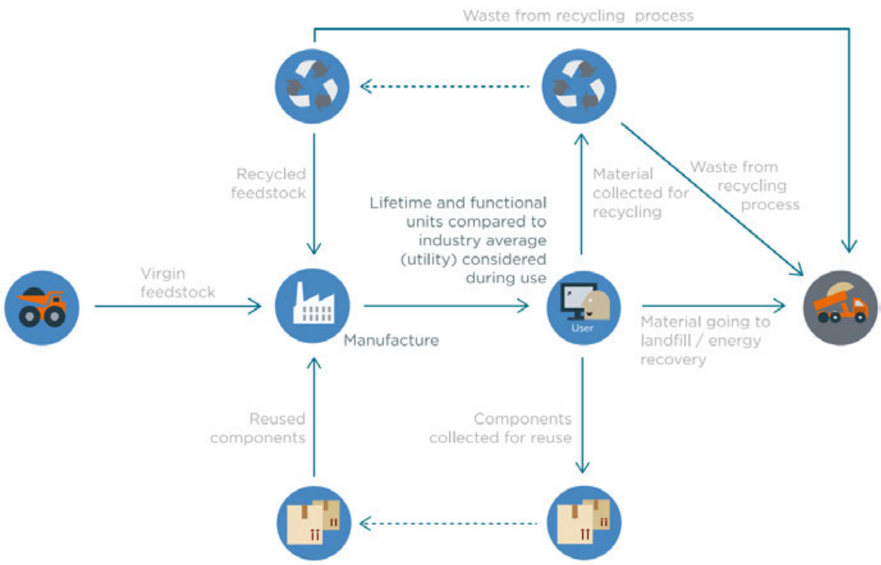


Figure 2-16: Exemplary circular material flow according to EMF (EMF, 2015b, p. 5)

Examples of BCA methodologies that build on the MCI approach, arranged in order of incremental improvement, are those from Verberne (2016), Van (2018), Alba Concept (2018), and Madaster (2021). The developmental trend of these methodologies was observed in the review conducted by Zhai (2020). 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 trend began with the work of Verberne (2016). The BCI developed by Verberne (2016) builds on the MCI methodology by EMF (2015a) and adopted it into the built environment by employing Elma's (2006, p. 158) concept of the “design for transformable structures”. The building circularity is assessed beginning at the material level with the MCI, progressing to the product level with the product circularity indicator (PCI), and to the building-system level with the system circularity indicator (SCI). Finally, the BCI is calculated by aggregating the SCI values.

Van (2018) adopted the same BCI structure as Verberne (2016) but modified the PCI, SCI, and BCI calculation methods, with the modifications based on the method used for assessing building detachability (Table 2-3). Contrary to seven indicators used by Verberne (2016), Van (2018, p. 120) considers twelve indicators (Figure 2-17), grouped into technical, process-based and financial-based indicators. These indicators decision was made based on the work of Elma (2006), Verberne (2016) and van Oppen (2017); however, the technical indicators used builds on the work of Elma (2006) and Verberne (2016). The other indicators considered by Van (2018) are: disassembly instructions, disassembler expertise, number of operations and deconstruction safety as process-based indicators, and disassembly cost as the financial-based indicator. The process-based indicators serve as preconditions for disassembly, and the financial-based factor measures cost as a driver for building disassembly. Van (2018, p. 92) further subdivided the technical disassembly factor into connection, and product disassemble factors, providing a more detailed methodology for assessing building detachability. Due to the modifications made by Van (2018, p. 92), it is possible to determine the building level at which the whole building, its systems, and products can best be disassembled. (Zhai, 2020, p. 43)

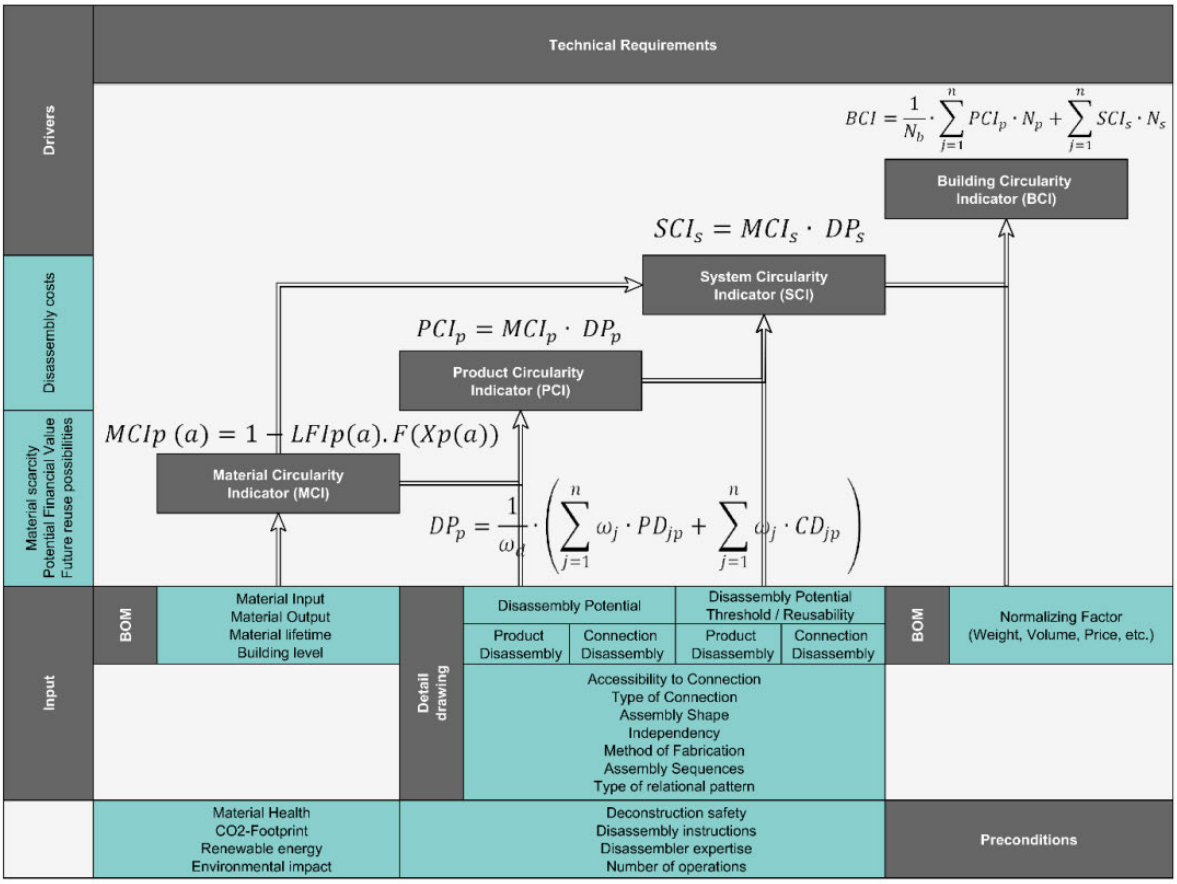


Figure 2-17: BCA methodology by Van Vliet (Van, 2018, p. 78)

Alba Concept (2018), 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. Similarly, the hierarchy for the assessment was changed. In place of SCI, Element Circularity Index (ECI) was assessed. According to Alba Concept (2018), elements are clusters of products that cannot be separated from each other without causing pronounced damage to the element or its surrounding elements. Therefore, a building element ends when there is a detachable connection. (Zhai, 2020, p. 44)

The most recent development in the detachability assessment research trend was ascribed to Madaster (2021) as it is currently being applied in the madaster MPP; however other organizations, such as the Alba concept, were also involved in the research process (Vliet et al., 2021). In this methodology, four indicators are considered namely the connection type, connection accessibility, edge confinement, and enclosure form as shown in Table 2-3 below, which all belong to the physical decomposition category of Elma's 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 2-3 below has the same meaning across the methodologies in which it is being considered.

Table 2-3: Detachability assessment indicators trend

Decomposition categories	DfD factors by Elma (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 Access bility	Connector Accessibility	Connector Access bility
	Tolerance				
	Morphology of Joints				

In general, the observations drawn from this research trend are: firstly, the BCA methodology adopted by each research is based on the MCI assessment framework developed by EMF (2015a). 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 Elma (2006, p. 117), as shown in Figure 2-18. 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.

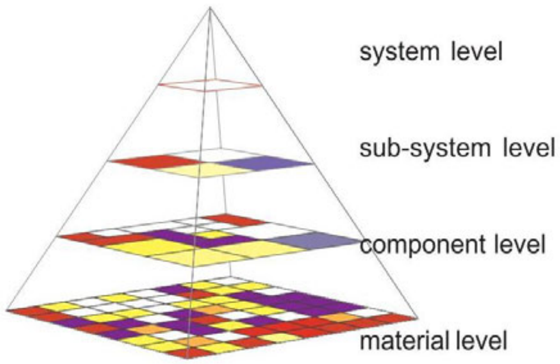


Figure 2-18: Hierarchy of material levels in building (Elma, 2006, p. 117)

2.3.2 Current indicator-based BCA models

In this section, recent and relevant BCA methodologies that employ the use of indicators will be reviewed and analysed. Following the MCI-based BCA methodology research trend discussed in section 2.3.1 above, Madaster (2022), being the most recent in this trend, will be reviewed further. Similarly, the BCA model from Cottafava and Ritzen (2021) and Platform CB'23 (2020) will be discussed, as they fall into the class of the most recent indicator-based BCA methodologies, according to a study carried out by Fayez and Lina (2021, p. 28). In their research into discovering the most relevant BCA models, Fayez and Lina (2021) reviewed 52 studies on the topic and pointed out the work of Cottafava and Ritzen (2021), Platform CB'23 (2020), EMF (2015a), Madaster (2021), and Verberne (2016).

However, EMF (2015a), Madaster (2021), and Verberne (2016) already fall within the trend discussed in section 2.3.1; therefore, the work of Cottafava and Ritzen (2021) and Platform CB'23 (2020) were adopted from this research for further review. Furthermore, to create a well-rounded understanding of building circularity and detachability assessment, Urban Mining Index (2021), as well as BCA concepts from DGNB and ISO, will be examined to gain a more comprehensive understanding of the topic and the range of detachability indicators considered.

2.3.2.1 Madaster

Madaster is a digital material passport platform (MPP) created in 2017 to address the issue of information availability in the circular building ecosystem. The platform stores building material and product information, which can be updated and evaluated throughout the building's lifecycle. Information stored by Madaster includes materials and products quality, quantity, source, location, etc. It also provides additional information such as their environmental impact, circularity, and the potential salvage value of buildings and their components. (Madaster, 2022)

The current Madaster BCA is called Circularity Indicator V2. It assesses the building circularity based on its material input, output, and detachability; and builds on the MCI research trend that originated from Verberne (2016). For the input flow, the amount of virgin and secondary materials used in construction are evaluated, and their results are displayed in kilograms (kg) and percentages (%) in relation to the entire input materials. Similarly, for the output flow, materials are categorized according to their EoL scenario, which is divided into reuse, recycle, and landfill, with the result displayed in kg and %.

Madaster uses the detachability assessment method developed by Vliet et al. (2021, p. 5). It is the second version of the uniform measurement method for detachability assessment, which is based on the improvement trend of Elma's (2006, p. 83) detachability assessment method. The building's detachability is evaluated at the material and element levels, and the indicators used are grouped as connection detachability index and composition detachability index (Figure 2-19). 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 components arrangement. (Madaster, 2021, p. 15; Vliet et al., 2021, p. 12).

The value for the three indicators employed, i.e., input flow, output flow, and detachability, are outputted per the building's functional layer (Figure 2-14) according to Brand (1995).

Figure 2-19: Madaster Detachability Indicators (Vliet et al., 2021, p. 12)

2.3.2.2 Platform CB'23

The Dutch national government aims to achieve a completely circular economy by 2050 and to reduce primary resource consumption by half by 2030. Platform CB'23 was created as a platform for construction stakeholders such as designers, recyclers, scholars, and others to help the Dutch government achieve its goal in the construction sector. Developing the Platform CB'23 circularity assessment framework is one step in that direction.

The circularity assessment framework has three main goals: to assess how well available material stocks are protected, how well the environment is protected, and how well material value is retained; and the indicators for this assessment methodology are based on these goals. Indicators 1–3 (Table 2-4) evaluates material stock protection, indicator 4: environmental protection, and indicators 5–7 material value retention. On the other hand, this framework was created for the entire built environment, not just buildings.

Detachability assessment is critical for this methodology because it is required to evaluate indicators 2, 5, 6, and 7. Indicator 2 measures the amount of available material for the next cycle, within which component and material detachability play an essential role. Indicators 5–7, which deal with the value retention of construction products and materials, also use detachability assessment to derive its indicator value. However, the detachability assessment methodology for this framework has yet to be developed and will be included in future developments.

Table 2-4: Platform CB'23 indicators, adopted from (Platform CB'23, 2020)

Indicator		Sub-indicator (examples)	Aim
1	Quantity of materials used (input)	* Quantity of primary materials used * Quantity of secondary materials used * ...	Existing material stocks protection
2	Quantity of materials available for the next cycle (output)	* Quantity avaialble for reuse * Quantity available for recycle	
3	Quantity of materials lost (output)	* Quantity used for energy production * Quantity sent to landfill	
4	Impact on the environment	* Ozone depletion * Climate change - overall * ...	Environmental protection
5	Quatity of initial value (input)	* Techno-functional value * Economic value	Material value retention

6	Quatity of value available for the next cycle (output)	* Techno-functional value * Economic value	
7	Quantity of existing value lost (output)	* Techno-functional value * Economic value	

2.3.2.3 Cottafava et al (2021)

The BCA framework developed by this research builds on the EMF’s (2015) MCI methodology. Therefore, this method can also be said to fall with the MCI-based BCA research trend, as the adjustments made were the addition of more environmental indicators and the adoption of an additional assessment hierarchy called the Predictive Building Circularity Index (PBCI).

On the material level of the building, in addition to carrying out circularity assessment, the environmental impact of the materials is assessed by evaluating their embodied energy (EE) and embodied carbon (EC) emissions. Likewise, the calculation of the PBCI only differs from that of BCI in how the detachability index (DI) weights are applied. The BCI in this framework is calculated similar to the previous methodology by Verberne (2016). However, to compute the PBCI, the DI weight is applied directly to compute MCI, to derive the recovery potential of each component individually.

The detachability assessment methodology adopted is, however, the same as that used by Madaster. Detachability is evaluated at the material and element levels, and the indicators used are grouped as connection detachability index (connection types and accessibility) and composition detachability index (assembly sequence and component shape).

2.3.2.4 Urban Mining Index (UMI)

"The Urban Mining Index is a system for the quantitative assessment of the recycling potential of building structures in new construction planning. Over the entire life cycle of the structure, all incoming materials and all resulting valuable and waste materials are calculated and evaluated according to the quality levels of their subsequent use" (Urban Mining Index, 2021).

To derive the UMI value of a building, the circularity of its input and output materials is examined and classified as closed-loop or loop-potential materials. Materials in the closed loop can be reused and recycled after their first lifecycle without loss in quality, while loop-potential is the sum of materials in a closed and open material loop. Open-loop materials are those whose quality reduces after their first lifecycle and can either be energetically reused or downcycled. To summarise, closed-loop materials are re-usable and recyclable materials, and open-loop materials are energetically reusable and downcycling materials. (Rosen, 2021, p. 91)

The UMI BCA methodology evaluates building circularity on six hierarchical levels: raw material, material, component layer, element, building component, and building level, focusing more on the first three. In the framework, the raw material and material levels are grouped together and assessed for renewability and reusability, the component level is assessed for detachability, and building circularity is assessed on an economic level (Rosen, 2021, p. 89).

On the material level, the pre-use (manufacture), use and post-use phases of the material are evaluated to determine its circularity (Figure 2-20). Material toxicity plays a vital role in this level as environmentally harmful materials are entirely omitted from the evaluation. For material input flow, the degree of circularity is measured as material recycling content (MRC) which is the percentage of secondary or recycled material used. Similarly, for material output flow, circularity is measured as material loop potential (MLP), which is the percentage of recyclable material in the building's output. (Rosen, 2021, p. 93)

Detachability and the degree of disassembled element purity are assessed on the component level (Figure 2-20). Non-destructive detachability is considered only for materials in the closed loop and not materials or components to be downcycled or incinerated. For the UMI framework, non-destructive material detachability serves as a qualifying criterion, as elements that are not detachable belong to the open loop and are exempted from the analysis. The detachability of elements is analyzed based on their connection types, referencing DIN 8593. Similarly, the degree of purity of disassembled parts is an exclusion criterion, as a required % purity must be achievable for an element before it is included in the UMI evaluation. (Rosen, 2021, p. 96)

On the economic level of the framework, two major factors are examined: the work factor and the value factor. The work factor measures the effort or energy required for deconstruction in Joules or Megajoules [MJ], while the value factor compares the salvage value of components to their disposal cost. The value factor is graded into two quantiles: the upper quartile represents revenue generated by selecting disassembly over demolition, and the lower quartile represents the extra cost inquired by selecting selective deconstruction. To calculate the work factor, building components were divided into five major groups based on their function, then analysed using various benchmarks and graded into quintiles. Overall, these three levels of evaluation are all interrelated, as shown in Figure 2-20 below, and the economic level can be regarded as an extension of the detachability assessment.

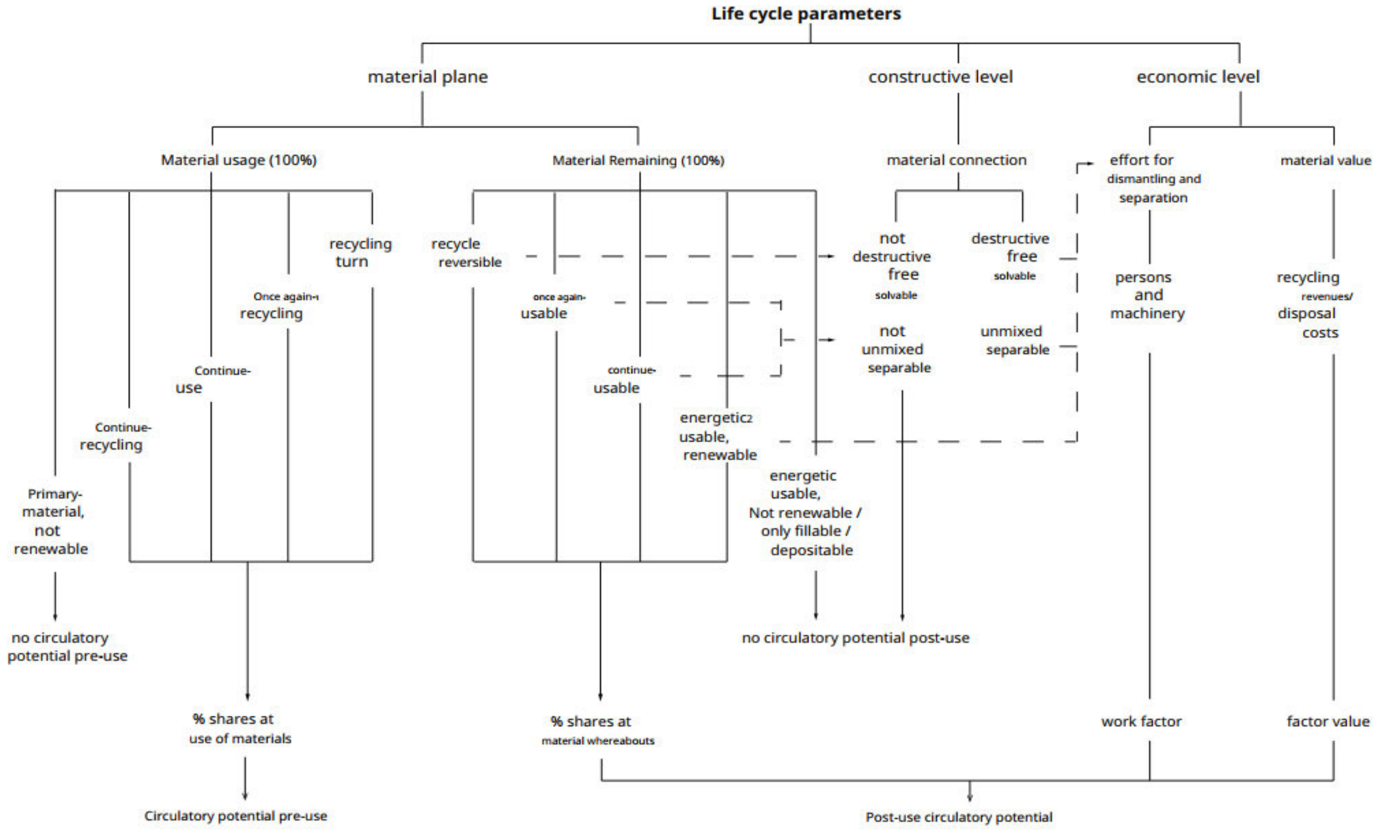


Figure 2-20: UMI BCA model (Rosen, 2021, p. 91)

Table 2-5 below gives an overview of the four BCA methodologies discussed in this section (section 2.3.2). It can be observed that the BCA model from Madaster and Cottafava and Ritzenat al (2021) are similar and have the same detachability assessment model. UMI and platform CB'23, on the other hand, takes a different approach. All four BCA model considers detachability as a key component in their model; however, while its assessment model is yet to be developed in platform CB'23, UMI takes a different approach compared to others. In the UMI BCA model, detachability serves first as qualifying criteria, assessed based on connection types, and undetachable components are entirely excepted from the assessment. Subsequently, the economic assessment level of the UMI BCA model can be considered as an extension of its detachability assessment, as it evaluates, in practical detail, the effort needed to carry out disassembly per component and the profitability of the process over normal demolition.

Table 2-5 Summary of BCA Methodologies with Indicators

BCA Methodology	research developed upon	Assessment Method	Detachability Considered	Detachability Assessment Methodology
Urban Mining Index (2021)	Nil	* Material Level (EoL scenario & environmental impact) * Component Level (detachability is assessed) * Economic Level (Work factor & Value factor)	Yes * Assessed on Component Level (p. 96)	* Considers Detachability as a non-quantifiable parameter * Detachability assessed based on connections types used based on DIN 8593 (p. 97), Work factor, and Value factor
Madaster (2021)	* Elma Durmiservic (2006) * Ellen MacArthur Foundation (2015) * Verberne Jeroen (2016) * Van Vliet (2018) * Alba Concept (2018)	* Material Flow Analysis (MCI) ** Input flow (Primary and secondary material sources) **Output flow (% reuse, recycle, landfill and incineration) * Drachability index	Yes	* Connection Detachability Index ** Connection Type ** Connection Accessibility * Component Detachability Index ** Element Intersection ** Edge shaped
Platform CB'23 (2020)	Nil	* Based on 7 indicators divided into 3 main classes (Table 2-4) ** Indicators for protecting existing stocks of materials (Indicator 1 to 3) ** Indicators for protecting the environment (Indicator 4) ** Indicators for Value retention (Indicators 5 to 7)	Yes * Assessed in Indicator 2 * Assessed in Indicator 5, 6, 7	* Assessment method not yet developed
Cottafava et al (2021)	* Ellen MacArthur Foundation (2015) * Verberne Jeroen (2016) * Van Vliet (2018) * Alba Concept (2018)	* Material Level (Material Environmental Inpact) * Supply Chain Level (MCI) * Component Level (Detachability Assessment)	Yes * Assessed on Component Level * Adopted from Alba Concept	* Connection Detachability Index ** Connection Type ** Connection Accessibility * Component Detachability Index ** Element Intersection ** Edge shaped

2.3.3 BCA from Standards and Building Certifications

2.3.3.1 DGNB TEC 1.6

DGNB TEC 1.6, according to its name “ease of recovery and recycling”, is an evaluation system within the DGNB certification system focused on assessing the implementation of building circularity in the building design phase. TEC 1.6 falls under the technical aspects of the DGNB system, and its evaluation score ranges from 2.5% to 2.9 % of the total building grading score, depending on the type of building being assessed.

TEC 1.6 measures building circularity using two main indicators, "ease of recycling" and "ease of recovery," referred to as indicators 1 and 2, respectively. The third indicator evaluates the incorporation of circularity design strategy into the design phases of the building from HOAI 1 to 5. In all three indicators, only some building components are considered, and they must be designed such that they can be constructed using standard methods, i.e., without needing special expertise. These components are the foundation, external walls, interior walls, floors, ceilings, and roof and are called "standard building components (SBC)" (Figure 2-21).

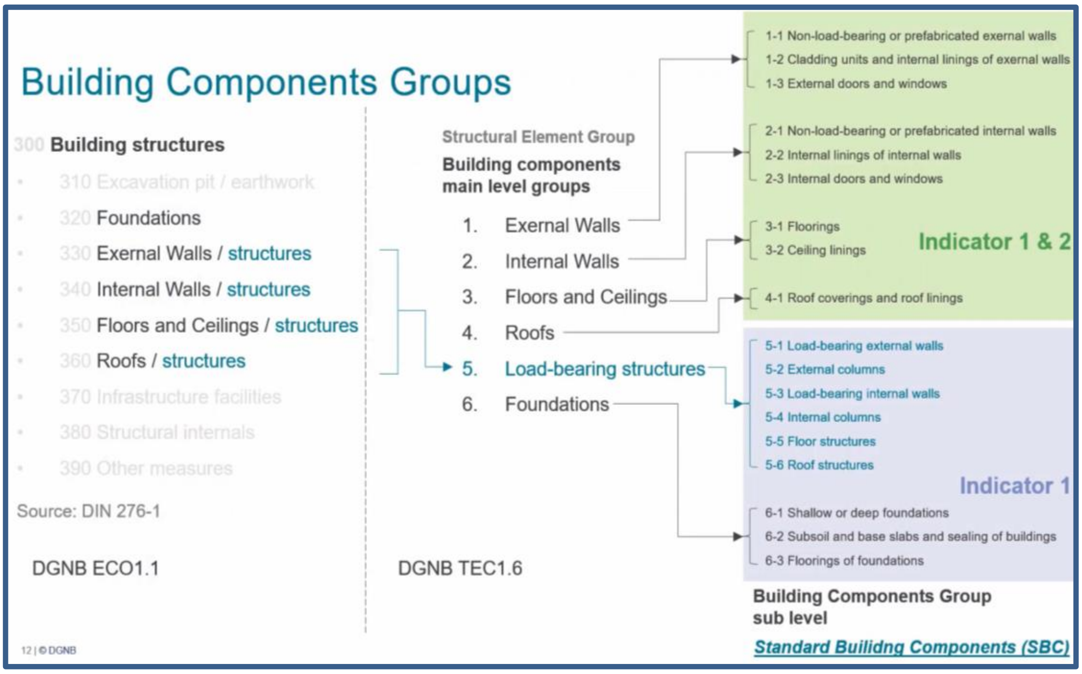


Figure 2-21: DGNB TEC 1.6 Standard Building Components, based on (Shizhe, 2021)

Indicator 1 examines the input flow of products and materials into the building and classifies them into groups, called quantity levels (QL), based on their EoL scenario. There are 3 QLs in this indicator, ranging from QL0 to QL2, with QL0 being the most linear EoL scenario and QL 2 being the most circular. Additionally, a circular economy bonus is awarded for direct component reuse and avoidance of unnecessary structural components such as ceiling covering or painting.

Indicator 2 evaluates the detachability of building elements and materials based on the connectors used. Indicator 2 has two QLs, the first represents elements with undetachable connections, and the second represents elements that can be separated. To fulfil QL2, one of two requirements must be met. First, elements and their containing materials must be separatable without functional or structural damage to them or their surrounding components. Second, components are designed so there is no need for detachment, as they both possess similar EoL scenarios. However, for indicator 2, foundations and load-bearing structures in the SBC are not assessed (Figure 2-21). This is because load-bearing structures are assumed to be generally undetachable.

2.3.3.2 International Organization for Standardization (ISO) 20887

ISO 20887 is part of the ISO document suite dealing with the topic of sustainability in the built environment. As illustrated by its title, “Design for disassembly and adaptability (principles, requirements and guidance)”, it is focused on giving the “how-to” for design for disassembly and adaptability. It provides a framework that can be followed to integrate adaptability and easy disassembly into the building design right from its early design phases. ISO 20887 highlights seven major factors to consider when designing for disassembly and adaptability, which are (ISO 20887, 2020, p. 13):

i. "Ease of access to components and services
ii. independence
iii. avoidance of unnecessary treatments and finishes
iv. supporting circular economy business model
v. simplicity
vi. standardization
vii. safety of disassembly”

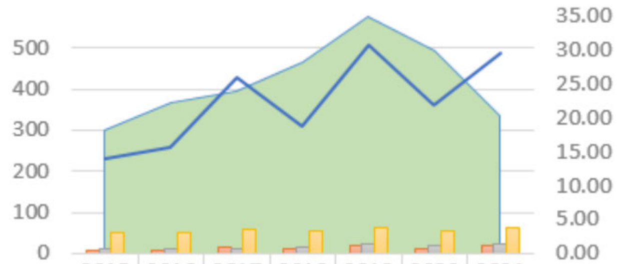
While some of these factors are related to each other, some are dependent on the effective implementation of others. For instance, standardization is related to simplicity, and “safety of disassembly” depends on the successful application of the other factors in the building design. Five of the seven factors are concerned with the detachability of building components, “avoidance of unnecessary treatments and finishes” is concerned with the environmental impact of components, and “supporting circular economy business model” deals with the reusability and recyclability of used components.

Table 2-6: Summary of BCA Methodologies from Standards and Building certifications

BCA Methodology	Assessment Method	Detachability Considered	Detachability Assessment Methodology
DGNB TEC 1.6	Indicator 1 *Ease of recycling (material inflow) Indicator 2 * Ease of recovery (material outflow) Indicator 3 * Design for Circularity in the planning phase	Yes * Indicator 2	Evaluation based only on Standard Building Components (SBC) which are: Exterior Walls, Interior Walls, Ceiling & Decks, and Roof Based on * Non-destructive Element and Material separation * use of connections that allows non-destructive separation * no need for separation due to similar material property Indicators * QL 1 -- Undismantleable * QL 2 -- Dismantlable
ISO 20887: 2020-1	Based on seven key criteria that allow for building Disassembly and Adaptability * Ease of Access to components and services * Independence * Avoidance of unnecessary treatment and finishes * Support Circular Economy business model * Simplicity * standardization * Safety of disassembly	Yes	* Ease of Access to components and services * Independence * Simplicity * standardization * Safety of disassembly

2.4 BIM applied to the CB framework

BIM is currently being used in green building and sustainable building concepts for tasks such as building energy assessments and lifecycle assessments. Similarly, its use has been recommended and is increasingly being implemented in the circular building framework on topics such as DfD and MP (Akbarieh et al., 2020). An example can be made of the EU Horizon 2020 BAMB project, which is targeted at the integration of MPP and BIM in the process of promoting circularity in the built environment (Heinrich & Lang, 2019). Similarly, Figure 2-22 below shows the amount of research carried out on the subject of DfD, BIM, BIM-based DfD, and BIM-based LCA between 2015 and 2021. Observing the ratio of BIM-based DfD research conducted in relation to general DfD research, an increase of over 15% was observed in 2021 compared to 2015. This points to the increase in the adoption and implementation of BIM in the circular building framework. (Akbarieh et al., 2020, p. 4; Lukianova et al., 2022, p. 2)



	2015	2016	2017	2018	2019	2020	2021
BIM	298	368	395	465	577	492	337
BIM DfD	7	8	15	10	19	12	18
BIM LCA	10	13	10	17	23	20	23
General DfD reseach	50	51	58	53	62	55	61
Percentage of BIM DfD to general DfD research	14.00	15.69	25.86	18.87	30.65	21.82	29.51

Figure 2-22: BIM, DfD and BIM-based DfD and LCA research trend (Lukianova et al., 2022, p. 2)

The use of BIM in the CB workflow poses advantages, one of which is the availability of a wide range of essential data and information required for the CB design and assessment process in a BIM model and its ability to store more (Akbarnezhad et al., 2014, p. 132). This is particularly beneficial for MP because the concept requires much information for its implementation. Similarly, a connection between BIM and MPPs can facilitate the incremental storage of building information on the MPP platform as changes occur throughout the building lifecycle. Another property of BIM that can serve as an advantage to the CB workflow is its 3D visualization. This coupled with the semantic richness of these visualized components can facilitate the EoL deconstruction planning process of buildings. On another note, BIM provides a medium for easy comparison of different design variants during the building design phase, which can be used to advantage in the DfD process, as this property has been capitalized on by concepts such as LCA and building energy simulation. (Akbarieh et al., 2020, p. 3; Atta et al., 2021, p. 3; Honic et al., 2019, p. 1; Munaro & Tavares, 2021, p. 775)

In the BIM-based CB research ecosystem, while some research focuses on assessing the compatibility of BIM for CB-related assessments, others work on developing tools for carrying out these assessments. For instance, Kovacic et al. (2021, p. 8) researched the possibility of generating MP for already existing buildings using BIM. From their analysis, they observed its difficulty and recommended incorporating the CB concept into the early design phases of the building using BIM for easier MP creation. Honic et al. (2019, p. 1), on the other hand, assessed the application of BIM-based MP to early BIM models and discovered limitations, such as the unavailability of the required information, semantic mismatch across used platforms, and lack of data standardization. According to their research findings, early-phase conceptual and preliminary design models do not provide all the required information for circularity implementation as they contain elements with lower LOD, which lead to the use of generic model information, and, therefore, a reduction in the accuracy of the generated MP. These two pieces of research point to the limited compatibility of BIM with the CB framework, which is an area requiring further research.

Examples of BIM tools developed for application within the CB framework are the “BIM-based Whole-life Performance Estimator” (BWPE), and the “Building Information Modelling based Deconstructability Assessment Score” (BIM-DAS) created by Akanbi et al. (2018, p. 175) and Akinade et al. (2015), respectively. The BWPE is applied in the building design phase to assess the salvage potential of building components after use. Its assessment considers factors such as the types of connection used, the use of prefabricated assemblies in building construction, the environmental impact and durability of building materials, and the avoidance of secondary finishes. These factors are, however, not readily available in the BIM models and were included in the model using custom parameters in the Revit software. Thereafter, the simulation was carried out in a MATLAB environment. Similar to the implementation of BWPE, BIM-DAS, in aid of assessing the detachability of building components, also enriched the BIM model used for its analysis with properties needed for carrying out its analyses using custom parameters created in Revit.

Another example of a BIM-based CB tool is the steel structure deconstructability assessment scoring (SS-DAS) tool, developed by Basta et al. (2020) based on the assessment methodology of the BIM-DAS tool, but focused on steel structures, and the analysis is conducted using Revit Dynamo. Revit Dynamo was also adopted by Zhai (2020) for implementing the workflow of the building circularity assessment scoring (BCAS) tool created by this research. BCAS is based on the BCI assessment approach. It takes input both from the Revit model and Microsoft excel tables, analyses the building circularity using Dynamo and outputs its result by overriding the model colour by the colour assigned to the indicator value as a pop-up window in the Revit software.

Another BIM-related tool is the “ResourceApp”, developed by Volk et al. (2018, p. 226). Unlike the previously described tools, ResourceApp is not used in the design phase but is applied to existing buildings. ResourceApp is a hardware and software module that scans existing buildings and generates the as-built information of the building components, which can then be used for better planning the building deconstruction. Though this tool does not assess the circularity of buildings, it contributes to the CB framework by providing the required information for creating as-built MP and assessing existing buildings' circularity. This plays a crucial role in achieving circularity in the built environment, as most of the buildings speculated to be in existence in Europe by 2050 have already been built since the 90s (BPIE, 2011).

Among the indicator-based BCA methodologies introduced in section 2.3.2 above, Madaster is the only solution that uses BIM in its workflow. Though in their research, Cottafava and Ritzen (2021, p. 1) employ a similar BCA methodology as that of Madaster (2021), BIM implementation was not included in their workflow. Also, Madaster has been identified as the only platform that, till now, supports open-BIM workflow for BCA (Theißen et al., 2022, p. 3). The IFC exchange format is one of the two ways building data can be read into the Madaster platform to assess building circularity and detachability. The second method is by using a Microsoft Excel file format. Upon uploading the IFC model into the Madaster platform, building elements are matched with their corresponding products on the platform. Thereafter, the circularity degree of the input and output flow of the building elements are computed as explained in section 2.3.2.1 on page 38.

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 2-7.

Table 2-7: Madaster detachability Pset data field

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

Values required for computing building detachability will be assigned to each building element or material, provided this information already exists in their corresponding products on the platform. However, if the information has been provided in the IFC model before upload to the Madaster platform, the IFC-based information will override the platform-based product information.

To assess the functioning of the Madaster-based BCA workflow, Theißen et al. (2022) carried out a study using Madaster to assess the circularity of a ventilation and air-conditioning (VAC) system. Their study observed the subjectivity of the detachability analysis and the need for construction expertise to carry out the detachability assessment using Madaster. The subjectivity in the assessment result arises from the planner's need to fill out the detachability assessment data field in the Pset-Madaster. Therefore, 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. Similarly, using the detachability assessment methodology from Vliet et al. (2021), the same adopted by Madaster, Lukianova et al. (2022, p. 4) reviewed the workflow for assessing building detachability using Revit-Dynamo. However, similar to the research by Theißen et al. (2022), there is a need to manually enter information, which is dependent on the expertise of the planner and thereby leads to the subjectivity of the evaluation result.

These researches by Lukianova et al. (2022) and Theißen et al. (2022) further validate the need for this thesis. As the aim of this thesis (section 1.2) is to develop a workflow that can help automate the detachability assessment process and limit the need for expert knowledge and, thereby, the subjectivity of the assessment result using BIM.

Nevertheless, it is essential to note that, though different BIM-based CB research focuses individually on different topics under the building circularity framework, such as detachability, waste management, MP, DfD etc., these individual aspects are interrelated, and the successful implementation of one requires the adoption of the other. For instance, Atta et al. (2021, p. 1), in their research focused on developing an MP tool, developed indicators for assessing the detachability, recovery potential and environmental impact of building component in the process. Due to MP’s definition (stored circularity data), this research cannot be said to be based solely on MP as it touched on other aspects of building circularity.

Overall, this section has pointed out some CB-related BIM tools: Revit-based (closed BIM) and IFC-based (open BIM), focused on different areas of the CB framework. The

Revit-based tools include BWPE, BIM-DAS, SS-DAS and BCAS, while Madaster employs IFC in its workflow. Therefore, in the following chapter (chapter 3), the degree to which building detachability can be assessed will be analysed for both the closed and open BIM approach by evaluating the availability of information required for detachability assessment in both cases.

3 Integration Analysis of BCA methodology in BIM

The review conducted on the current BCA methodologies in chapter 2 indicates detachability as a key factor when analysing building circularity. Similarly, it has helped fulfil the first research objective by pointing out the current detachability assessment methodology used within the available BCA methods, similarly answering our first research question.

This chapter is focused on tackling this thesis's second and third research objectives, which are primarily based on evaluating the currently available detachability assessment methodologies, identifying the information needed to assess each indicator and the availability of this information in BIM models. To achieve this, with respect to the BCA methodologies discussed in sections 2.3.2 and 2.3.3, indicators used in computing building detachability were identified in section 3.1, and the information needed for deriving each indicator was assessed in section 3.2. Sections 3.2.1 and 3.2.2 went into more detail about the availability of this information within the Revit and the IFC framework, respectively. To conclude, section 3.2.3 discuss some of the key observations made in this chapter.

3.1 Detachability Indicators

This section (section 3.1) will discuss indicators used for assessing building detachability within the previously discussed BCA frameworks in sections 2.3.2 and 2.3.3. Section 3.1.1 introduces the detachability indicators from the indicator-based BCA models, while section 3.1.2 touches on those from DGNB TEC 1.6 and ISO 20887. Furthermore, Table 3-1 and Table 3-2 give the indicators list from sections 3.1.1 and 3.1.2, respectively.

3.1.1 Detachability Indicators from Indicator-based BCA Models

Table 3-1 below shows the list of indicators discussed in this section. In the table, the cells marked "green" signifies the presence of an indicator in a BCA model, the last row gives the total number of detachability indicator employed by each BCA model, and the last column shows how often a particular detachability indicator is considered across the different BCA models.

Table 3-1: Detachability Indicators based on BCA methodologies

Indicators	Madaster	Urban Mining Index	Platform CB'23	Cottafava et al	Count
Connector types					3
Connection accessibility					2
Degree intersection					2
Enclosure form					2
Work factor					1
Value factor					1
Total	4	3	0	4	

1. Connection Type: This indicator's assessment is based on the type of connectors used to connect two or more building elements, products, or materials together. Based on the used connector (e.g. nail, glue, weld, etc.), the ease with which these building elements or materials can be separated is assessed. This indicator is considered across most of the BCA models, as shown in Table 3-1, except for Platform CB'23 (2020), as they are yet to develop a detachability assessment methodology. However, in the Urban Mining Index (2021) BCA methodology, connection type is not implemented as an indicator but serves as a qualifying criterion. This implies that, for an element to be assessed for detachability using the main indicators employed in the UMI workflow (work factor and value factor), it must be connected using detachable connectors (Rosen, 2021, p. 96).
2. Connection Accessibility: This indicator evaluates the ease with which building components' connection points and connectors can be reached during deconstruction. As explained by Vliet et al. (2021, p. 14), this indicator evaluates the ease of deconstructing a particular object without causing damage to its surrounding objects. This indicator proves relevant as it appears across two BCA methodologies and in the ISO 20887 (2020). Other indicators with a similar occurrence are the "degree intersection" and "enclosure form".
3. Degree Intersection: This indicator analyses how much two or more elements are integrated into or intersect each other. It is more relevant for renovation purposes when the intersecting elements have different lifespans (characterized by their shearing layer (Figure 2-18)), and disassembling the element with a

shorter lifespan can potentially affect its intersecting element with a longer lifespan.

4. Enclosure Form: This indicator mainly deals with building materials' shape and arrangement. It assesses the possibility of removing a component from its composition without using the reverse build order, i.e., without first deconstructing all its surrounding components. It assesses how well other materials enclose a material or a series of materials enclose each other. Like the “degree intersection” indicator, this indicator is mainly relevant for building renovation, as at building EoL, reverse build can be employed for deconstruction. (Vliet et al., 2021, p. 16)
5. Work factor: This indicator is particular to the UMI BCA model (explained in section 2.3.2.4) and assesses the effort required to disassemble building elements or components. Before this indicator and the “value factor” indicator is assessed, two key checks are carried out on the material and element level of the building. These are the toxicity check of the building materials and the detachability check of the building components. The detachability check is based primarily on the type of connectors used to connect elements or materials together (Rosen, 2021, p. 96). To derive the “work factor” indicator, empirical research was carried out on selected element types with different construction methods and materials. The elements selected fall within the following groups: flat components such as walls and slabs, linear components such as columns, non-structural components in façades such as doors, non-structural interior elements, and non-loadbearing roof components. The deconstruction of load-bearing elements was excluded from the evaluation process.
6. Value factor: This indicator assesses the salvage value of building products and materials after deconstruction. The grading system for this indicator was derived by surveying the disposal cost and potential salvage value of building materials and products in Germany. From the data gathered, a grading system was developed to classify materials based on their profitability when selectively deconstructed.

3.1.2 Detachability Indicators based on DGNB TEC 1.6 and ISO 20887

Similar to Table 3-1 above, Table 3-2 lists the detachability indicators identified in this section. The “green” cells signify the factors considered by the DGNB TEC 1.6 and the

ISO 20887, and the last column shows how often a factor is considered. Since these are not primarily BCA models, the detachability assessment process for the DGNB TEC 1.6 and ISO 20887 is discussed rather than discussing each indicator listed in Table 3-2.

Table 3-2: Detachability Indicators based on DGNB TEC 1.6 and ISO 20887

Indicators	DGNB TEC 1.6	ISO 20887: 2020-1	Count
Connector Types			2
Connector Accessibility			1
Degree Intersection			1
Enclosure Form			1
No of material layers			1
Component Size			1
Standard construction technique			2
Standard Components			2
Total	3	8	

1. DGNB TEC 1.6 mainly considers “connection type” as its primary indicator for assessing building detachability; however, its detachability assessment is only carried out on selected building components built using standard construction techniques, as explained in section 2.3.3.1. Though these are not primarily indicators in the TEC 1.6 BCA model, they serve as a guideline in the BCA model and, therefore, are represented as indicators in Table 3-2 above. Furthermore, load-bearing structural elements are exempted from the TEC 1.6 assessment of building detachability, as they are generally considered undetachable (Figure 2-21).
2. For ISO 20887, as explained in section 2.3.3.2, the standard simply provides guidance on how to design for disassembly and adaptability, with five out of the seven factors listed correlating to the detachability of buildings. These factors are summarised as indicators and compared with indicators from other BCA models.

To summarize, with respect to sections 3.1.1 and 3.1.2 above, connection types appear to be the most significant indicator as it was considered across all the BCA models (DGNB TEC 1.6 and ISO 20887 included). This was followed by connection accessibility, degree intersection, and enclosure form, which appeared in three of the six reviewed BCA models. The above-listed indicators belong to the detachability assessment methodology developed by Vliet et al. (2021) and have been adopted both by Madaster (2021) and Cottafava and Ritzen (2021). Furthermore, these indicators have been previously adopted into the BIM workflow by Madaster, and their application reviewed by researchers, as discussed in section 2.4.

The work factor and value factor indicators are particularly UMI-based detachability indicators. They are, however, not BIM-based and are yet to be tested within a BIM workflow. Other indicators with only one appearance are: “number of material layers” and “component size”. However, these are not primarily indicators but adapted as one from the recommendation by ISO 20887.

Similarly, other factors of note are “the use of standard components” and “standard construction technique”, both considered by DGNB TEC 1.6 and ISO 20887. To this effect, the elements used in the case studies for developing and validating the methodology for this thesis will fall within the SBCs considered by DGNB TEC 1.6. Furthermore, only the indicators present in Table 3-1, i.e., those from indicator-based BCA models, will be analysed further in the following sectors since most indicators identified in TEC 1.6 and ISO 20887 (Table 3-2) are not primarily indicators. They are building detachability assessment guidelines, considered to give a more holistic view of building detachability assessment.

3.2 Analysis of Identified Indicators

In this section, the previously identified indicators from the indicator-based BCA methodologies (section 2.3.2) were assessed. Here, the second objective of this thesis was met by identifying the information required to assess each indicator and checking for the availability of the required information within the BIM (closed and open BIM) framework.

Since the BCA model from Cottafava and Ritzen (2021) and Madaster (2021) employs the same detachability indicators (Table 3-1), and Platform CB’23 (2020) has no detachability assessment within its workflow, only two detachability assessment workflows will be analysed in this section. The first is from Madaster, with four indicators: connection type, connection accessibility, degree intersection and enclosure form. The second is from UMI, with two indicators: work factor and value factor.

Table 3-3: Detachability indicators assessment

INDICATORS	ASSESSED ON		INFORMATION NEEDED	
	Element Level	Material level	Semantic Information	Geometric Information
Connection Type			Examples Screw, Bolt, Nail, Ce-ments-sand mix	
Connection Accessi-bility				* Component Arrange-ment * Connection points *distance surrounding connection points (m, mm, m^2)
Degree Intersection			* Element Life span (years) * Building Layer (Struc-ture, Skin, Space ...)	* Component Arrange-ment
Enclosure Form			* Material life span (years)	* Component Arrange-ment
Work Factor			*Energy expended for deconstruction [MJ]	
Value Factor			* Material value after use [euros] *Cost of selective disas-sembly [euros]	

With reference to the four main levels (material level, component or element level, sub-system level and system level) in the building hierarchy, as shown in Figure 2-18, the detachability assessment of both Madaster and UMI focuses mainly on the material and element level of the building. Table 3-3 shows the levels in which each of the six detachability indicators is applicable. While most are applied to both hierarchy levels, degree intersection is applied to the element level only, while enclosure form and value factor are applied mainly to the material level. Also, the table shows examples of information needed to derive each indicator, sub-categorized between semantic and geometric information.

Following the review conducted on the current application of BIM to the CB framework in section 2.4, Revit-based and IFC-aided workflows are observed as the two primary methods for BIM implementation. Therefore, the availability of information required for deriving each detachability indicator will be assessed both in the Revit ecosystem and in the IFC schema, in sections 3.2.1 and 3.2.2, respectively. Thereafter, section 3.2.3 discusses the observation from the analysis carried out in these sections.

3.2.1 Assessment of Autodesk Revit model structure for Detachability Analysis

Here the Autodesk Revit ontology was assessed for the availability of required information for deriving each of the six previously identified detachability indicators. Also, the possibility of extending the available information in models with those required for deriving each indicator was assessed. To assist in this analysis, a 3D model of 2 connected walls was created in Revit (Figure 3-1), and the available geometric and semantic information in this model was analysed in relation to our indicators. Similarly, BIMForum (2021) specification on information requirements in model elements of different LODs (Table 2-1) was assessed in relation to the required information for deriving each detachability indicator.

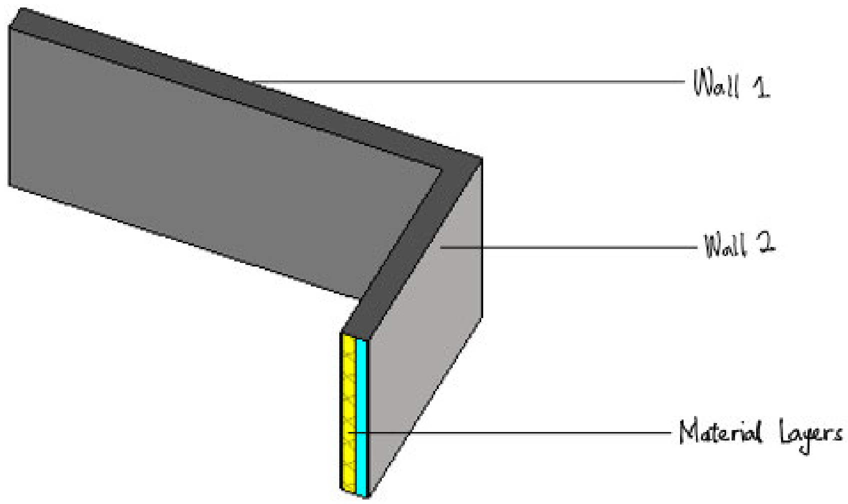


Figure 3-1: Cross-section of the model used for the assessment of each detachability indicator in Revit

Table 3-4 summarizes the output of our analysis. The second column of the table (titled building hierarchy) points to the different levels in which the indicators are being assessed. The third column shows the design phase in which the indicator information can more easily be extracted, ranging between the early and detailed design phases, according to the explanation in section 2.1.3. Lastly, the fourth column states the availability of the indicator information within the Revit model structure, classifying them as “directly implemented”, “not available”, and “needs further processing from model information”.

Table 3-4: Indicator information availability check in Revit-model structure

Indicator	Building Hierarch	Design Phase	Indicator Information
Connection Type	Element Based	Detailed Design	Directly implemented
	Material based	Detailed Design	Not available
Connection Accessibility	Element based	Early phase design	Needs to be processed from model information
	Material based	Detailed Design	Not available
Degree Intersection	Element based	Early phase design	Needs to be processed from model information
Edge Confinement	Material based	Detailed Design	Not available
Work factor	Element based	Detailed Design	Not available
	Material based	Detailed Design	Not available
Value factor	Material Level	Detailed Design	Not available

3.2.1.1 Connection Type

The connection type indicator is assessed both on the material and element level of the building. It requires information on the type of connector, such as nails, screws etc. (Table 3-3), used to connect two or more elements or materials. According to BIM-Forum (2021, p. 16), this information can be derived from model elements of LOD 350 and above, which according to Table 2-2, falls within the detailed design phase of the building design process. While this information can more easily be accessed and provided for steel structures, providing this information within the Revit software for basic wall constructions, such as that used for this assessment (Figure 3-1), proved limited compared to steel structures. This limitation also extends to the material level of building elements; however, it can be resolved by adding the connection type information as custom parameters.

3.2.1.2 Connection Accessibility

This indicator measures how easily connection points or connectors between elements or materials can be reached for disassembly without destroying the objects around them. In its assessment, for instance, geometric analysis can be carried out to compute the distance between connection points and their surrounding elements, to derive the ease with which they can be reached. Likewise, the material layer arrangement can be assessed to determine the ease with which they can be accessed. Therefore, though the information is not directly represented in a Revit model, it could be extracted following the analysis of available model information.

For the element level, this indicator can be assessed right from the early phases of the design process. However, according to BIMForum (2021), material layers get specified in elements from LOD 350. Therefore, a more detailed design will be required to carry out this assessment on the material level.

3.2.1.3 Degree Intersection

This indicator assesses the intersection between elements from different shearing layers (Figure 2-14). Therefore, it requires both semantic and geometric information. The semantic information helps classify elements into their respective shearing layers, while elements intersections can be identified geometrically. Though the information on elements' shearing layer is not readily assigned to Revit elements, this semantic information can be added as custom parameters. Likewise, similar to the connection accessibility indicator, the information on elements' intersection can be derived from the model, either visually or by using Revit-based clash detection plug-ins (e.g. Clash Navigator).

3.2.1.4 Enclosure Form

This indicator is assessed on the material level of the building hierarchy. According to BIMForum (2021), more precise information on the materials in elements is provided from LOD 350 and above (Table 2-1). Therefore, this indicator requires a detailed design model. This indicator assesses the ease with which a product or material can be removed from a series of products without disassembling the surrounding products. This depends, both, on the shape and arrangement of the product. For this to be assessed using Autodesk Revit, a more detailed geometric representation of the materials within elements is required. In Revit, elements' materials are mainly represented in layers (Figure 3-3); however, this indicator requires a more detailed material representation, detailing the edge shape of the individual materials (Figure 3-2). However, while this level of material representation can be visually presented in Revit, its geometric representation is not practical.

Figure 3-2: Exemplary material representation required for “Enclosure form” indicator assessment (Vliet et al., 2021, p. 17)

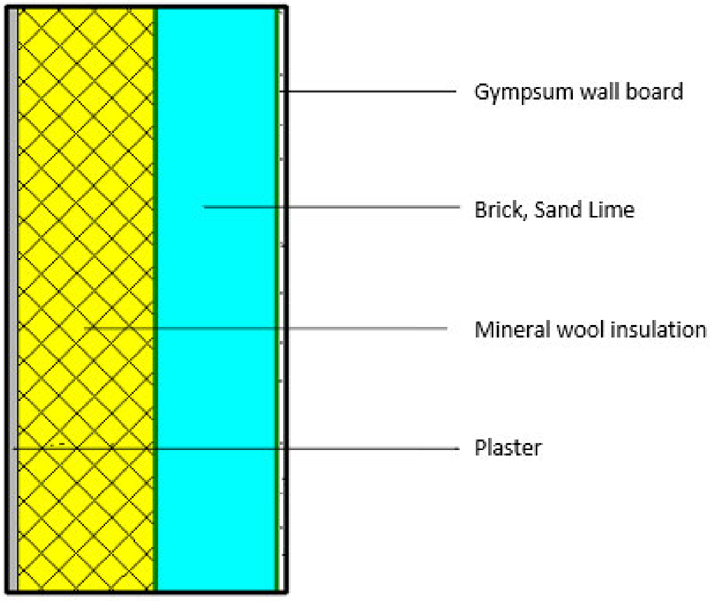


Figure 3-3: Material arrangement with a wall; extracted from Autodesk Revit

3.2.1.5 Work Factor

The work factor indicator assesses the energy expended in disassembling building components with detachable connections and non-toxic materials. For this indicator, a component catalogue was created after the practical evaluation of the effort (human and machine) needed to deconstruct a select group of building elements (section 3.1.1, No 5). From this catalogue, the work factor of each assessed element’s construction type can be derived and classified as shown in Table 3-5. Though this value (work factor) is not automatically represented in Revit models, it can be assigned to building elements as custom parameters.

Table 3-5: Work factor indicator grading; extracted from (Rosen, 2021, p. 147)

Work	*Valuation of dismantling effort*
≤ 7.1 MJ/m²	Very Low
≤ 8.7 MJ/m²	Low
≤ 11.5 MJ/m²	Medium
≤ 12.6 MJ/m²	High
> 12.6 MJ/m²	Very high

3.2.1.6 Value Factor

Similar to work factor (section 3.2.1.5), value factor is preceded by the check for material toxicity and element detachability. To derive the value factor, research was conducted on the salvage value of common construction materials in Germany after use and was standardized into an indicator. Figure 3-4 below shows an extract of the salvage value of some materials, from the research conducted. Similarly, these values can also be assigned to model elements as properties, to assist in the implementation of BIM for the UMI workflow.

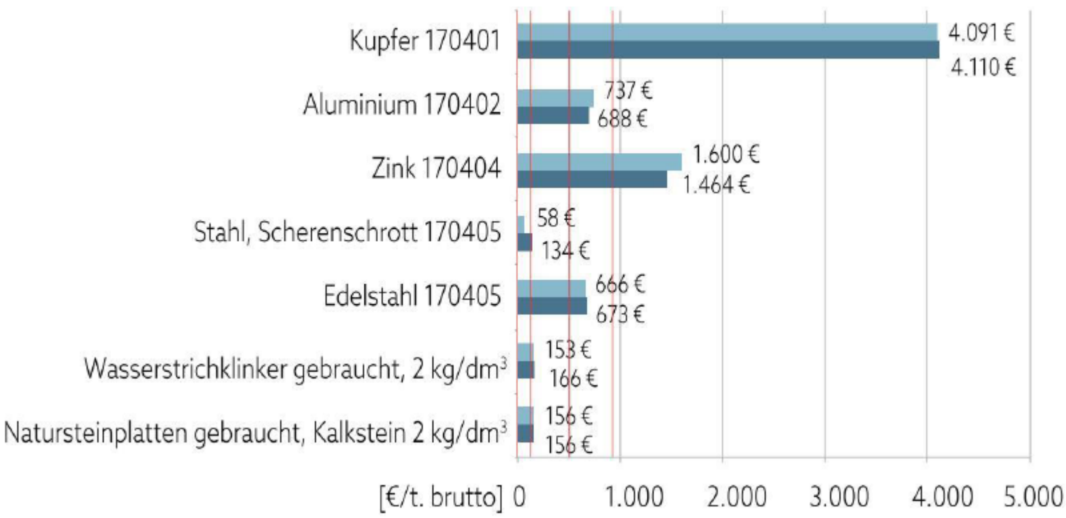


Figure 3-4: Revenue potential of different materials; extracted from (Rosen, 2021, p. 113)

3.2.2 Assessment of the IFC Schema for Detachability Indicators Analysis

For this assessment, the IFC documentation by BuildingSMART was analysed for the availability of IFC schemas containing the information required for assessing each detachability indicator. Similarly, to better understand these schemas and check the availability of their values in an IFC model, the wall model (Figure 3-1) from section 3.2.1 above was exported to IFC format using the IFC4 “Design Transfer View” MVD and the “Blender” software and “IfcOpenShell” were used these checks.

Blender is an open-source 3D computer software that allows for 3D manipulation; and includes a scripting interface that supports Python programming language (Blender, 2022). For processing (i.e. writing, reading and analysing) IFC files using the IfcOpenShell software package, BlenderBIM add-on is used within the Blender software. IfcOpenShell helps parse IFC files from their implicit geometry to explicit geometry and allows for the viewing, editing or modification of IFC model schema using python programming language (IfcOpenShell, 2022). 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 3-6: Indicator information availability check in IFC Schema & IFC Model

Indicator	Information Needed	Available in IFC Schema
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
Work factor	Element Level	Not Available
	Material Level	Not Available
Value factor	Material Level	Not Available

Table 3-6 above summarizes the availability of an IFC schema for each of the six selected detachability indicators, while “Appendix A” gives detailed information on the IFC4 schema assessment, showing the schemas identified for evaluating each indicator. In this section, the relatively derivable indicators: connection type, connection accessibility and degree intersection, as shown in Table 3-6 above, are discussed in more detail in sections 3.2.2.1, 3.2.2.2, and 3.2.2.3, respectively. Whereas, the remaining three indicators (enclosure form, work factor and value factor) are discussed in section 3.2.2.4.

Firstly, the IFC4 documentation was analysed for the availability of IFC schema that provides the information needed for deriving each indicator value. This assessment determined if the schema was available or not, as shown in column three of Table 3-6. Thereafter, the exported IFC file schema was further assessed to determine the availability of the indicator-required information in the IFC file. Furthermore, in the case of unavailable IFC schema for an indicator, the possibility of deriving this information by further processing the available model information was assessed and indicated in the fourth column of the table (Table 3-6).

It is howsever, key to note that the information present in an IFC model is dependent on a number of details, such as the MVD with which it was exported, the authoring software with which the IFC model was exported from, the person who created the model, the LOD of the model, etc. (Chateauvieux-Hellwig et al., 2021)

3.2.2.1 Connection Type

In the IFC documentation, the connection between elements can be established using the *IfcRelConnectsElements* relationship class, which is an attribute of the *IfcElement* class and is inherited by classes such as *IfcWall* (walls), *IfcSlab* (slabs), etc., which are subclasses of the *IfcElement* super-class. The *IfcConnectsElements* have two subclasses: *IfcRelConnectsPathElements* and *IfcRelConnectsWithRealizingElements* (Figure 3-5), and describes the connection points geometry using the *IfcConnectionGeometry* class. The *IfcRelConnectsPathElements* show where the connection occurs as “At Start”, “At End”, and “At Path”, signifying the beginning, end, and along the element, respectively. Likewise, the *IfcRelConnectsWithRealizingElements* points at the connector used between the element as “RealizingElements” and specifies the type of connection at the connection point.

While these schemas are available in the IFC documentation and could potentially help provide values for deriving the connection type indicator, there are some limitations. Firstly, for walls, there is no schema defining the relationship between the wall and the slab. To define this relationship, there is potentially a need for semantic enrichment to extend the “At Path” entity with sub-classes such as “At Top” and “At Bottom” to accommodate the relationship between walls and slabs above and below it. This limitation was similarly pointed out by Chateauvieux-Hellwig et al. (2021) in their research.

Secondly, while the *IfcRelConnectsWithRealizingElements* points to “RealizingElements”, which can potentially accommodate the different connectors used to connect elements, the “RealizingElements” attribute is an IfcElement type. This means the connectors must be modelled as elements and assigned the “IsConnectionRealization” attribute. However, modelling connectors such as sand-cement mix, sealant etc., as model elements might prove impractical. In light of this, though the schema is available, the availability of this information in an IFC model depends heavily on how the model is created and the authoring software used in creating the model. Furthermore, the IFC documentation has no schema used to define the connection type between materials.

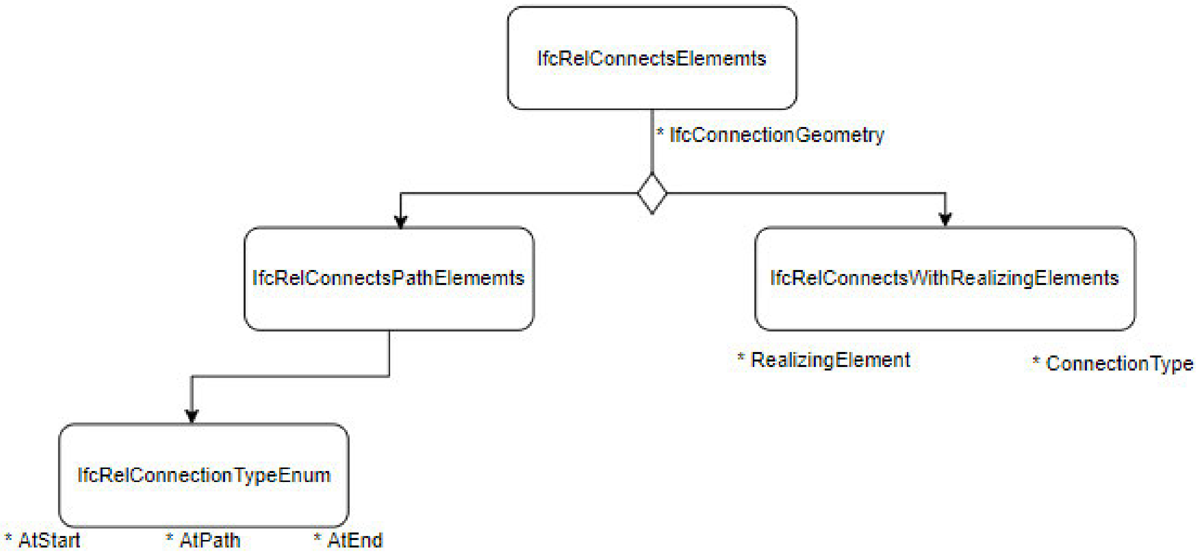


Figure 3-5: IfcRelConnectsElements inheritance graphical illustration

3.2.2.2 Connection Accessibility

The accessibility of elements connection points can, potentially, be assessed by employing a couple of IFC schemas. For instance, the building level to which an element belongs can be obtained using the *IfcRelContainedInSpatialStructure* class; thereafter, all elements in that level could be identified. Using the *IfcObjectPlacement* class, the location coordinate of each identified element can be obtained, after which their distance from a given element's connection points can be computed and compared to a limiting distance that allows for easy access to these connection points.

Likewise, the materials in each element can be derived using the *IfcRelAssociatesMaterial* class, and the number of materials present in an element, their thickness, and their arrangement can be derived using the *IfcMaterialLayerSetUsage* (Figure 3-6) class. Thereafter, the ease with which each material can be detached from the set of other materials in an element can be assessed. However, this class *IfcMaterialLayerSetUsage*, only provide a simplified material arrangement representation as shown in Figure 3-6 below.

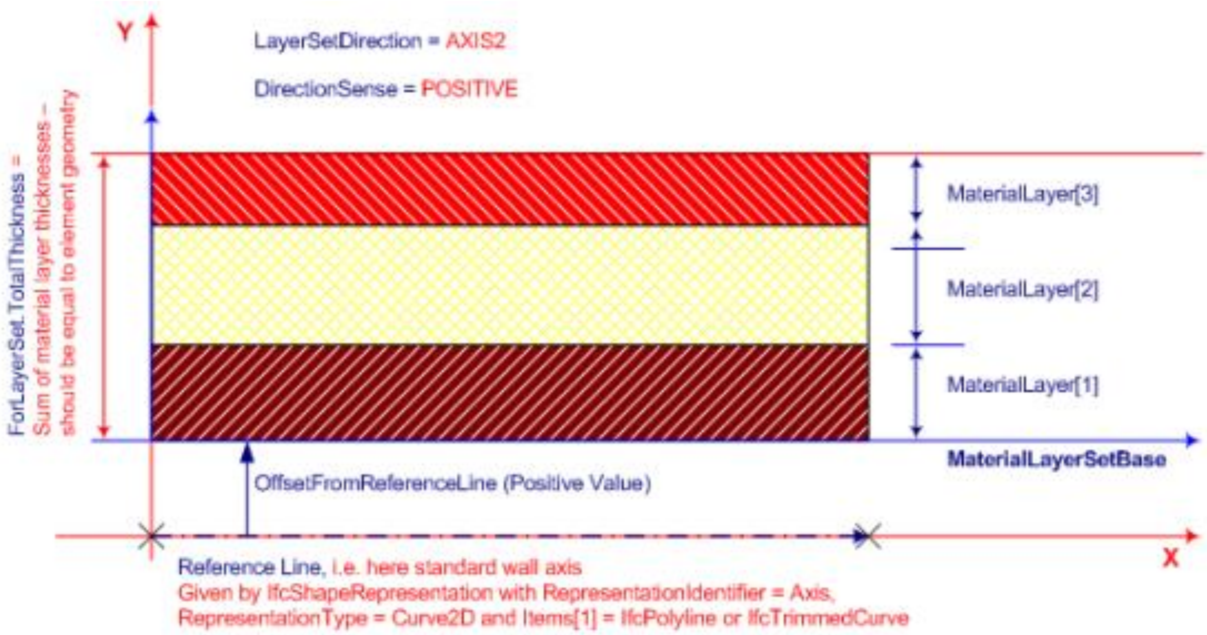


Figure 3-6: IfcMaterialLayersetUsage illustration for a wall; extracted from IFC4 documentation (BuildingSMART, n.d)

3.2.2.3 Degree Intersection

The intersection between two elements can be represented using the *IfcRelInterferesElements* relationship class. This class gives a one-to-one relationship between the intersecting element and the element being intersected. Also, the geometry of the point of intersection is represented by the *IfcConnectionGeometry* class. Which has subclasses such as *IfcConnectionCurveGeometry, IfcConnectionPointGeometry, IfcConnectionSurfaceGeometry* and *IfcConnectionVolumeGeometry*, used to further represent the different geometry types present at the intersection point.

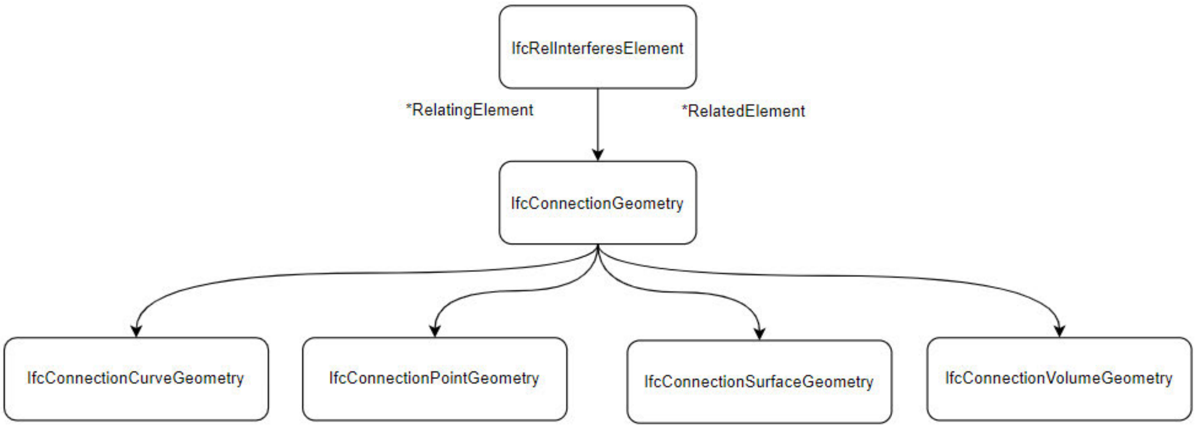


Figure 3-7: IfcRelInterferesElements inheritance graphical illustration

3.2.2.4 Enclosure Form, Work Factor and Value Factor

For the enclosure form indicator, no IFC schema was found that could directly give the information needed for its evaluation. This indicator is based on the material level of buildings, and 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 might prove challenging with the IFC schema.

For the work factor and value factor indicators, there was also no schema identified in the IFC documentation for representing their required information in an IFC model. However, the information required by these indicators as well as the enclosure form indicator, could potentially be assigned to the model elements as property sets.

3.2.3 Observation from the Revit model structure and IFC schema assessment

From the assessment carried out in section 3.2.1 on the use of Revit for assessing each detachability indicator, it was observed that only three (connection type, connection accessibility, and degree intersection) out of the six indicators reviewed could readily be assessed within Revit (Table 3-4). Also, for these indicators, this assessment is limited to the element level of their application. However, it was also observed that enriching the model elements and materials with additional properties could potentially enable the derivation of each detachability indicator within the Revit ecosystem. This is possible as the added properties will hold information needed for calculating each indicator. This approach has been implemented in previous research on the development of BIM-based tools within the CB framework (section 2.4), and the ability to extend the property of a BIM model is one of the key features of building information modelling (Basta et al., 2020).

In section 3.2.2, similar to section 3.2.1, the same three indicators could be derived using an IFC model according to the IFC documentation (Table 3-6). This is also mainly limited to the element level of these indicators' application. 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, as this is dependent on factors such as the LOD of the model element, the authoring software from which the IFC model was exported, the MVD used for exporting the IFC model etc. These variables affecting the information level in an IFC model can, however, serve as a future research topic. Research should be conducted to determine the optimum method of processing an IFC file for use in a BCA. Also, similar to the Revit model, the IFC model elements and materials can also be enriched with property sets that can enable the assessment of each indicator.

Overall, the analysis conducted in this chapter identified the key detachability indicators employed in the previously identified BCA methodologies (section 2.3) and discussed the information needed for assessing each of these indicators both in a closed BIM (Autodesk Revit) and open BIM (IFC) ecosystem. From the six reviewed indicators, the information needed for deriving three indicators could be derived both from a Revit and IFC model. However, due to different factors, this information might prove difficult to access. Nevertheless, the information needed for assessing all six indicators could be added to the model elements and materials as property sets for both Revit and IFC workflow.

Therefore, this chapter helped fulfil the second and third objectives of this thesis which are to assess how quantitative each identified indicator is, the availability of their required information within the BIM framework and how they can be further assessed using BIM. In the following chapter (chapter 4), how to automate the derivation of these indicators and reduce the level of subjectivity in their analysis will be researched and discussed. Likewise, the observation made in this chapter (chapter 3) will assist in deciding on indicators to assess further.

4 BIM-based Building Detachability Assessment

4.1 Study on BIM-automation approaches for building assessment

To devise a suitable workflow that can be implemented for automating the BIM-based building detachability assessment process, in line with the fourth objective of this thesis (section 1.2), previous studies related to this were reviewed and analysed. From the conducted review, studies from Calquin (2017), Růžička et al. (2022), Khoshdelnezamiha et al. (2020), Narayanaswamy et al. (2019), and ONIB (2020) were identified, which will be shortly introduced in the following paragraphs within this section.

The research by Calquin (2017) was based on the use of BIM for building environmental assessment methods (BEAM), such as DGNB, and the ability to connect BIM to building performance simulation (BPS) software tools for conducting these assessments. The research stated the absence of direct integration between BEAM and BIM, reducing the assessment accuracy, and moved to fill this research gap. The developed workflow involves (i) the analysis of the assessment methods' requirements, (ii) the creation of a BIM model to be assessed, (iii) the evaluation of the model within a BPS software, according to the BEAM requirements, (iv) the incremental improvement of the BIM model, using the BPS results until all BEAM requirements are met. A key step in the workflow involved mapping BIM and BEAM information to each other and discovered a strong match between several variables. As a result, assessment results from the BIM model could be automatically relayed into the BEAM spreadsheet. (Calquin, 2017)

The research by Růžička et al. (2022) focused on developing a data-driven BIM workflow for BEAM. Their study outlined three levels of BIM-BEAM integration, which are "(i) low structured model data, and manual workflow, (ii) utilized IFC data structure and semi-automatic workflow, and (iii) highly structured model data and automatic workflow" (Růžička et al., 2022). Of the three levels, they found the second to be the most appropriate implementation approach. Their proposed workflow involves the analysis of the building assessment methodology's data structure, the analysis of the BIM model's data structure with respect to the assessment's data structure, the enrichment of the BIM model with additional properties when required, and the conduction of the BIM-model-based assessment using the required BPS tool. Analysing the BEAM data structure is a vital part of this workflow. It involves understanding the BEAM requirements and their input parameters, which are compared with the BIM-model data structure, to determine whether or not it requires data enrichment. (Růžička et al., 2022)

Khoshdelnezamiha et al. (2020) research was based on automating the assessment process for deriving buildings' green building index (GBI) using Revit Dynamo. They aimed to optimize the existing manual process of conducting this assessment and automate it using BIM. In their workflow, (i) the GBI subcategories were identified, (ii) based on the identified subcategories, a set of "green parameters" were created to be integrated into the BIM model, automatically or manually, (iii) the required assessment data were collected from the model for further processing (iv) based on the interpretation of the GBI guideline, conditional statement for evaluating the required information were created (v) the assessment results were outputted. (Khoshdelnezamiha et al., 2020)

The research by Narayanaswamy et al. (2019) was based on designing a BIM-based workflow for automating a municipal bylaw and wall framing code compliance check for residential buildings in Edmonton. Their workflow consists of four main steps, which are (i) the interpretation of the compliance rules from natural language into a "computer-interpretable format" (Narayanaswamy et al., 2019, p. 1045), (ii) the creation of BIM-model to be assessed using a BIM-authoring tool (Revit), (iii) the assessment of the BIM-Model for rule compliance, using the interpreted rules, (iv) generating the assessment result. In their study, the first step was stated as the most important, as it defines the success of the other steps. The compliance rules are grouped into three classes: easy, intermediate, and difficult, based on the difficulty of translating them into a computer-interpretable format and the complexity of retrieving their required information from a BIM model. In the first step, the compliance code is represented based on the building objects it evaluates, the attribute to be extracted from the model and the range of expected values, thereby promoting clarity in the preceding steps. (Narayanaswamy et al., 2019)

The research by ONIB (2020) similarly focused on integrating building sustainability assessment into BIM. They aimed at creating a workflow using BIM, with which selected DGNB criteria can be completely assessed right from the early design phase of the building project. Their workflow involves (i) representing the criteria assessment process using a business process model and notation (BPMN), (ii) developing an attribute matrix for these criteria according to the created process model, (iii) the creation of BIM model according to the requirement within the attribute matrix (iv) assessment of the chosen sustainability criteria using the BIM model. (ONIB, 2020)

From the reviewed studies, the BIM-based automation process from each research was observed to follow a similar approach, irrespective of the specific assessment for which it is being implemented. This approach involves analysing the conventional assessment’s criteria to determine its BIM model-content requirements, creating a BIM model using a BIM-authoring tool (mostly Revit), adding additional parameters to the BIM model (when required) based on the criteria’s requirement, analysing the created BIM model based on the criteria interpretation, and outputting the assessment result. These studies also outlined the significance of adequately analysing and interpreting the actual assessment requirements. Firstly, this aids in determining the availability of parameters within the BIM model required for the assessment process. Secondly, it outlines the need for model enrichment with additional parameters when required. Thirdly, it helps in developing the rulesets for conducting the assessment using a BIM model.

However, while the above five studies follow a similar trend, the ONIB (2020) research gave more detailed information on how these steps can be implemented. Firstly, using a BPMN, the conventional building assessment process can be represented. This visual and detailed representation allows for transparency and clarity in the criteria interpretation process. Likewise, it promotes the ease with which the criteria analysis can be updated when required. Secondly, creating attribute matrices for the assessment criteria based on the developed process model also promotes the efficiency of the BIM-automation process, as all required attributes for the assessment process are clearly stated within the matrix. The data structure of the attributes and the naming convention of additional parameters to be added to the model are defined, promoting the clarity of the BIM-integration process. Thirdly, they stated how this workflow can be incorporated into a BIM-based project through the definition of project EIRs and BEPs. For these reasons, the ONIB workflow will be adopted for this thesis’s methodology as it is similar to other reviewed approaches but provides more detailed information on its application.

4.2 Detachability Assessment Workflow

Following the assessment carried out in chapter 3, three indicators were chosen (section 4.3), for our workflow, from the six previously identified detachability indicators. For these indicators, process models were created (section 4.4), from which attribute matrices were developed (section 4.5). Creating the process models for each indicator was crucial as they pointed to the parameters and factors needed within the model and the rulesets required for deriving each indicator's values. Likewise, the attribute matrix guides the addition of parameters to the model (model enrichment) when needed. Following the attribute matrix creation and the model enrichment, the process model was represented in a BIM software (Revit-Dynamo), such that the value for each indicator can be derived using a BIM model (chapter 5.1).

4.3 Detachability Indicators Selection and Boundary Conditions

The indicators assessed in this chapter were selected based on the derivability of their values from a BIM model. Among the six indicators reviewed in chapter 3, only the “connection type”, “connection accessibility”, and “degree intersection” indicators will be considered for this thesis’s scope. These indicators were chosen due to the possibility of deriving their values from the geometric and semantic information in BIM models according to the analysis conducted in section 3.2. The “enclosure form” indicator was exempted from the workflow due to the form of material layer arrangements required for its analysis. As shown in Figure 3-2 and Figure 3-3 from section 3.2.1.4, the material layer representation required by this indicator (Figure 3-2) is more advanced than that representable in the Autodesk Revit authoring software (Figure 3-3), or the material layer representation provided within the IFC standard (Figure 3-6). Therefore, the enclosure form indicator was exempted.

Similarly, the “work factor” and “value factor” indicators were exempted from further assessment as a practical approach is required for deriving their indicator values. To derive the work factor of building elements, they were practically deconstructed to measure the effort required for their deconstruction. Likewise, the salvage value of construction materials was researched in Germany to derive the value factor of the construction materials (Figure 3-4). Furthermore, catalogues have been created for both indicators by Rosen (2021) in her research, and this information could be added to BIM elements and materials as property sets, when needed. Since this thesis is focused on deriving each indicator value using a BIM model, the derivation of these indicators (value factor and work factor) is, therefore, outside the scope of this thesis, as they require a hands-on approach.

Overall, this thesis considers three indicators: “connection type”, “connection accessibility”, and “degree intersection”. As these indicators fall within the four indicators considered in the Madaster detachability assessment methodology (Figure 4-1), the formula used by Madaster in deriving the final detachability index of elements will be adopted with an exemption of “enclosure form” in the formula, as shown in Equation *4-1* and Equation *4-2*.

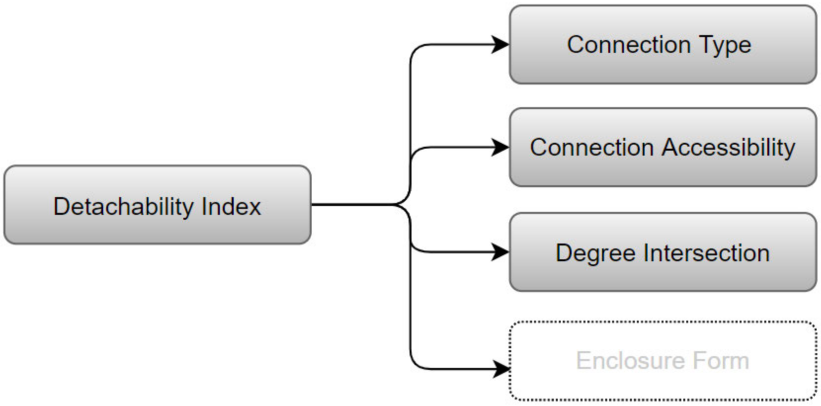


Figure 4-1: Considered detachability indicators, with reference to Madaster's methodology

$$LIp_n = \frac{4}{\frac{1}{TV_n} + \frac{1}{ToV_n} + \frac{1}{DK_n} + \frac{1}{RO_n}}$$

Equation 4-1: Madaster detachability Index formula

$$LIp_n = \frac{3}{\frac{1}{TV_n} + \frac{1}{ToV_n} + \frac{1}{DK_n}}$$

Equation 4-2: Applied detachability Index formula

Where:

LIp_n = Detachability index of product or element

TV_n = Connection type

ToV_n= Connection accessibility

DK_n= Degree intersection

RO_n= Enclosure form

Furthermore, the prototypical case study conducted in chapter 5 for the implementation of the defined workflow in this chapter will focus mainly on the building's exterior and interior wall elements. This will set a basis for further adaptation of the workflow for application to other building elements. Similarly, the exterior and interior walls of buildings fall within the standard building component (SBC) considered within the DGNB TEC 1.6 BCA methodology, which was reviewed in section 2.3.3.1, to serve as guidance for our case study as discussed in section 3.1.2.

4.4 Indicators Process Model

The process models form the basis of this workflow (section 4.1), as it leads to the identification of model properties as well as rulesets needed for deriving each indicator value. Conventionally, assigning values to the detachability index indicators depends on the expert knowledge of the building circularity specialist. However, the process diagram help represent the domain knowledge and conventional process for selecting each indicator value by the specialist. This promotes the transparency of the assessment process and accommodates incremental improvement of the assessment process, with an increase in knowledge on the topic or the adjustment of the assessment requirements.

To create the process model for each indicator, process analysis of how they can be assessed and their values derived was carried out. As this requires understanding the requirements for deriving each indicator, the assessment carried out in chapter 3 plays a significant role. Building on this knowledge, the process diagrams for each of the three selected indicators: connection type, connection accessibility and degree intersection, were created based on the interpretation of the indicators' requirements. Sections 4.4.1, 4.4.2, and 4.4.3 below discuss the process models created for each indicator.

4.4.1 Connection type indicator process model

As discussed in section 3.1.1, the connection type indicator is graded based on the type of connection or connectors that exists between elements, products or materials that are joined together. To assess this indicator, connectors between objects are identified, classified and graded from 0.1 to 1.0 (Table 4-1). The grading is based on the ease with which the connection can be non-destructively detached, with 0.1 being the worst and 1.0 the best-case scenario.

Table 4-1: Connection types classification and grading adopted from (Vliet et al., 2021)

Connection Types	Classification	Grading
None	DryConnection	1.0
Click		
Velcro		
Magnetic		
BoltAndNut	WithAddedConnections	0.8
Spring		
Corner		
Screw		
Peg	DirectConnection	0.6
Nail		
Sealant	SoftChemicalConnection	0.2
Foam		
Glue	HardChemicalConnection	0.1
Landfill		
Weld		
Concrete		
ChemicalAnchor		

As shown in Table 3-3 (page 58), the connection type indicator is assessed both on the element and material level of the building. Therefore, for each element being analysed, the connection type between the element and other elements will be assessed. Likewise, the connection type between this element's material layers will be assessed. The material layer assessment involves checking if an element is composed of more than one material layer and checking how these materials are connected. For the element layer, provided the element is connected to more than one element with different types of connections, the worst connection type value will be chosen as the representative connection type for this element. Similarly, the worst connection type between the element material layer will be chosen as the material layer connection type. After which, the average of the element and material level connection type value will be assigned to the element as the final value for this assessment. Figure 4-2 below shows the process diagram for the connection type indicator.

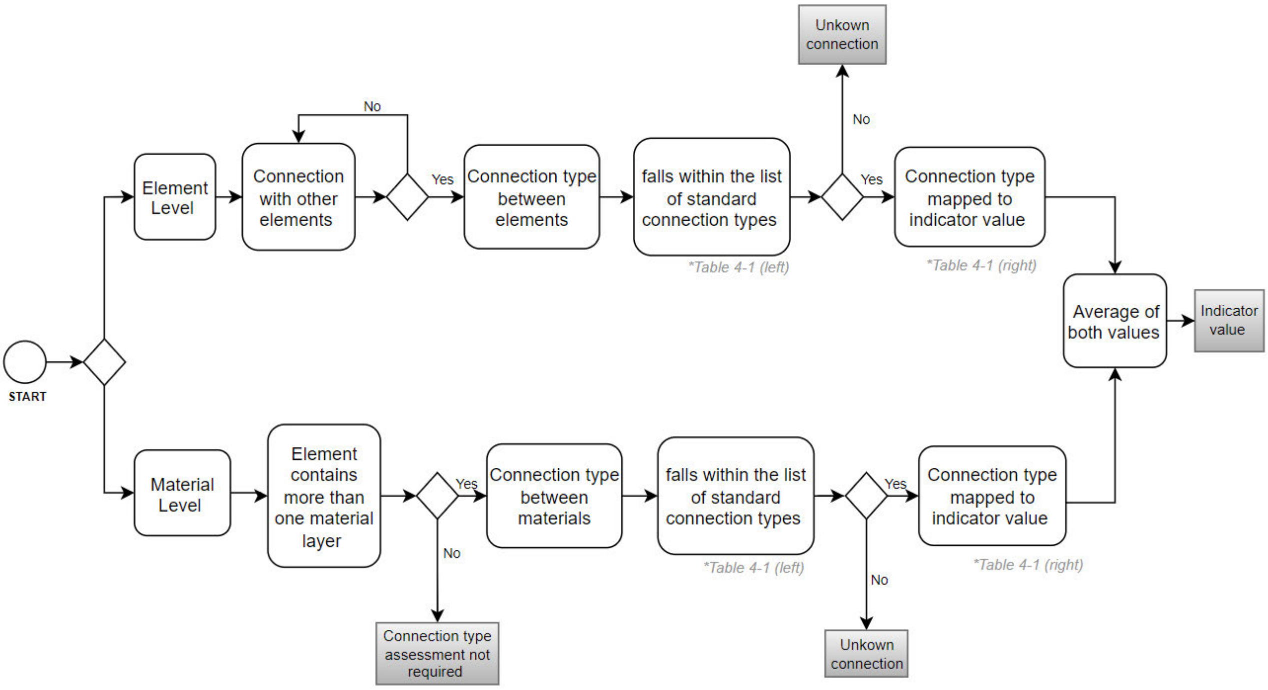


Figure 4-2: Connection type indicator's process model

4.4.2 Connection accessibility indicator process model

The connection accessibility indicator, similar to the connection type indicator, is assessed both on the element and material level of the building, as shown in Table 3-3. It can be considered a continuation of the connection type indicator as it assesses the ease with which the connectors between elements, materials or products can be reached for deconstruction without affecting their surrounding objects (section 3.2.1.2). To assess this on the element level, the free distance between the elements' connection point and their surrounding elements is computed and compared to a limiting value that allows easy access to these connection points. For the material layer of the building elements, their arrangement in relation to their lifespan is assessed. A material layer consisting of only one material type has the highest indicator value of 1.0, as it has no connection to other materials. For a material layer consisting of more than one material, the material layer arrangement that allows materials with shorter lifespans to be disassembled without disassembling those with longer lifespans attain better accessibility value, and vice versa. Figure 4-3 below shows the process diagram for assessing the connection accessibility indicator on the element and material level.

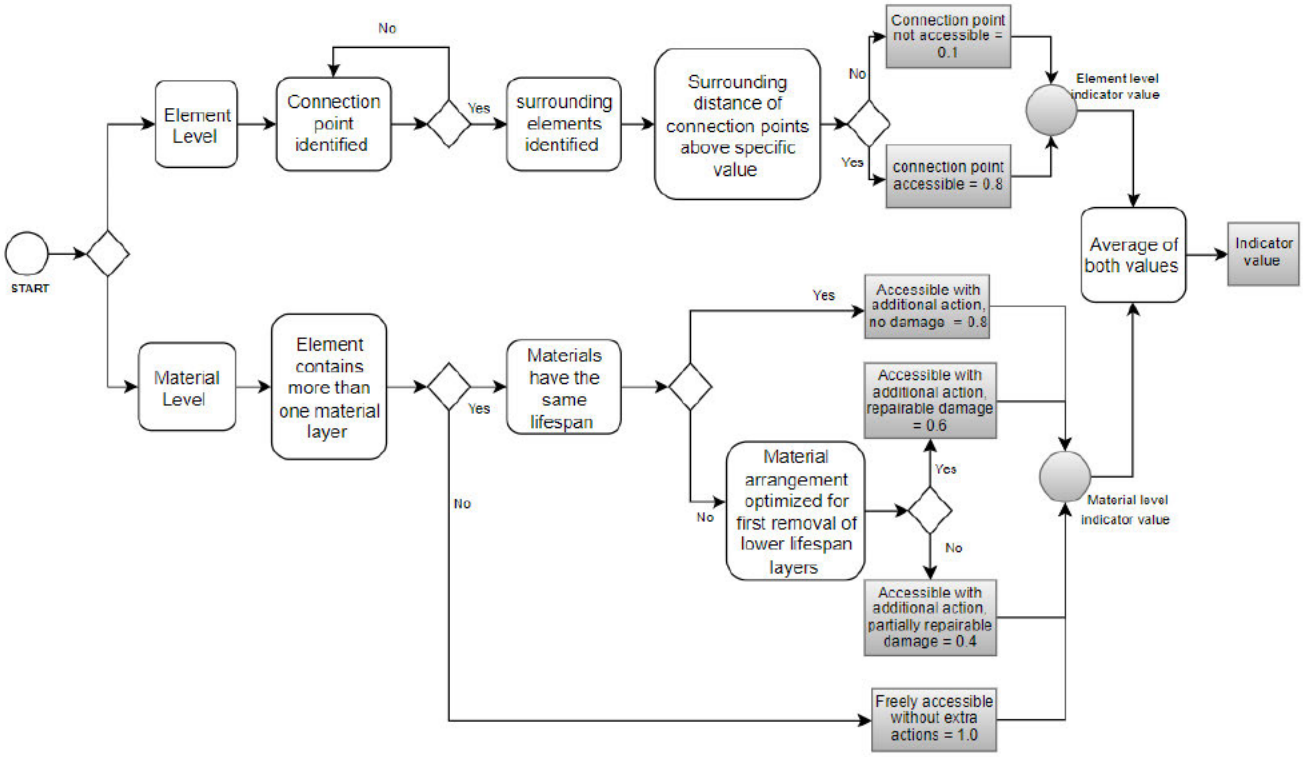


Figure 4-3: Connection accessibility process model

4.4.3 Degree Intersection indicator process model

As shown in Table 3-3, the degree intersection indicator is assessed only on the element level of the building and measures the rate at which elements from different shearing layers, according to Brand (1995) (Figure 2-14), intersect each other (section 3.1.1). Its assessment process involves the identification of intersections between elements, how often these intersections occur and the shearing layer in which these intersecting elements belong. Therefore, according to the intersection frequency, the assessment is assigned a grade between 0.1, 0.4 and 1.0, as shown in Table 4-2 below. Represented in Figure 4-4 is the process diagram for the degree intersection indicator.

Table 4-2: Degree intersection grading system; adopted from (Vliet et al., 2021)

Classification	Grading
No crossing	1.0
Occasional crossing	0.4
Full integration	0.1

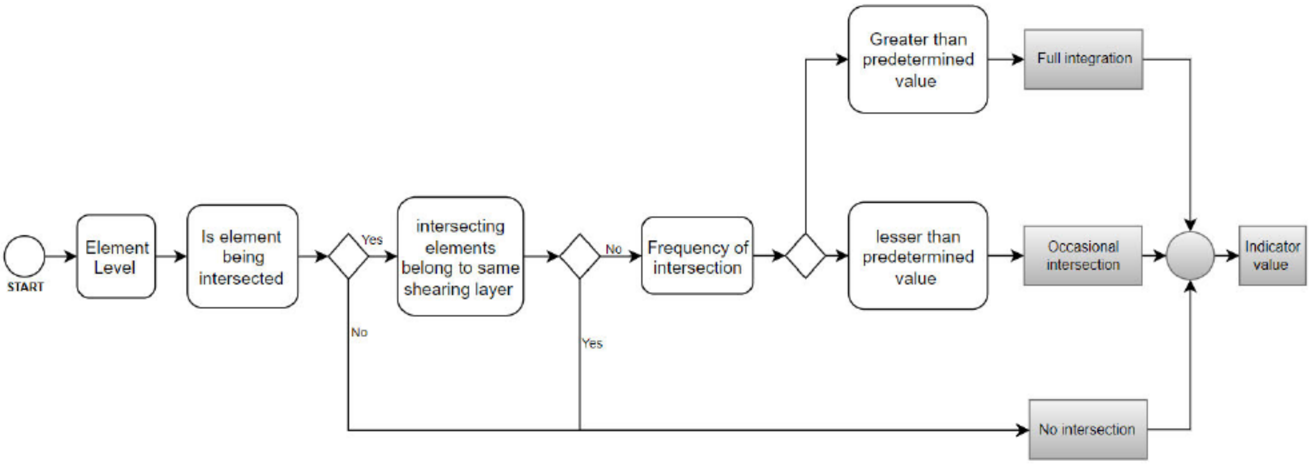


Figure 4-4: Degree intersection process model

4.5 Creation of Attribute Matrices

The creation of attribute matrices comes after the development of process diagrams for analysing each of the three chosen detachability indicators. Attribute matrices outline the geometric and semantic properties, as well as the factors required in a BIM model for the complete assessment of each indicator, according to their process model. Therefore, to ensure creating of 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 4-3 below outlines the structure and exemplary content for the attribute matrices (Appendix B) created for our workflow.

Table 4-3: Information content requirement for the attribute matrices, based on (ONIB, 2020)

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	the attribute defines the expected lifespan of the material
Attribute datatype	the data type of the attribute [string, int, boolean etc.]	int
Unit	the attribute unit [m, years, etc.]	year

On a similar note, to ensure clarity and uniformity when defining the custom parameters required within the process models, using a standard naming convention is essential. This makes it easier to identify parameters that are particular to the detachability assessment workflow, among others, within the BIM model. Figure 4-5 below shows the naming convention adopted in this thesis.

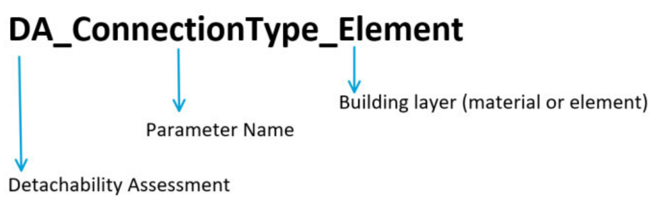


Figure 4-5: Custom parameters naming convention

4.6 EIR and BEP requirements for the assessment process

For the successful implementation of the above-described 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, prior to the project's start. This is essential as a high level of information standardization is required for this assessment process. According to ONIB (2020), some of the information included within the EIR and BEP for the successful use of BIM for building sustainability optimization, which is also applicable for this workflow, are project information, BIM goal, BIM use case, collaboration mode between project participants, software requirement, and the roles and responsibilities of project participants.

The project information establishes the project’s fundamental standards. Here the project’s definition of a circular and detachable building is specified, the detachability indicators to be assessed within the project as well as their evaluation methodology is defined, building components to be considered within the assessment are specified, and so on. The BIM goal specifies which detachability indicators are to be evaluated using the BIM model, while the BIM use case outlines the details of how BIM will be used for the assessment process. The roles and responsibilities section defines the project-required roles, such as building circularity specialists, and their responsibilities, such as the development of the detachability indicators process models and attribute matrices. Similarly, the required BIM-based detachability assessment tool will be specified when defining the project’s software requirement. More importantly, the modelling guidelines and data requirements for the BIM model, such as the LOD requirements of the model elements, required elements attributes and parameters, parameters naming convention etc., will be defined such that the model can be used for the complete assessment of the chosen detachability indicator for the project.

Overall, the success of this workflow’s implementation in a BIM-based project depends on the integration of the BIM requirement for the detachability assessment use case in the project's EIR and the development of the BEP to meet the EIR requirements.

5 Case Study & Prototypical Implementation

To validate the BIM-based detachability assessment workflow proposed in chapter 4, a case study was conducted and will be discussed in the sections of this chapter. The model used for the case study was created using the Autodesk Revit software (section 5.1). Following this, according to the developed process model and attributes matrices for deriving each indicator's value (sections 4.4 and 4.5), the required model elements are enriched with attributes required for the assessment process (section 5.2). Thereafter, using Revit dynamo, the assessment was conducted (section 5.3). After the analysis, the model wall elements are visualized according to their detachability index.

5.1 BIM Model Creation

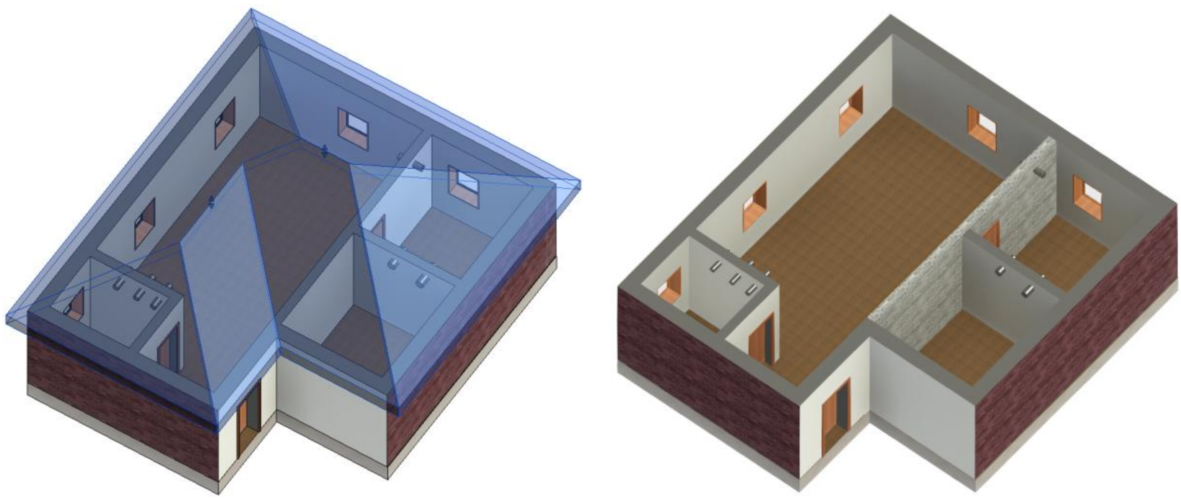


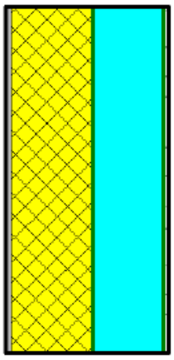
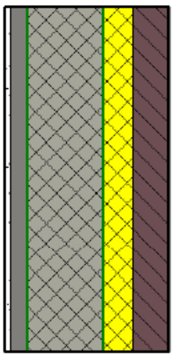
Figure 5-1: Building for the case study, modelled in Autodesk Revit

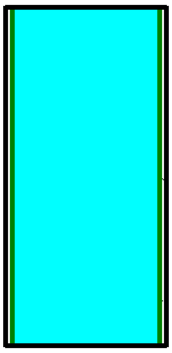
Figure 5-1 above shows the model used for this case study, created using Autodesk Revit 2021. The model was created to meet the basic requirements of the indicators to be assessed according to section 3.2 (Table 3-4), which resulted in the creation of a multi-LOD model. As this prototypical assessment is based on the wall elements, they were modelled to a LOD of 350. This is because the connection type and connection accessibility indicators involve material level assessment of building elements, and the required material information are modelled in LOD 350 (Table 2-1). For the other model elements, LOD 200 suffices, as only their approximate representation is required for this case study. This includes the pipes in the model. The pipes in the model were specifically included for the assessment of the "degree intersection" indicator (section

0), and as shown in Table 3-4, early phases model elements, i.e. LOD 200 (section 2.1.3), 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 (Schneider-Marin & Abu-aldenien, 2019).

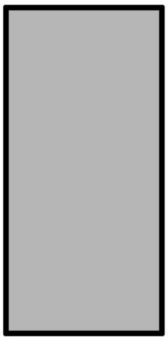
To allow for variety in the case study assessment, four different wall construction types (two exterior and two interior wall types) are represented in this model, differing mainly in their material arrangement. These different wall constructions are particularly targeted at the connection type and connection accessibility indicators, as they involve the material level assessment of the wall elements. Table 5-1 below shows the details of these walls.

Table 5-1: Revit model wall construction

<table>
<tr><th>Visual Image</th><th>Material layer</th></tr>
<tr><td></td><td>
<table>
<tr><th></th><th>Function</th><th>Material</th><th>Thickness</th></tr>
<tr><td>1</td><td>Finish 1 [4]</td><td>Gypsum Wall Board</td><td>15.0</td></tr>
<tr><td>2</td><td>Thermal/Air Layer [3]</td><td>Rigid insulation</td><td>200.0</td></tr>
<tr><td>3</td><td>Core Boundary</td><td>Layers Above Wrap</td><td>0.0</td></tr>
<tr><td>4</td><td>Structure [1]</td><td>Brick, Sand Lime</td><td>175.0</td></tr>
<tr><td>5</td><td>Core Boundary</td><td>Layers Below Wrap</td><td>0.0</td></tr>
<tr><td>6</td><td>Finish 2 [5]</td><td>Plaster</td><td>15.0</td></tr>
</table>
</td></tr>
<tr><td></td><td>
<table>
<tr><th></th><th>Function</th><th>Material</th><th>Thickness</th></tr>
<tr><td>1</td><td>Finish 1 [4]</td><td>Brick, Common</td><td>90.0</td></tr>
<tr><td>2</td><td>Thermal/Air Layer [3]</td><td>Rigid insulation</td><td>75.0</td></tr>
<tr><td>3</td><td>Core Boundary</td><td>Layers Above Wrap</td><td>0.0</td></tr>
<tr><td>4</td><td>Structure [1]</td><td>Concrete Masonry Unit</td><td>190.0</td></tr>
<tr><td>5</td><td>Core Boundary</td><td>Layers Below Wrap</td><td>0.0</td></tr>
<tr><td>6</td><td>Substrate [2]</td><td>Metal Furring</td><td>40.0</td></tr>
<tr><td>7</td><td>Finish 2 [5]</td><td>Gypsum Wall Board</td><td>15.0</td></tr>
</table>
</td></tr>
</table>



	Function	Material	Thickness
1	Finish 1 [4]	Gypsum Wall Board	10.0
2	**Core Boundary**	**Layers Above Wrap**	**0.0**
3	Structure [1]	Brick, Sand Lime	240.0
4	**Core Boundary**	**Layers Below Wrap**	**0.0**
5	Finish 2 [5]	Gypsum Wall Board	10.0



	Function	Material	Thickness
1	**Core Boundary**	**Layers Above Wrap**	**0.0**
2	Structure [1]	Brick, Common, Gre	240.0
3	**Core Boundary**	**Layers Below Wrap**	**0.0**

5.2 Model element enrichment and attributes integration

With respect to the attribute matrix developed from each indicator's process model (section 4.5), some additional attributes are required for the indicators' evaluation process. For instance, the shearing layer of the model elements, such as the walls, and the pipes, need to be defined for the assessment of the "degree intersection" indicator. To integrate these attributes into the model element, the creation of custom parameters is essential, and these parameters were created and added to the model through the Revit interface. Before specific parameters could be created, a text file was created by Revit to store the share parameters to be created. The file created for this case study was named "DetachabilityAssessmentIndicator" (digital Appendix). Thereafter, the custom shared parameters were created following the name convention and data type specified in the attribute matrix, after which they could be added to the Revit project under "Project parameter". Upon adding the parameters to the project, it is necessary to determine the model elements to which the parameters will be assigned and then populate them with data for the element types or instances.

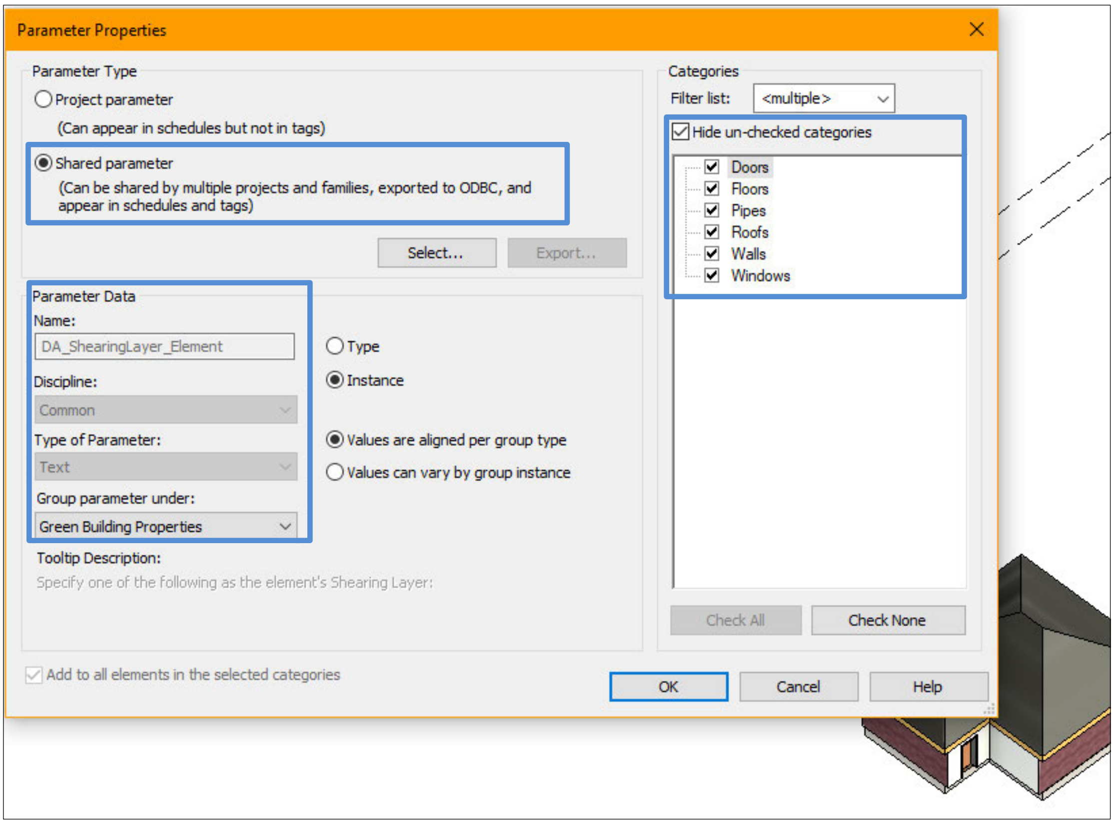


Figure 5-2: Adding a shared parameter to selected Revit project elements

The use of shared parameters is advantageous as this document, once created, can be shared with other projects and nullifies the need to create these parameters from scratch for every project where the detachability assessment is to be carried out, facilitating reusability. Also, this file can easily be extended with more parameters based on changes in the assessment process requirements.

5.3 Indicator Assessment

For the assessment process, Revit Dynamo was used for conducting the analysis required for evaluating each detachability indicator. A major reason for the adoption of Dynamo for this case study is its good integration with Revit, ensuring easy and seamless access to the assessed model's geometric and semantic information within the dynamo scripting environment. Dynamo reduces the interoperability challenges that may occur from adopting an open BIM approach (exemplary open BIM limitation discussed in chapter 6) and enables the focus on the prototypical testing of the proposed workflow.

Revit Dynamo is a visual programming interface that enables users to set up and automate building information workflows. It is often used during the design phases for building performance testing and process automation, enabling real-time assessment of the Revit model and offering instant result visualization (Sandzhiev et al., 2018). Particularly for non-programmers, It offers a relatively simpler and user-friendly approach of computer programming compared to textual programming languages such as C++, Java, etc. (Mengana & Mousiadis, 2017). This enables researchers to more efficiently and effectively represent prototypical implementation, which research successors can easily interpret for further development (Zhai, 2020).

For this case study, Dynamo version 2.16, pre-installed in the Autodesk Revit 2021 software package, was used. Upon running the created dynamo script (section 5.3.2), the detachability index of the model wall elements will be assessed and visualized. The dynamo script was created using nodes from the default dynamo library and additional custom libraries (custom packages) installed in dynamo. Appendix C gives a list of custom packages used within the created script.

5.3.1 System Architecture

This section describes the system architecture of the prototypical dynamo tool developed for this case study (Figure 5-3). It is divided into three main sections, which are the input, the analysis and the output section. The input section extracts the geometric and semantic data required for the assessment process from the Revit model. This information is made available within the dynamo script through direct extraction from the model elements or the element schedules created in Revit. In the analysis section, according to their process models (section 4.4), the rulesets for evaluating each indicator are programmed using the dynamo script. Here the connection type, connection accessibility and degree intersection indicators are evaluated, and using Equation *4-2*, the detachability index of individual wall elements is derived. The output section details how the assessment values are visualized. The result visualization occurs in three ways: through a pop-up window in Revit, through element colour coding according to the index value and by saving the outputs as parameter values which can then be exported to an excel sheet for further processing.

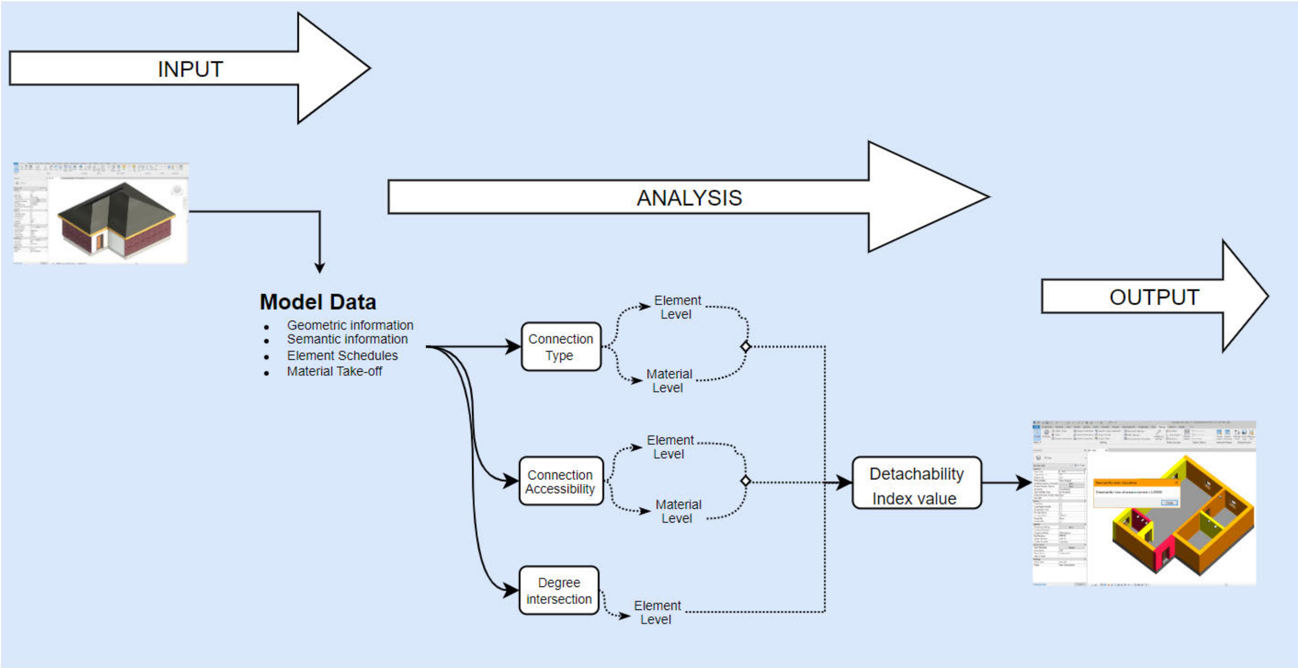


Figure 5-3: Structure of the Dynamo-based assessment tool

5.3.2 Dynamo Script

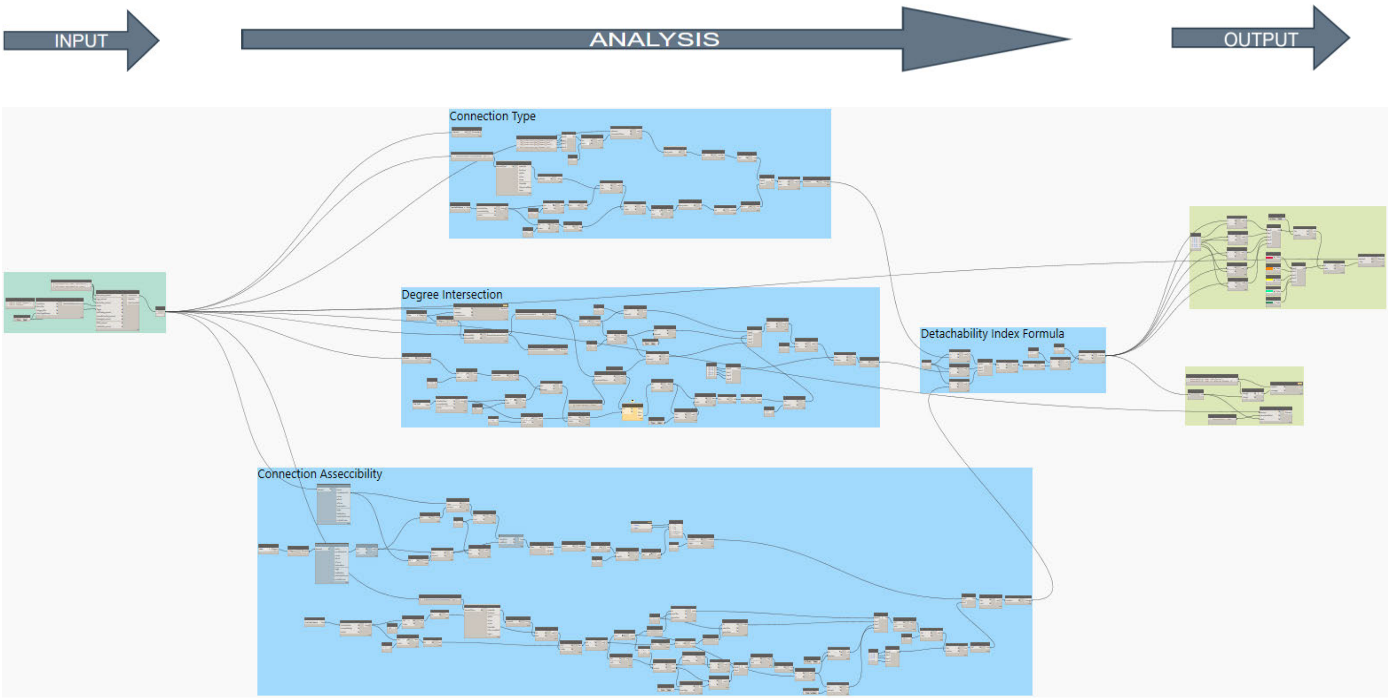


Figure 5-4: Dynamo script for the detachability index assessment

The dynamo script created for this case study follows the structure described in section 5.3.1 (Figure 5-3). As shown in Figure 5-4 above, It consists of the input, analysis, and output sections, each containing nodes performing their required task. The input section contains a group of nodes which delivers a pop-up window to the Revit interface (Figure 5-5) for the selection of the wall element to be assessed. After selection, the “Calculate detachability Index” button in the pop-up window is clicked to commence the evaluation process using the other sections of the script.

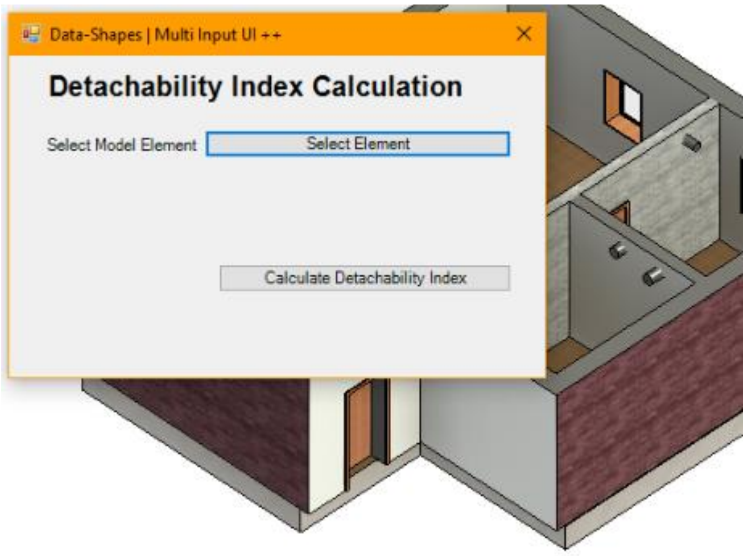


Figure 5-5: Start of the assessment process

The analysis of each indicator was conducted following their individual process model, as stated in section 5.3.1. According to these process models, each indicator requires different information from the BIM model for its evaluation process. For the element-level connection type assessment, this information is the types of connectors with which the assessed wall is connected to other walls at both its ends, the roof at its top and the floor at its bottom. According to the created attribute matrix for this workflow (Appendix 5), this information was added to the wall elements as custom shared parameters (section 5.2) and their values extracted by the dynamo script for the evaluation process (Figure 5-6). The connection types assigned to these parameters were chosen at random, within the standard list of connectors for this assessment methodology (Table 4-1), to prevent a monolithic indicator result for this assessment. Similarly, for the material level assessment of the connection type indicator, the materials connection types were defined using custom parameters and used for the indicator’s assessment.

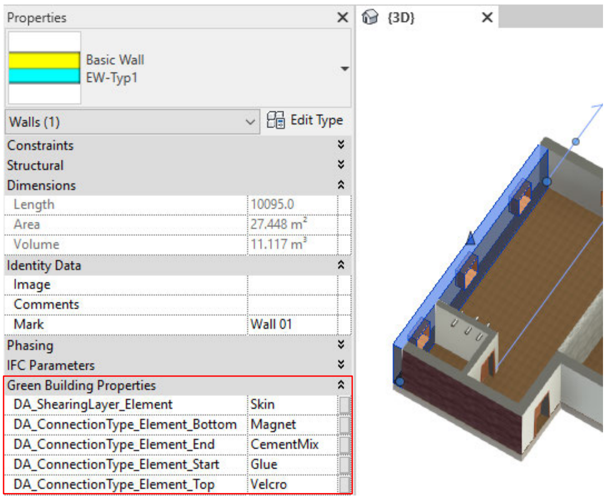


Figure 5-6: Custom parameters for element-level connection type assessment

The assessment of the connection accessibility indicator, on the element level, however, requires no additional custom parameter. Here a geometric evaluation is conducted to compute the free distance between the assessed wall's connection points and its surrounding walls. This was achieved by deriving the endpoint coordinate of the assessed wall and the coordinate of its surrounding wall elements. Through this, the separating distance between the assessed wall's connection point and its surrounding walls can be computed, and the lowest distance compared to a specified range, as depicted by the indicator's process model (Figure 4-3). For the material level assessment, the lifespan of the materials within the wall elements was required to assess if the materials are arranged such that the materials with lower lifespan can be replaced without deconstructing those with longer lifespan.

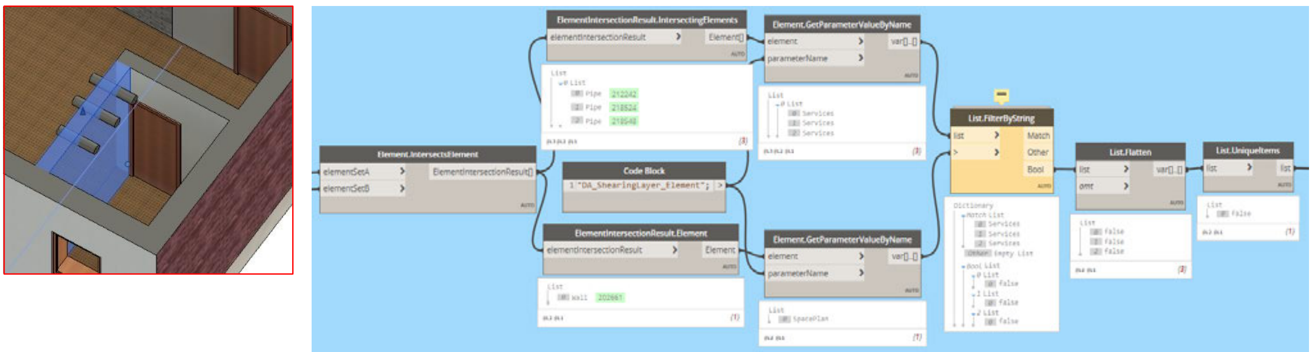
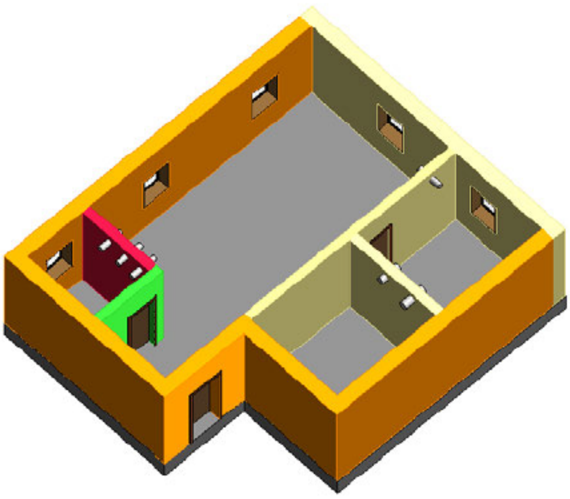


Figure 5-7: Degree Intersection indicator assessment

For the script illustration of our degree intersection indicator (Figure 5-7), a wall with three intersecting pipes was selected as shown above. Similar to the other indicators, the dynamo scripting follows its defined process model (Figure 4-4). First, the presence of intersection between the assessed wall and other elements was checked. Provided there are, the script checks if the intersecting and intersected elements belong to the same shearing layer. The shearing layer information of the assessed elements is extracted from the created custom parameter "DA_ShearingParameter_Element" assigned to these elements. Finally, the frequency of intersection is checked, and the assessed wall is assigned an indicator value according to the assessment result.

Following the completion of each indicator's assessment, the final detachability index of the assessed wall is computed using the formula in Equation *4-2*. After which, all resulting indicator values and the final detachability index value are saved as wall parameter values. For the connection type, connection accessibility and degree intersection indicators, respective, the "DA_CT_iIndex", "DA_CA_Index" and "DA_DI_Index" custom shared parameters were created for storing their values, and the final detachability index value is saved as "DA_DetachabilityIndex". This allows for easy visualization of all the assessment values within the Revit interface.



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 5-8: Detachability index result visualization

Following the detachability index computation, the wall elements are visualized in Revit, as shown in Figure 5-8 above, according to their index value. Similarly, assessment results saved as parameter values are extracted from the model and exported to an excel file. Figure 5-9 below shows an exemplary graphical representation of the assessment results, visualizing each assessed indicator value as well as the final index value for the walls, using the information exported to Microsoft Excel.

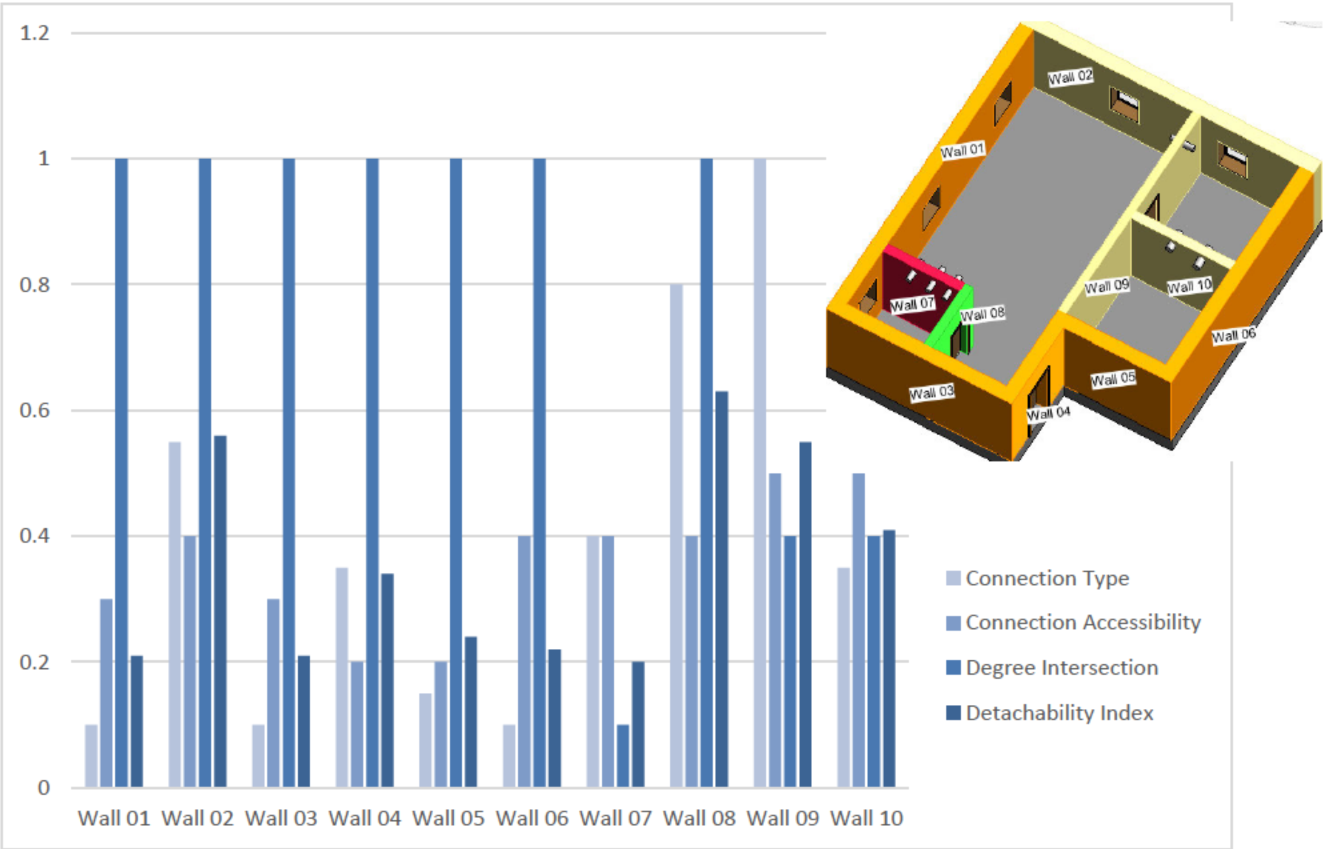


Figure 5-9: Graphical visualization of assessment result

6 Discussion

The methodology proposed in this thesis has shown the possibility of automating and better integrating the building detachability assessment process into BIM. However, both the proposed workflow and its prototypical implementation have some limitations, as discussed in this chapter.

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 3.2, this is because some semantic information required to completely assess the indicators are not readily available in the model and needs to be added as property sets. An example is the model elements' shearing layer (according to Brand (1995)), which is required for assessing the degree intersection indicator. The required geometric information, however, could be derived from the model.

As discussed in section 3.2, 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 wall materials as required by the indicator and the simplification of the indicators' process model to the level that can be accommodated by the possible wall 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.

Additionally, to facilitate open BIM implementation, research into the possible extension of the IFC schema to accommodate the geometric and semantic information required for the detachability indicators assessment is recommended. From the analysis conducted in section 3.2.2, an example of where the IFC schema was found lacking for the detachability assessment process; was in the definition of elements connections. In defining elements connection (IfcRelConnectsPathElements), the connections at both ends of the elements (AtStart, AtEnd) and along the element (AtPath) can be specified. However, the IFC documentation does not define the connection at the top and bottom of elements (e.g. AtTop, AtBottom). Therefore, the relationship between the wall and the floor above and below it cannot be defined in the case of wall elements.

Another limitation, due to the non-standardized format of the conventional indicators assessment requirements (Vliet et al., 2021), is in effectively representing these requirements as BIM-based requirements, using the process models. The indicators' assessment rules are not explicitly defined and are generalized across all building components, making it difficult to effectively represent their requirements for specific building components. Similarly, as these indicators' assessment processes and requirements are not specifically created for BIM implementation, they require details which could not be effectively represented by the process model and assessed using BIM. An example of this resulted in the omission of the enclosure form indicator from the assessed detachability indicator in the proposed workflow (section 4.3).

Another key limitation in the prototypical implementation of the proposed workflow, due to its high reliance on custom parameters, is data management. This is a challenge as some parameter values required for the assessment (the dynamo script) have to be manually entered, and the provision of wrong information can alter the assessment result. For instance, in the evaluation of the connection type indicator, entering "Nails" instead of "Nail" as the "DA_ConnectionType_Material" custom parameter value will result in this value being ignored in the assessment process. This challenge could potentially be resolved with the possibility of defining the created custom parameters as "Enumerated" or "Array" data types. This way, the allowed parameter input values are pre-specified and can be selected from, by the modeller. However, the definition of these data types is currently not possible in Revit or other BIM authoring software (Fugas, 2022).

Overall, the proposed workflow gives an overview of a possible approach in which the building detachability assessment can be automated using the BIM method, which was prototypically tested mainly for the functioning of the workflow using a closed BIM approach. While the proposed workflow proves promising, there are some basic limitations, as discussed above. Some recommendations for future research to resolve these limitations are outlined in chapter 7 below.

7 Conclusion and Outlook

To aid in achieving this thesis's aim, five guiding research questions were defined in section 1.2. Table 7-1 below highlights these research questions, the section in which they were answered and a brief description of these sections' findings.

Table 7-1: Research Questions and Findings

Research Questions	Answered in	Main findings
1. What are the existing detachability assessment methods in the current BCA methodologies?	Section 2.3	Here the BCI-based and UMI-based detachability assessment models were identified as the main currently available methods
2. Is BIM currently being used by these methods? If yes, are there limitations to be improved?	Section 2.4	Of the two, only the BCI-based model has been BIM integrated (by Madaster). However, as pointed out by research, this BIM-based assessment method has a high level of subjectivity.
3. How detailed are these detachability assessment models, and how quantifiable are they such that they can be quantitatively assessed?	Section 3.2	Both models are relatively detailed. UMI takes a practical approach to its assessment. Building elements were practically constructed and deconstructed and a catalogue created from the research output. On the other hand, BCI gives requirements for deriving its four indicators' values and a formula for deriving the final detachability index from these indicators.
4. What information would be needed for them to be assessed, and is it readily available in the BIM models?	Section 3.2	Some available information within the BIM model can be used for their assessment; however, additional assessment-specific attributes can also be added to the model as property sets, using custom parameters.
5. How can the Detachability assessment BIM-based process be automated?	Chapter 4	By creating process models and attribute matrices for each detachability indicator's conventional assessment process, BIM requirements can be identified and integrated into the model to automate the BIM-based detachability assessment process.

This thesis contributes to the knowledge of BIM-based building detachability assessment and building circularity assessment as a whole. To establish the most relevant detachability indicators to be adopted in the proposed workflow, research was conducted into the most recent BCA method and the detachability assessment model implemented within them. Among these BCA methodologies, only Madaster has integrated BIM for its assessment process. However, as pointed out by researchers, the BIM-based workflow involves a high level of subjectivity.

To reduce this subjectivity and automate the BIM-based building detachability assessment process, analysis was conducted into the degree to which the detachability indicators could readily be assessed using BIM (Autodesk Revit and IFC). Thereafter, a suitable workflow for better closed-BIM-based detachability assessment was researched, proposed, and prototypically tested.

Contrary to the current BIM-based implementation (Madaster), which takes the final indicators' values as input, with no means of reviewing or verifying its decision-making process, 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. Likewise, as the process models represent the expert knowledge for conducting this assessment, it clearly outlines the decision-making process for deriving these values, which can be peer-reviewed, accepted, or updated as required. Thereby promoting the transparency and objectivity of the assessment process. Furthermore, through 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 this thesis's findings and limitations, there are some research recommendations that would enable a better BIM-based detachability assessment workflow. Among these is the development of a more standardized and explicitly rule-based detachability-indicators assessment criteria, by circularity specialists. In developing these requirements, a practical research approach similar to that of Rosen (2021) in the UMI research could be adopted. 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 developed. This will improve the accuracy and clarity of the assessment process and make it easier for BIM integration.

Additionally, to facilitate open BIM implementation, research into the possible extension of the IFC schema to accommodate the geometric and semantic information required for the detachability indicators assessment should be conducted. This involves research into the possibility of a more detailed and advanced material-level representation and the addition of entities, attributes, and relationships to the IFC schema, that would facilitate the building detachability assessment process. However, this is more achievable following the standardization of the conventional assessment criteria (as stated above) and further research into the IFC schema limitation with respect to these criteria for each key building element.

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Appendix A

Table A: IFC-Schema Analysis

Indicator	Available IFC schema		Further Explanation
	Attribute	Type	
Connection Type	• ConnectedTo • ConnectedFrom	• IfcRelConnectsElements • IfcRelConnectsPathElements	• Gives information on the element in which the selected element is connected to • Gives further information on where the connection is occurring (particularly for a wall) either AtStart, AtEnd, or AtPath
	• ConnectedTo.ConnectionGeometry	• IfcConnectionGeometry • IfcConnectionCurveGeometry • IfcConnectionPointGeometry • IfcConnectionSurfaceGeometry • IfcConnectionVolumeGeometry	• Gives information of the shape of the connection point between the two connected elements. Only connection between two elements can be described
	• isConnectionRealization	• IfcRelConnectsWithRealizingElements	• This is an element that is used to connect other elements together. For this to used, the connecting element has to be created or modelled and assigned this attribute
Connection Accessibility	• ContainedInStructure • ContainedInStructure.RelatedElements • ContainedInStructure.RelatingStructure	• IfcRelContainedInSpatialStructure • IfcProduct • IfcSpatialElement	• This set of relational schemas can be used for getting element location and identifying its surrounding elements
	• ReferencedInStructure	• IfcRelReferencedInSpatialStructure	• This is used to identify element that was not created in a building level or story but has a presence in this level. For example,

			a continuous wall that start from level 1 to level 3, needs to be referenced in level 2
	• ObjectPlacement • ObjectPlacement.RelativePlacement • ObjectPlacement.RelativePlacement.Location.Coordinate	• IfcObjectPlacement • IfcAxis2Placement	• These schemas point at elements or object location coordinate within the model. This can then be further processed to derive the distance between the selected element and its surrounding elements
	• HasAssociations • HasAssociations.RelatingMaterial • HasAssociations.RelatingMaterial.ForLayerSet.MaterialLayers	• IfcRelAssociatesMaterial • IfcMaterialSet • IfcMaterialLayerSetUsage	• This IFC schema (IfcRelAssociatesMaterial) point to the materials within the building element. • The last two schemas further point as the relating materials in the element and further illustrates how they are arranged
Degree Intersection	• InterferesElements • InterferesElements.InterferenceGeometry • InterferesElements.InterferenceType • IsInterferredByElements	• IfcRelInterferesElements • IfcConnectionGeometry • IfcIdentifier	• This schema indicates if two elements overlap each other, potentially more important for clash detection • This defines the shape of the point of intersection between the two elementsGives details on the type of interference eg Clash or “ProvisionForVoid” etc
Enclosure Form	• HasAssociation • HasAssociations.RelatingMaterial • HasAssociations.RelatingMaterial.ForLayerSet.MaterialLayers	• IfcRelAssociatesMaterial • IfcMaterialSet • IfcMaterialLayerSetUsage	• This IFC schema point to the materials within the building element. However, has no provision for the level of detail (LoD) required by this indicator
Value factor	--	• IfcCostValue • IfcCostItem	• These schemas, however, have no relation to this indicator’s aim.
Work factor	--	• IfcSchedulingTime • IfcWorkTime	• IFC schema for construction work schedule planning. These schemas, however, have no relation to this indicator’s aim.

Appendix B

Table B: Attribute Matrix

Indicator	Building layer	Documented via	check via	Logical check	Additional parameters required?	Type of parameter	Attribute Name	Attribute explanation	Attribute datatype	Unit
Connection type	Element Level	component geometry	model geometry	check 1: is wall connected to other elements such as walls, ceilings, or roof	No	IfcRelConnectsElements IfcRelConnectsPathElements	[-]	[-]	bool	[-]
		component attribute	logical check of component attribute	check 2: what are the types of connectors between the connected elements	yes	Custom-shared parameter	DA_ConnectionType_Element	the attribute defines the type of connector between connecting elements	string	[-]
		component attribute	logical check of component attribute	check 3: Does the identified connection type fall within the list of standard types of connectors assessed by this indicator	No		[-]	[-]	bool	[-]
	Material level	component geometry	model geometry	check 1: Does the wall element contain more than one material layer	No	IfcMaterialLayerSet	[-]	[-]	bool	[-]
		component attribute	logical check of component attribute	check 2: what are the connection types between the material layer of the element	yes	Custom-shared parameter	DA_ConnectionType_Material	the attribute defines the type of connector between material layers	string	[-]

		component attribute	logical check of component attribute	check 3: Does the identified connection type fall within the list of standard types of connectors assessed by this indicator	No		[-]	[-]	bool	[-]
				the value of the connection type indicator equals the sum of the values from the element and material level, divided by two						
Connection Accessibility	Element Level	component geometry	model geometry	check 1: is wall connected to other elements such as walls, ceilings, or roof	No	IfcRelConnectsElements IfcRelConnectsPathElements	[-]	[-]	bool	[-]
		component geometry	model geometry	check 2: are there elements surrounding the two connected elements?	No	IfcRelContainedinSpatialStructure	[-]	[-]	bool	[-]
		component geometry	model geometry	check 3: Is the distances between the selected element's connection point and surrounding elements above specified standard	No	IfcobjectPlacement	[-]	[-]	bool	[-]
	Material level	component geometry	model geometry	check 1: Does the wall element contain more than one material layer	No	IfcMaterialLayerSet	[-]	[-]	bool	[-]
		component attribute	logical check of component attribute	check 2: Does all the materials in the material layer have the same lifespan	yes	Custom-shared parameter	DA_Lifespan_Material	the attribute defines the expected lifespan of the material	int	year
		component geometry	model geometry	check 3: is the material arrangement optimized for the easy removal of the lower lifespan layers	No	IfcMaterialLayerSetUsage				

				the value of the connection accessibility indicator equals the sum of the values from the element and material level, divided by two						
Degree Intersection	Element level	component geometry	model geometry	check 1: is the element being intersected by other element(s)	No	IfcRelInterferesElements	[-]	[-]	bool	[-]
		component attribute	logical check of component attribute	check 2: Does the intersecting and intersected elements belong to the same shearing layer	yes	Custom-shared parameter	DA_Shearing Layer_Element	the attribute defines the building shearing layer in which an element belongs to	string	[-]
		component geometry	model geometry	check 3: How often is the selected element being intersected by other elements	No	IfcRelInterferesElements	[-]	[-]	int	[-]
				the degree intersection indicator is outputed based on the fulfillment of the three checks above						

Appendix C

Table C: Dynamo-script custom packages

Package	Version	Description
Rhythm	2021.7.3	Rhythm is mostly made up of nodes that combine default dynamo nodes together and use them in creative way. In our script, for instance, it was used to give a pop-up for an element's detachability index in the Revit interfaces after its computation
bimorphNodes	4.0.10	BimorphNodes contain nodes mainly used for Revit model geometric assessment and clash detection. It is used, for instance, in our script to identify the intersection between elements and to extract values from schedules created within Revit to dynamo.
Clockwork for Dynamo 2.x	2.3.0	Clockwork package has numerous nodes focused on geometric operation and computations. For instance, it was used in our script to get the location and other geometric attributes of elements.
LunchBox for Dynamo	2015.7.21	Lunchbox is a set of Grasshopper and Dynamo computational design tools and has good interoperability with Microsoft Excel.
Data-Shapes	2022.2.96	Data-shape nodes provide added functioning to the dynamo player and interact with the Revit UI. For instance, it was used in our script for a pop-up dialogue that allows for the selection of element to be assessed.
Genius Loci	2021.9.23	Genius Loci are Python-written nodes that create interoperability and perform various specialized functions within dynamo. Used in our script, for instance, to perform more detailed list operations and to access the material within elements
SteamNodes	1.2.3	The SteamNodes package was used in our script, for instance, to perform more detailed list operations
Spring nodes	204.1.0	The Spring Node package seeks to improve the interoperability between Dynamo and Revit and help improve the speed of functions called within Dynamo. Used in our script, for sinstance, to perform more detailed list operations

Affirmation

Hereby I declare to have written the Master Thesis autonomously. Only the cited sources and means have been used. Verbally or semantically transferred intellectual property I distinguished as such.

Further I assure not to have handed in the Thesis for another examination.

München, 29. November 2022

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