BIM-based Building Circularity Assessment from the Early Design Stages

A BIM-based framework for automating the building circularity assessment from different levels of a building's composition and providing the decision-making support on the design of circular building from the early design stages

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Preface

This master thesis is the result of the graduation research at the Eindhoven University of Technology (TU/e), and it is carried out in collaboration with Alba Concepts. It finalizes my master program Construction Management and Engineering (CME) and marks the final stop of my student career. At this moment, I feel how time flies! Two-years study life at TU/e is fulfilling and full of challenges.

My interest in this subject started when I knew the concept of Circular Economy. Its great potential in bringing benefits to mitigate the negative impact of the construction industry on the environment attracted me. Combining this with a keen interest in Building Information Modelling (BIM), I soon decided the graduation topic: BIM-based building circularity assessment from the early design stages. In my research, I delved into the measurement of building's circularity and the possibilities of integrating it with BIM. Furthermore, I accomplished my first prototype, which mainly utilizes Dynamo for Revit (i.e., a visual programming platform) and felt quite satisfied with the prototype. The gained knowledge on building circularity assessment and visual programming language will surely benefit my future career.

Looking back on this seven-months journey that I spent on my master thesis, I would like to express my gratitude to all the people who helped and supported me. I would like to thank the company Alba Concepts for giving me the opportunity to execute this research. Especially, many thanks to my company supervisor Mike van Vliet, who took time out of his busy schedule to direct me. His continued guidance during the period of home isolation motivated me to make progress on my project. Furthermore, I would like to extend this thank to my colleagues Thijs de Goede and Hanne Spekreijse, who helped in collecting research data. Also, I want to thank Tiny van Menzel and Vincent Derksen from BIM-optimaal for providing me with the model to validate my prototype. Within the university, I would like to express a special thanks to my supervisors Qi Han and Pieter Pauwels for their guidance, advice, and insights through the entire graduation process. They always took time to discuss with me and addressed the key issues in my thesis.

Furthermore, I want to thank my lovely friends Siddharth Panjwani, Xiuxian Huang, Xingyu Piao, Hua Du, and Rob Peters, for their efforts on my thesis. Lastly, I would like to thank my mom, dad, and other family members for their mental and financial support. Especially, my mom suffered from my negative energy and kept encouraging me.

I wish you enjoy reading this thesis, and I hope you will get inspiration from it.

Jianli Zhai

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September 2020

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Contents

Summary

Globally, demand for raw material has been seeing rapid growth over the past few decades (Government of Netherlands,2016). The construction industry, as a highly material-intensive sector, has a great contribution and responsibility to this rise. The linear approach of resource consumption, which follows the pattern “take-make-use-depose”, is the vital cause of making it be the major consumer of natural resources. This approach was acceptable when there were plenty of cheap natural resources. However, the growth of the world’s population and the changes in lifestyle increase the demand for these resources, making the consumption rate of natural resources much faster than their generation rate. These raw materials become scarce and expensive, consequently leading to the difficulties in acquiring them (Arup,2016). These critical situations have aroused the increasing attention and awareness of individuals, corporate entities, and government to find alternative methods of souring and using materials. The transition from a linear economy (LE) model to a circular economy (CE) model is considered to have great potential to address these problems. The CE model, as opposed to the current LE model, adopts a more sustainable approach “take-make-use-reuse and recycle” (Akanbi et al., 2018). It aims to not only close the material loop by recycling and reusing the disposed of products but also slow the loops by using durable products (Leising et al.,2018). Because of the adoption of recycling and reusing the technical components, and the increasing use of sustainable renewable materials, fewer resources will be extracted, and there will be little waste brought to the landfill.

Despite the circular economy’s great potential in reducing natural resources usage and mitigating environmental pressure, its application in the construction sector is limited to the management of construction demolition and waste (CDW) (Circle Economy et al., 2014). To promote the implementation of CE from the design phase of building, it is suggested that the stakeholders (e.g., architects, engineers, project managers) should have tools to support them in exploiting the value of building’s circularity (Di Biccari et al., 2019). A large amount of data is needed to supply the measurement of building’s circularity, especially for information collection, and it takes time and resources to gather and manager these data. To smoothen the data access and facilitate the assessment, it is suggested to integrate Building Information Modelling (BIM) into the assessment (Rahla et al., 2019).

To show how BIM can be combined to automate the building circularity assessment and facilitate the decision-make regarding the design of a circular building, a BIM-based building circularity assessment (BCA) framework, which utilizes the developed building circularity assessment scoring (BCAS) tool, is formulated. Dynamo for Revit is employed to establish an automatic and efficient link between the Revit model and external databases, and conduct the (BCA) in Autodesk Revit. It assesses the building’s circularity on four different levels of a building’s composition, namely material, product, system, and building. Moreover, the developed tool is capable of presenting the assessment results in the form of charts and overriding the Revit model elements with different colours. The framework is validated by a real case that aims to design for circularity. The results prove that it is possible to assess the building circularity from an early stage schematic design and promote the circular design based on the assessment results of different design options.

Abstract

The target of this research is to develop a BIM-based Building Circularity Assessment (BCA) framework that enables an automated assessment for measuring the building's circularity from different levels of building's composition (material, product, system, and building). Meanwhile, this framework can facilitate the design of the circular building by providing decision-making support. A literature review is carried out to identify the indicators that can reflect the progress towards a circular building throughout the whole lifecycle and determine the assessment model to be adopted by the BCA. Furthermore, the integration approaches between Building Information Modelling (BIM) tool and BCA are explored and evaluated. After that, the BIM-based BCA framework, which utilizes Dynamo for Revit as the essential tool to establish an automatic and efficient link between BIM model and external building circularity database, conducts a quantitative BCA and generates the outcomes in Autodesk Revit. The designed Dynamo prototype, which is called Building Circularity Assessment Scoring (BCAS) tool enables to present the assessment results in the form of charts and override the Revit model elements with different colours. To validate the feasibility of this BIM-based framework and the designed BCAS tool, a case study is adopted. Accordingly, the circularity performance profiles of the case study are generated. The results reveal that the BCAS tool can assess a building's circularity on four different levels of a building's composition and provide the value of individual circularity indicators for the whole building. Moreover, the results also demonstrate that the design of a circular building can be promoted through the BIM-based BCAS framework.

Keywords: Circular economy, Circular building, Building circularity assessment (BCA), Building Information Modelling (BIM), Early design stages, Decision-making support, Autodesk Revit, Dynamo,

List of terminologies in this thesis

Term	Definition
Building's circularity	The building's circularity describes a way of designing and managing the circular building during its lifecycle. Being consistent with the circular building design principles, it aims to protect the materials stock of building by reducing the use of raw materials, maximizing the reuse and recycle of materials, and eliminating the waste.
Building circularity assessment	Building circularity assessment measures the value of the building's circularity that is affected by various circular building design principles. It employs indicators to assess the impact of building's circularity on different domains such as technical, environmental, social, and economic aspects. The outcomes of building circularity assessment are utilized to see how well the circular building design principles perform and how far the progress towards a circular building is.
Bill of material	A bill of materials (BoM) is a list of the parts or components that are required to build a product. For each of the components, the precise type and amount of material are listed.
Circular building	A circular building represents a temporary and dynamic material depot that is designed and managed in a manner consistent with CE principles throughout the life cycle. It aims to decrease the use of raw materials, keep its materials, products, components as long as possible (on a high-value level) in the construction chain, and avoid negative influence on the living environment and ecosystems.
Circular economy	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 return to the biosphere, and eliminate the waste through the superior design of materials, products, systems and business models. It operates at the micro-level (e.g., products, companies, consumers), meso-level (e.g., eco-industrial parks), macro-level (e.g., city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously increase environmental quality, economic prosperity and social equity, and benefit current and future generations.
Linear economy model	The model follows the "take-make-use-depose" pattern. The virgin materials keep being extracted and the products are disposed of as waste at the final stage without efficient recycle or/and reuse.

List of abbreviations

Abbreviations	Full Name
AEC	Architecture, Engineering, and Construction
AOC	Accessibility to Connection
API	Application Programming Interface
BAMB	Building as Material Banks
BCA	Building Circularity Assessment
BCAS	Building Circularity Assessment Scoring
BCI	Building Circularity Indicator
BCIX	Building Circularity Index
BIM	Building Information Modelling
BIM-BCA	Building Information Modeling-Building Circularity Assessment
BIM-LCA	Building Information Modeling-Life Cycle Assessment
BIM-DAS	BIM-based Deconstructability Assessment Score
BoM	Bill of Material
BWPE	BIM-based Whole-life Performance Estimator
CBA	Circular Building Assessment
CDW	Construction and Demolition Waste
CE	Circular Economy
CI	Circularity Indicators
C2C	Cradle to Cradle
COBie	Construction Operations Building Information Exchange
DDF's	Disassembly Determining Factors
DFAD	Design for Adaptability
DFD	Design for Disassembly
ECI	Element Circularity Index
EMF	Ellen MacArthur Foundation
GUI	Graphical Users Interface
IDM	Integrated Dynamic Model
IFC	Industry Foundation Classes
LCA	Life Cycle Assessment
LOD	Level of Development
MCI	Material Circularity Indicator
NIBE	Nederlands Instituut voor Bouwbiologie en Ecologie
NMD	Nationale Milieu Database
KPI	Key Performance Indicator
ReSOLVE	Regenerate, Share, Optimize, Loop, Virtualize and Exchange
PCI(X)	Product Circular Indicator (Index)
SCI	System Circular Indicator
SS-DAS	Steel Structure Deconstructability Assessment Scoring
TOC	Type of Connection

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1. Introduction

The rapid growth of demand for raw material has become one of the most significant challenges in the 21st century (Government of Netherlands,2016). **Figure 1** shows the development in global use of mineral, fossil fuels, construction materials, and biomass in the last century. As can be seen, the demand for all type of raw materials has seen an explosive rise, and it is expected to have further increase due to the growth of the global population. The extraction and use of raw material brought negative influence on the natural environment, including a loss of biodiversity, climate change, the exhaustion of natural capital (Government of Netherlands,2016). In such a context, the Circular Economy (CE) was brought to mitigate this issue.

This chapter provides an outline of the research. It begins with a research context, which describes the background information. Then, the problem statement is given to illustrate the importance of the research problem. Based on the research context and problem, the research questions are proposed. Subsequently, the research design explains how to address the research questions. Finally, this chapter ends with a reading guide that describes the overall structure of this research.

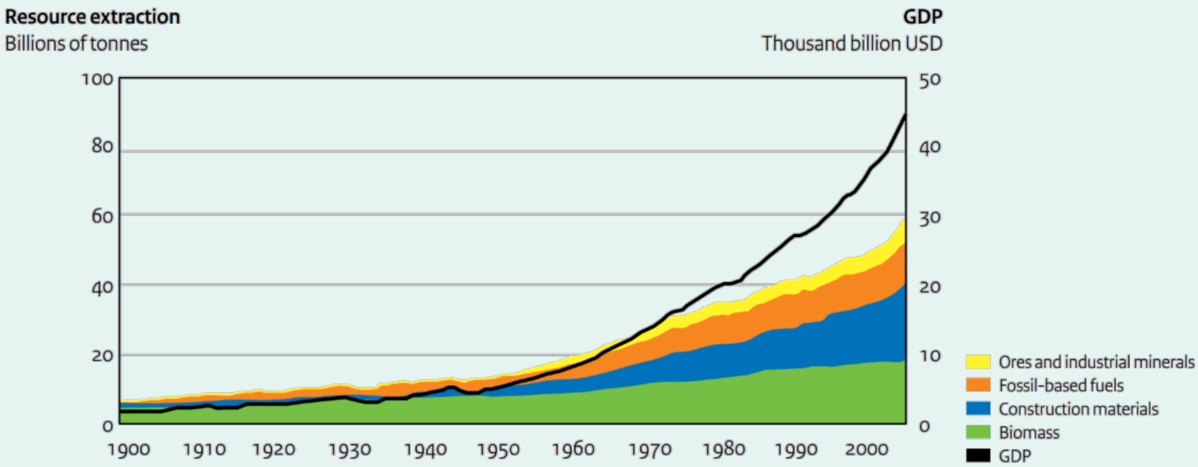


Figure 1: Global material extraction and Gross Domestic Product (GDP) growth, 1900-2005 (Government of Netherlands,2016).

1.1 Research Context

The construction industry, as a highly material-intensive sector, puts a heavy burden on the natural environment (Pomponi & Moncaster,2017; Adams et al., 2017; Munaro et al.,2020). In the Netherlands, the construction industry consumes around half of the used raw material, 40% of total energy, and 30% of total water (Rijkswaterstaat, 2015). Apart from being the largest consumer of natural resources, the construction and demolition activities generate an enormous amount of waste and carbon dioxide, accounting for 40% and 30% of the total (Rijkswaterstaat, 2015). Such negative impact of the construction industry is triggered by the linear economy (LE) model of production and consumption (Durmisevic et al., 2017). It follows the "take-make-use-depose" pattern, where the virgin materials keep being extracted and the products are disposed as waste at the final stage without efficient recycle or/and reuse(Ellen MacArthur Foundation, 2015a). Thus, to mitigate the pressure from the construction sector, a new way of rethinking the use of materials and energy is of importance.

The CE model, as opposed to the current LE model, adopts a more sustainable approach "take-make-use-reuse and recycle" (Akanbi et al., 2018). It gains increasing attention among government, industry, and academia (Kirchherr et al., 2017; Adams et al., 2017; Pomponi & Moncaster,2017; Corona et al., 2019; Munaro et al., 2020). The CE model aims to not only close the material loop by recycling and reusing the disposed of products but also slow the loops by using durable products (Leising et al.,2018). Its concept has been variously defined because of different stakeholders with the diverse aims and interests, but the shared founding principles lie in the better management of resources (Pomponi & Moncaster,2017). When applying the CE model in the construction sector, the way a building is perceived changes. The building is no longer a single entity but a depot of materials that temporarily stores resources (Heisel & Rau-Oberhuber,2020). In such a context, the building's circularity aims to move this material bank from linear to the circular system (Iyer-Raniga, 2019).

The transition from a current LE model to a CE model can bring significant benefits to the construction industry in terms of environment, social ecosystem, and economy (Arup et al.,2017; Leising et al., 2018; Pomponi & Moncaster,2017). Because of the closed loops, technical components and the increase of sustainable renewable materials, fewer resources will be exploited, and there will be less waste going to landfill. Hence, the CE model can reduce the impact on the climate and decouple the economic development from the consumption of limited natural resources (Munaro et al., 2020). It is estimated that the adoption of CE will boost economic growth by up to 4% (Arup et al.,2017). However, despite the CE's great potential in reducing natural resources usage and mitigating environmental pressure, its application in the construction sector is limited to construction waste minimization and recycling (Rijkswaterstaat, 2015; Adams et al., 2017). To promote the transition to a CE model in the built environment, McKinsey and the Ellen MacArthur Foundation(EMF) developed the ReSOLVE framework, which consists of six actions: Regenerate, Share, Optimize, Loop, Virtualize and Exchange (EMF, 2015c; McKinsey & Company, 2016). These elements can be the guidance or design principles for improving the building's circularity (Iyer-Raniga, 2019).

The benefits of the circular principles are often measured (Corona et al., 2019). When the measurements apply specifically to the individual building to see how well the circular principles perform and unlock the potential benefits at the building level, it is called Building Circularity Assessment (BCA). Various studies have investigated how to quantify and evaluate the benefits of the CE model, whereas their assessment focuses on different aspects of a building's circularity. Life Cycle Assessment (LCA) is often used to assess the environmental embodied impacts along the entire life cycle of building (Jia et al., 2020). Moreover, since key performance indicators (KPI's) are widely applied in industrial practices, developing appropriate circularity indicators appears to be acknowledged in the construction sector (Saidani et al., 2017). The Material Circularity Indicator (MCI) that is created by the Ellen Macarthur Foundation (EMF) and Granta Design addresses the materials flow of a product or company (EMF,2015b). It aims to measure the extent of circularity at the building level (Gupta, 2019). Some studies or organizations build upon MCI to develop a new assessment model. For instance, the Circularity Indicators (CI) that are developed by the Madaster Foundation, provide a set of comparable circularity indicators to assess the performance of individual buildings regarding material consumption and their potential for reuse (Madaster, 2018a; Heisel &Rau-Oberhuber, 2020). The Building Circularity Indicator (BCI) developed by Verberne employs several KPI's to measure the circularity performance of different levels of building's composition (i.e. system, product, and material) (Verberne, 2016). Furthermore, Platform CB'23 widely connects construction parties in the Netherlands to publish a building's circularity measurement method with material-related aspects (Platform CB'23,2019). The development of measurement methods indicates that BCA plays a significant role in providing decision-making support in the context of transition to the CE model.

BCA should be implemented in the design stages of a project, especially when it is incorporated in Building Information Modelling (BIM) (Akanbi et al., 2018; Di Biccari et al., 2019; Heisel & Rau-Oberhuber, 2020; Jia et al., 2020). The design phase has various design alternatives due to the choice of different materials and ways of disassembling the structure, which is closely related to the building's circularity (Jia et al., 2020). Therefore, BCA should become a tool in the design stage to help designers make decisions in the context of CE (Heisel & Rau-Oberhuber, 2020). BIM has features that can facilitate the evaluation process of building's circularity (Durmisevic et al., 2017). It is a promising solution that enables the management and exchange of semantic information about 3D models between the different disciplines involved in a project (Di Biccari et al., 2019). By utilizing BIM, a building model works as a database which provides possibilities to incorporate the measurement of building's circularity (Di Biccari et al., 2019). Moreover, the wide application of BIM for diverse needs within the Architecture, Engineering, and Construction (AEC) industry such as 3D building visualization and building performance assessment, reveals that innovation should be BIM compliant (Akanbi et al., 2018).

1.2 Research Problem

In the construction industry, the decision-makers (e.g., architects, engineers, project managers), who are not well versed with the CE approach, need tools to support them to assess the circularity performance of their projects (Di Biccari et al., 2019; Platform CB'23,2019). Several approaches have been taken to incorporate the circularity assessment into a BIM model during the design phases of the project. Presently, the Building as Material Banks (BAMB) project is developing a BIM compliant online prototype that can assess the overall performance regarding the reuse potential of materials at the building level and present the assessment results in a 3D form (BAMB, 2019). The Madaster platform allows the import of 3D BIM models into their online database to achieve such integration between BIM and BCA (Madaster, 2018c; Heisel &Rau-Oberhuber, 2020). Nevertheless, the online platform requires users to extract information exchange file (e.g., Industry Foundation Class (IFC)) from BIM software tool and upload online (BAMB, 2019). These manual procedures reduce work efficiency and waste time, especially for the case in which multiple circularity assessments are demanded in the design phases. Therefore, there is a need for tools that act as plugins for a specific BIM design software and allow an instant evaluation of the building's circularity.

Akanbi et al. (2018) developed a BIM-based Whole-life Performance Estimator (BWPE) as a BIM software plug-in to estimate the overall salvage performance at the building level. Moreover, Di Biccari et al. (2019) also created a BIM software add-in as a prototype to visualize the circularity indicators directly in 3D form for layered elements such as walls. However, all these tools mentioned above do not take into account the circularity assessment on different levels of a building's composition. The building is a unique entity with the feature of inherent complexity. It is composed of many materials and products, which are assembled into different systems (Pomponi & Moncaster, 2017). Neglecting the lower level of technical composition in the building but only assessing the circularity at the building level makes it difficult for decision-makers to communicate and make changes (Verberne,2016). Hence, there is a need for tools that can assess the circularity of a building from different levels.

1.3 Research Objective and Questions

Based on the research context and the identified problem, the work of this research is to develop a BIM-based framework for automated assessment that can facilitate the measurement of building's circularity on different levels of its composition. The target is to see how this developed framework provides decision-making support from the early design stages. Derived from the problem analysis and objectives, the central question of this research is:

How can the integration of building circularity assessment with BIM enable an automated assessment on different levels of a building's composition and provide the decision-making support on the design of the circular building from the early stage?

Five sub-questions are established to help answer the main question:

Sub-Q1: What indicators can reflect the progress towards a circular building?

Sub-Q2: What assessment models are used for measuring the building's circularity?

Sub-Q3: What are the integration approaches between BIM and building circularity assessment?

Sub-Q4: How to integrate BIM into the building circularity assessment to automate the process?

Sub-Q5: How can a BIM-based prototype facilitate decision making about the design of the circular building from early design stages?

1.4 Research Design

Based on the formalized main question and four sub-questions, the research consists of five primary stages: (i) Literature review, (ii) BIM-based Building Circularity Assessment (BCA) framework, (iii) Building Circularity Assessment Scoring (BCAS) tool, (iv) Validation, and (v) Conclusion (**Figure 2**). The details are elaborated in the following paragraphs.

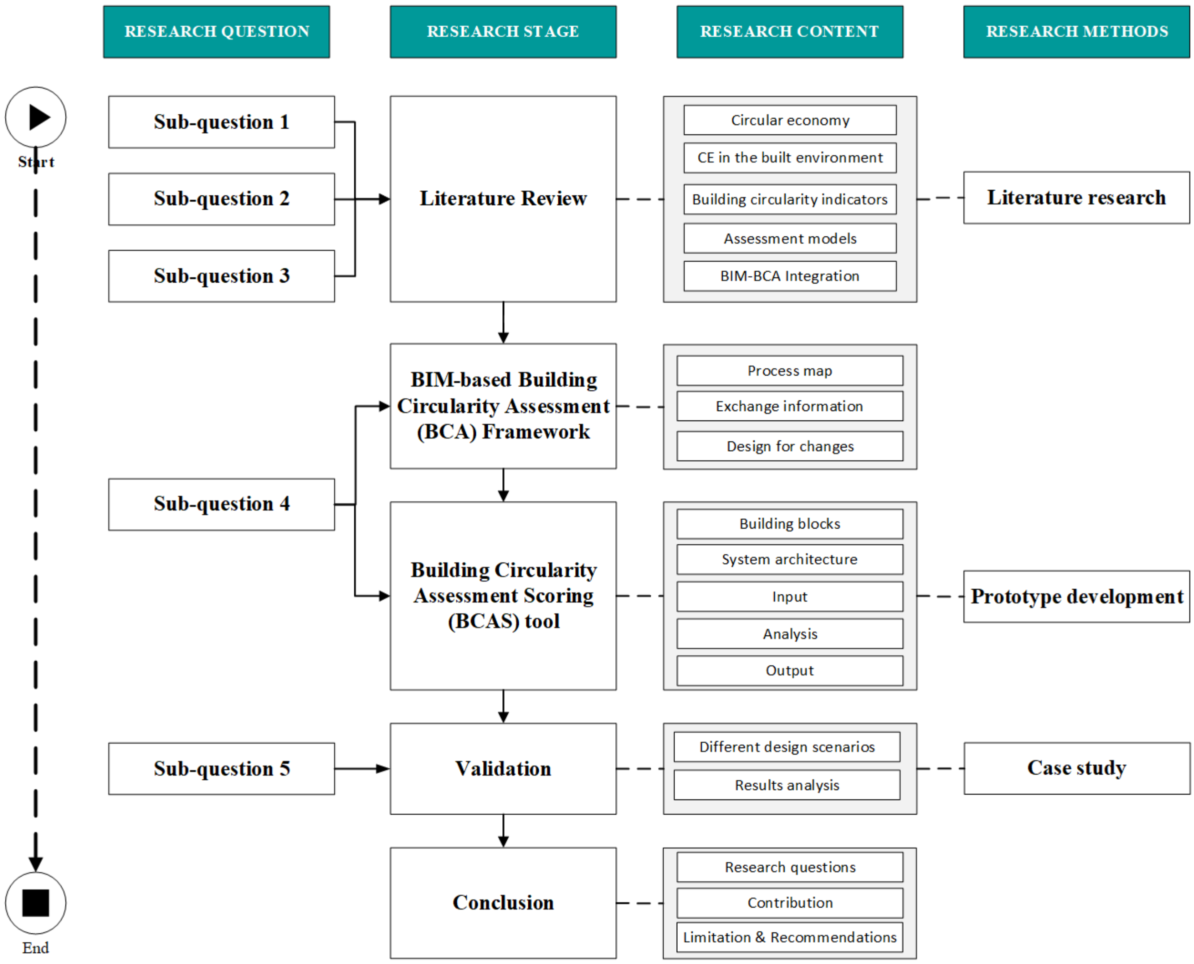


Figure 2: Research design model

The research begins with a review of the existing literature, which includes five main topics. The first topic concerns the CE concept and its core principles. Then, the second topic investigates the implementation of the CE model in the built environment. The current development of CE in the Dutch construction sector and the operation level of circularity are explored. The third topic intends to identify the indicators that can reflect the level of building's circularity. Subsequently, the existing assessment models are explored and evaluated. Lastly, possible integration approaches between BIM and BCA (BIM-BCA) are reviewed. This stage aims to gain an overview of the current situation, discuss the definition of some vital terminology, set the boundary of this research, review the state-of-the-art theory and methods. **Sub-Q1, Sub-Q2,** and **Sub-Q3** will be answered in this part of the work.

Based on the findings of the previous stage, a promising integration approach between BCA and BIM is adopted. The *BIM-based building circularity assessment (BCA) framework* stage utilizes a process map to illustrate how the proposed solution works and what information is required for each step. Importance and sequence of the main activities in the process map are individually described. Also, another process shows how to update information in the BIM-based framework.

In the BIM-based framework, the essential component is the BCAS tool. It facilitates the evaluation process, quantifies the building's circularity, and visualizes the assessment results on a different level of building's composition. Hence, the next stage *Building Circularity Assessment Scoring (BCAS) tool* entails the design and development process of this prototype. Besides, this stage combines the critical finding in the first stage to determine the measurement method of building's circularity in this thesis. Together with the previous stage *BIM-based framework,* these two stages answer **Sub-Q4**.

The *Validation* stage uses a case study to demonstrate the features of the proposed BIM-based BCA framework and the BCAS tool. A real building is assessed from the early design stages. The validation follows the steps in the BIM-based framework, and the assessment results will help to understand how decision-makers are supported from the design phase. Therefore, this stage will answer **Sub-Q5**.

Finally, the last stage *Conclusion* finalizes the research by answering specific research questions, highlighting the contributions and limitation, and giving recommendations for further study.

1.5 Reading Guide

The thesis is organized as follows. The literature review is covered in **Chapter 2**, where the definitions of several key terms regarding CE in the construction industry are discussed, and building circularity indicators are identified. Additionally, this chapter explores and evaluates the building circularity measurement methods and their integration with BIM. In **Chapter 3**, the methodology of this research is described as well as the research methods. Then, in **Chapter 4**, the proposed BIM-based BCA framework is illustrated, followed by **Chapter 5**, which concerns the development of the BCAS tool. Subsequently, the validation of the framework and tool is presented in **Chapter 6**, while **Chapter 7** ends the research report with the conclusion and further improvement

2. Literature Review

Chapter 2, as the starting point of research, aims to provide a comprehensive insight into the current situation through a literature review. **Figure 3** displays the main content and process of this systematic literature review. Firstly, an explanation is provided to describe the origin of the CE concept and help with understanding its development. Then, various definitions of the CE concept are discussed, and it is clarified which definition is adopted by this research. This is followed by the illustration of corresponding core principles to give a clear explanation of the CE concept. Thereafter, this chapter describes the CE transiting development in the built environment and how the ReSOLVE framework is applied to help with this transition. Subsequently, the "circular building" as an essential term, is discussed to specify its definition and relevant design principles.

Then, based on the investigated circular building design principles, BCA is reviewed in terms of its technical aspects. This chapter discusses the technical building circularity indicators that can reflect how well the design principles perform. Moreover, the existing technical assessment models that aim to measure the value of the building's circularity are described and evaluated.

The next part entails how BIM is incorporated to facilitate the building circularity assessment. It firstly clarifies the necessity to integrate BIM. Then, the state-of-the-art integration approaches are described and followed by an evaluation of the approaches. In the end, this chapter draws a conclusion about the significant findings from the literature review.

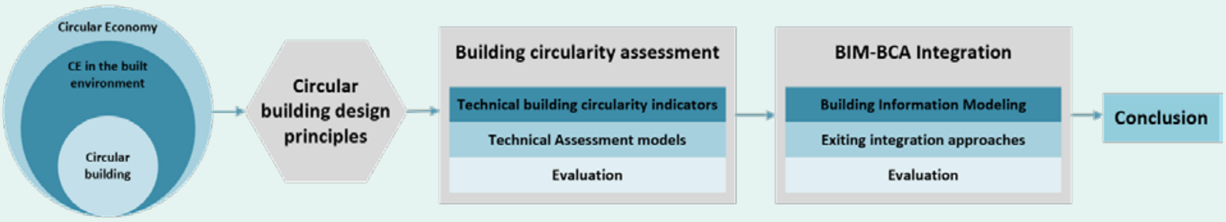


Figure 3: Summary of the systematic literature review

2.1 Circular Economy

2.1.1 The origin of the circular economy concept

The origin of the CE concept is deep-rooted and difficult to trace back since the general concepts have been informed and evolved by several primary schools of thoughts, namely Regenerative Design, Performance Economy, Cradle to Cradle (C2C), Industrial Ecology, and Biomimicry (EMF, 2013). Firstly, in the 1970s, the professor John T. Lyle launched a term “Regenerative Design” to represent an ideal society, where all systems can renew or regenerate the sources of energy and materials that they consume (Lyle, 1994; EMF, 2013). In 1976, Walter Stahel and his institute came up with four goals of an economy in loops, including product-life extension, long-life goods, reconditioning activities, and waste prevention. Additionally, they highlighted the significance of selling services instead of products, which refers to the notion of Performance Economy (EMF, 2013). Then, in 2002, Michael Braungart and Bill McDonough developed the C2C concept, which describes a new way of designing materials and products for effectiveness and producing positive impacts on the environment. C2C design considers all materials as nutrients, which belong to two distinct cycles: the biological metabolism and technical metabolism (**Figure 4**). The biological cycle refers to the products of consumption, which are expected to return safely back to the natural environment. The other cycle represents the products of human artifice, which circulate within a closed-loop system (Braungart & McDonough; 2002). The main idea of the Industrial Ecology, the 4th related school of thought, focuses on connecting all components in the industrial society and redesigning it as an ecosystem within the biosphere (EMF, 2013; Wautelet, 2018). The last vital concept, Biomimicry, which is defined by Janine Benyus, aims to solve the human problem by getting inspiration from nature (EMF, 2013).

Despite the various focuses of these five schools of thoughts, the common points lie in the importance of redesigning the current industrial economic system. Also, they share the same target that is to minimize the negative impacts of human activities on the environment and establish a positive interaction between human and nature. Moreover, the development of these thoughts gives many insights into the CE, especially C2C methodology’s significant inspiration on the famous butterfly diagram (**Figure 5**).

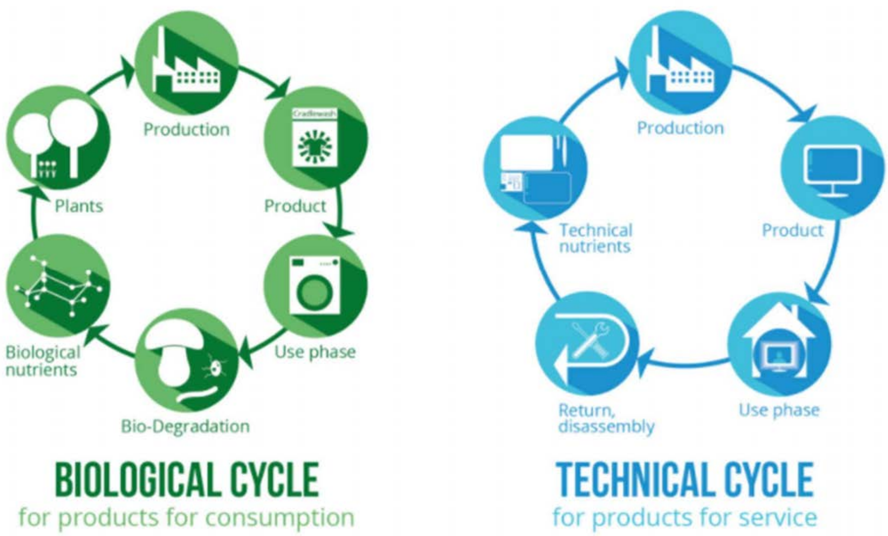


Figure 4: The biological and technical cycles in the Cradle-to-Cradle design (EPEM)

2.1.2 The concept of circular economy

The CE concept has gained ground among industry, politics, and academia, but there is no commonly accepted definition of CE (Kirchherr et al., 2017). Kirchherr et al. (2017) gathered and systematically analyzing 114 definitions of the CE concept. Their findings reveal that the combination of reduce, reuse, and recycle aspects is mostly used to describe the CE, whereas the necessity to implement CE in a systemic perspective is often neglected. Three fundamental levels of the CE system: The macro-level (city, region, nation and beyond), meso-level (eco-industrial parks), and the micro-level (products, companies, consumers), should be considered simultaneously. Furthermore, they argued that the gathered definitions are mostly concerned with economic prosperity and have weak linkages with sustainable development. Also, the influence of CE on social equity and future generations is not highlighted in most definitions of the CE concept (Kirchherr et al.,2017).

The most widely referred definition of CE concept is developed by Ellen MacArthur Foundation, who corporates with business, government, and academia to globally lead the thought of CE (Kirchherr et al., 2017; Leising et al., 2018). The foundation has published a series of reports to promote the application of CE and proposed several definitions of CE (EMF, 2012, 2013, 2014, 2015a). However, their common points lie in describing CE as an economic and industrial model that is restorative and regenerative by design. **Figure 5** depicts the CE model through a butterfly, which consists of three distinct parts: the economic model in the centre, the biological cycles on the left side, and the technical cycles on the right side. The middle refers to the start point of the model from increasing the extraction of renewable energy from nature, then manufacturing parts, product, and providing service in the market. At the end of the lifecycle, the model aims to design out of waste. Instead of deposing the materials and products as proposed in the LE model, the CE model tries to circle the consumed products back into the economic model through different circles. Besides, the biological cycles with 'regenerative' on the left side are strictly distinguished from the technical cycles with 'restorative' on the right side. In the biological cycles, the consumables like food and water are non-toxic materials, which are regenerative into the biosphere while rebuilding natural capital, after being cascaded into different applications. The technical cycles are the management of stocks of finite materials. The products, components and materials are restored into the market at the highest possible quality and for as long as possible, through repair and maintenance, reuse, refurbishment, remanufacture and ultimately recycling (EMF,2013). In this research, the definition of the CE concept builds upon the EMF definition and the key findings of Kirchherr et al. (EMF,2014; Kirchherr et al.,2017).

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 return to the biosphere, and eliminate the waste through the superior design of materials, products, systems and business models. It operates at the micro-level (e.g., products, companies, consumers), meso-level (e.g., eco-industrial parks), macro-level (e.g., city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously increase environmental quality, economic prosperity and social equity, and benefit current and future generations.

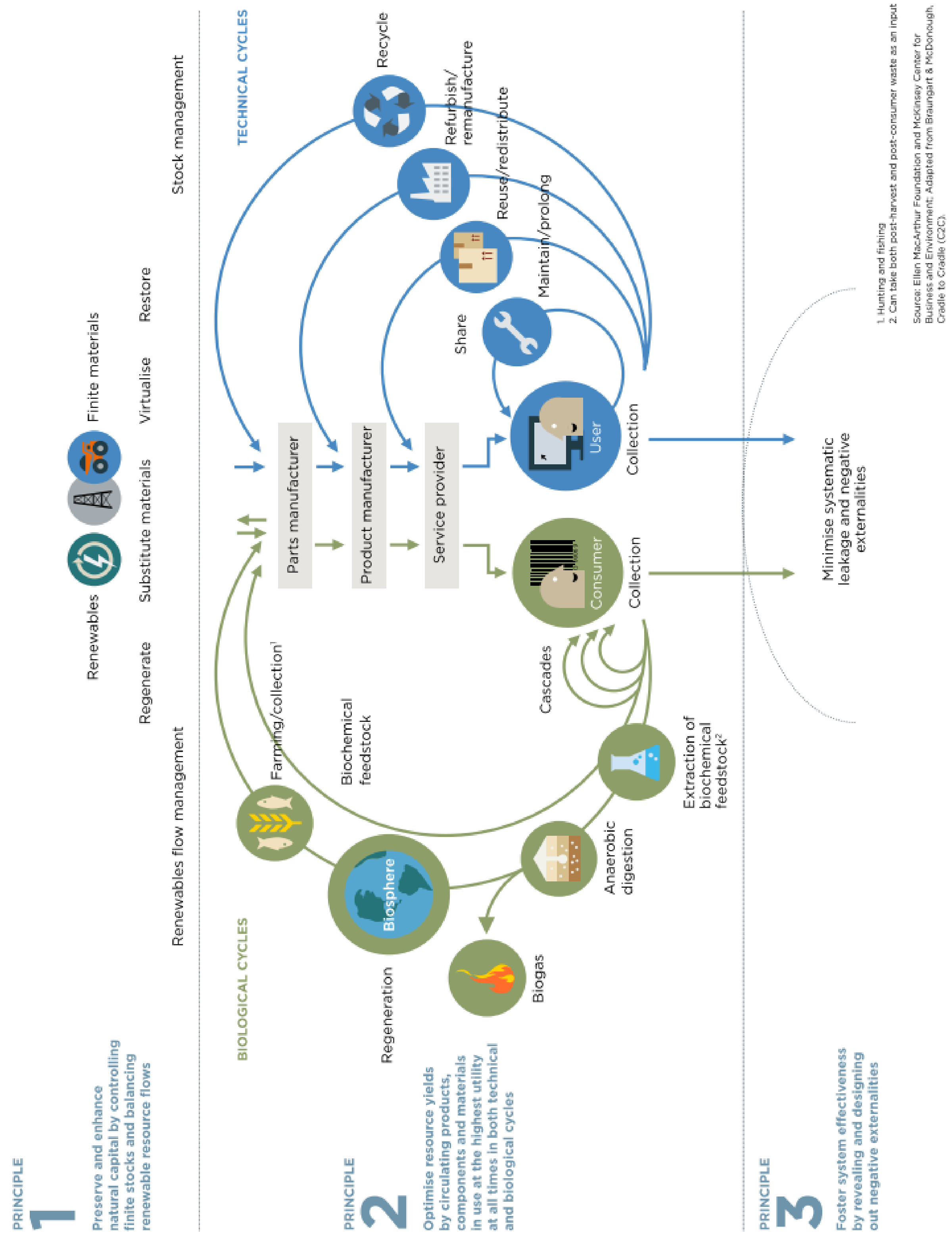


Figure 5: Butterfly CE model (EMF, 2015a)

2.1.3 Principles of circular economy

The Ellen MacArthur Foundation (EMF) outlines three core principles to have a better understanding of the CE model (**Figure 5**). The first principle is explicitly used at the beginning of the CE model. It aims to preserve and enhance natural capital by controlling finite stocks and balancing renewable flows. Dematerializing is the starting point of this principle. It is essential to think about the necessity of production firstly. When the production is needed, the selection of the resources should be wise, such as choosing renewable resources. The second principle is to optimize resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles. In technical cycles, the technical components and products should be designed to stay in the system (e.g., design for remanufacturing, refurbishing, and recycling). Moreover, the smaller the loops, the better they are. For the materials in the biological cycles, they are encouraged to reenter into the biosphere safely and contribute to a new cycle. The last principle is designing out of negative externalities to foster system effectiveness. This principle means the damage to systems like the release of toxic substances and other kinds of pollution should be minimized (EMF, 2015a).

Furthermore, the EMF establishes five key characteristics that can give a more detailed description regarding CE (EMF, 2015a).

Design out waste. There is no waste in a CE. The biological materials are non-toxic and can be returned to the soil. The technical materials, such as human-made materials are designed to be recovered, refreshed, and upgraded (EMF, 2013).

Build resilience through diversity. Comparing with efficiency-throughput maximization, the diverse systems with the feature of modularity, versatility, adaptivity, and flexible are more resilient when facing the external challenges (EMF, 2013).

Shift to renewable energy sources. There is still a need to get energy within the CE. The increase of renewable resources will reduce the demand from the restoration within CE. Consequently, resource dependence will be less (EMF, 2013).

Think in systems. In a CE, it is of importance to understand how different parts affect each other within a whole system and how the whole is related to the parts. The purpose is to have better management of the systems to avoid some unexpected consequences (EMF, 2013).

Think in cascades. This characteristic explicitly describes biological materials. In order to create the value in biological cycles, it is essential to have chances to extract additional value from products and materials by cascading them through other applications (EMF, 2013).

The exposition of core principles and characteristics gives more insights about how biological and technical materials cycle in the CE model. Different from biological materials which are cascaded to other applications, technical materials are maintained in the system through a series of design methods, which are more accessible for the human to interrupt and manipulate. Thus, the focus of this research lies in the technical cycles of the CE model.

2.2 Circular Economy in the Built Environment

2.2.1 Current development

Currently, many relevant measures have been taken to promote the transition from LE to CE. Dutch government proposes the vision for 2050 that sets the aim to obtain a 50% reduction in primary raw material consumption by 2030 and a fully CE by 2050. Regarding the vision in the construction sector, they aim to have an energy-neutral built environment and ensure the sustainable construction, use, reuse, maintenance, and dismantling of these objects (Government of Netherlands,2016). To achieve this target, the Dutch government has made several Green Deals regarding circular construction, which cover different fields of the built environment, including nature, city, urban, building, infrastructure to encourage stakeholders' initiatives (Government of Netherlands,2016). Towards the 2050 circular aim in the Netherlands, Platform CB'23(Circular Construction 2023) has been drafting some agreements and frameworks for the entire Dutch construction sector to follow. The Circular Construction Framework contains seven interconnected main topics, where 'Core method for measuring circularity in the construction sector' and 'Passports for the construction sector' have been drawn up for the topic three and four: Measuring Circularity and Information & Data (Platform CB'23,2019). Nowadays, following the guidance and 2050 Netherland circular target, some construction projects are being experimented to integrate CE principles. However, the application is still in its infancy.

The current application of the CE in the Dutch construction sector is primarily concerned with the management of construction and demolition waste (CDW) (Circle Economy et al., 2014). As shown in **Figure 6**, above 95% demolition of the commercial and non-residential building are recycled. However, most of them provide recycled aggregate for soil and civil engineering as foundation materials; only 3% of them is reused in making a new building. The way of recovering CDW through is downcycled since it has less value, quality, and functionality than the original product (Adams et al., 2017). In conclusion, more attention should be put on the prevention of CDW by applying CE across a building's life cycle. For example, design for deconstruction, design for product disassembly, increase lifespan, and more (Adams et al.,2017).

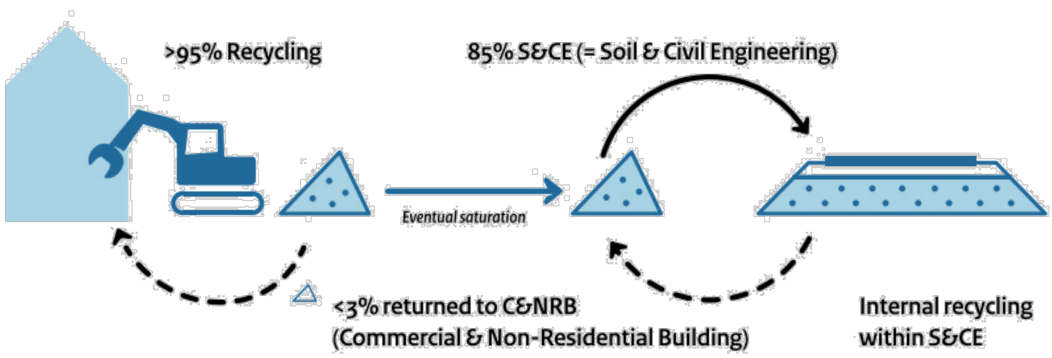


Figure 6: Demolition and recycling process (Rijkswaterstaat, 2015)

2.2.2 ReSOLVE framework

The Ellen MacArthur Foundation, McKinsey, and Arup contribute to developing the ReSOLVE framework, which is explicitly made for the built environment to transition towards a CE (McKinsey & Company, 2016; Arup, 2016). Six actions are outlined, including Regenerate, Share, Optimize, Loop, Virtualize and Exchange. For each element, there are practical examples to be implemented (McKinsey & Company, 2016; Arup, 2016).

The 'Regenerate' action refers to the shift to renewable energy and materials. It involves the regeneration and restoration of material capital, the increase of ecosystems' resilience, and the safe return of valuable biological nutrients to the biosphere. This element will allow the reduction of negative externalities, consumption of primary resources and waste. The 'Share' action includes the maximization of asset utilization by peer-to-peer sharing of privately owned products or public sharing products, for example, car-sharing. Furthermore, this action also refers to the reuse of products through their technical lifetime and extend products' life by maintenance, repair, and design for durability. The 'Optimize' action mainly concerns the improvement of products' performance and efficiency. In the built environment, the key lies in the maintenance of building materials and components at their highest value. Also, this 'Optimize' action include removing waste from production and supply chain as well as leveraging big data, automation, and remote sensing. The 'Loop' action is about keeping products and materials in closed cycles and prioritizing the inner cycles. In the built environment, this is achieved mainly by remanufacturing and refurbishing the products, components, and materials. The 'Virtualize' action engages the displacement of resource use with virtual use, replacement of physical products and services with virtual services, and the replacement of physical with virtual locations. A significant example is the application of BIM during all phases of an asset's lifecycle. Finally, the 'Exchange' is concerned with the four primary points, namely the wise selection of resources and technologies, replacement with renewable energy and material sources, the use of alternative material inputs, and replacement of traditional solutions with advanced technology. (McKinsey & Company, 2016; Arup, 2016; Iyer-Raniga, 2019).

All actions utilize different approaches to increase the utilization of physical assets, extend products' lifetime and promote the use of renewable resources. Additionally, each of them can have a positive effect on any of the other (Arup, 2016). Separately or together, the ReSOLVE framework is a suitable guidance for stakeholders in the AEC industry to take actions to accelerate the transition to a CE. Each element can be applied to all scales of the built environment, including products, buildings, neighbourhoods, cities, and regions (Iyer-Raniga, 2019). This research focusses on the elements: Regenerate, Optimize, Loop, and Virtualize at the building level.

2.2.3 Circular building

Current scientific research regarding the transition to a CE in the built environment tends to focus on macro-level (e.g., cities, neighbourhood, built environment) and micro-level (e.g., component, products) (**Figure 7**). However, there are insufficient studies considering meso-level (building), which is a fundamental level (Pomponi & Moncaster, 2016). When applying CE at the building level, a new term "Circular Building" emerged and has been increasingly mentioned in scientific research and reports.

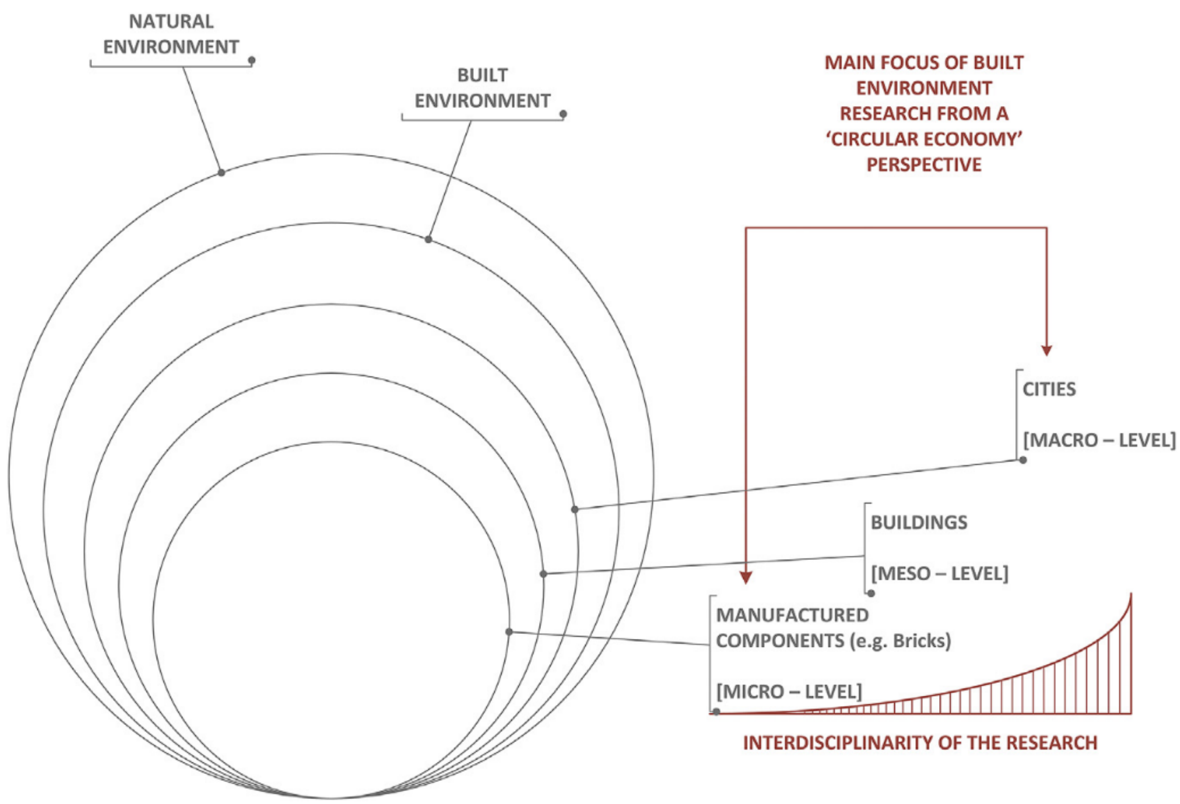


Figure 7: Framing of built environment research about CE (Pomponi & Moncaster, 2016).

Similar to the definition of the CE concept, there is also no commonly accepted definition for a circular building. To prevent misunderstanding, a clear definition of the circular building is formulated. Eleven definitions have been gathered from other literature and analyzed to create an unambiguous definition (**Table 1**). Some frequent keywords regarding circular building are "consistent with CE principle", "(temporary) material depot/ bank", "reduce the use of raw materials/ natural resources", "environment impact", " lifecycle of the building", and "keep the materials as long as possible". Based on the findings, a comprehensive definition of a circular building is established as:

A circular building represents a temporary and dynamic material depot that is designed and managed in a manner consistent with CE principles throughout the life cycle. It aims to decrease the use of raw materials, keep its materials, products, components as long as possible (on a high-value level) in the construction chain, and avoid negative influence on the living environment and ecosystems.

Table 1: Definitions of a circular building

Author	Focus	Definitions
Geldermans & Rosen-Jacobsen (2015)	Dynamic, temporary manifestation of all activities	The circular building, being a verb and not a noun, can be addressed as the 'dynamic total of associated processes, materials and stakeholders, led by the owner/user'. A building can be a temporary manifestation of that activity.
Green Deal Circulaire Gebouwen (2016)	Virgin materials, Raw materials, retain value, sustainable	A building that creates maximum value with the minimal use of virgin materials and other raw materials to meet a housing need in a sustainable way, at which the used materials retain their value during and after the use phase.
CE100 (2016)	Raw material depot	A truly circular building acts as a raw material depot, through modular and reconstructible design, documented in a raw materials passport.
Bakx et al. (2016)	self-sustaining, energy, disassembly and adaptability, sustainable materials	A circular building is a type of building that is self-sustaining with renewable energy and stimulate diversity. Whereby the building is built up of the circular building product levels that are designed for disassembly and adaptability. To guarantee the possibility of the proposed re-life options in a hierarchical way and effectively accommodates the evolving demands of its context, the selection of sustainable materials should enable the re-life option.
Pomponi &Moncaster (2017)	Consistent with CE principles	A building that is designed planned, built, operated, maintained and deconstructed in a manner consistent with CE principles.
Bokkinga (2018)	Decrease raw materials, maximizing reuse	A building that is designed, developed, managed, and used according to the CE system, a central aspect of the building is a decrease in the use of raw materials and maximizing reuse. The aim is to use as few new raw materials as possible and where products, raw materials and systems are used, keeping them as long as possible (on a high-value level) in the construction chain.
Transitieteam Circulaire Bouweconomie (2018)	Natural resources, environment, ecosystems	Circular building means the development, use and reuse of buildings, areas and infrastructure, without unnecessarily exhausting natural resources, polluting the environment and affecting ecosystems. Building in a way that is economically sound and contributes to the welfare of humans and animals. Here and there, now, and later.
Leising et al. (2018)	A lifecycle approach, Optimizes lifetime, Material bank	A lifecycle approach that optimizes the buildings' useful lifetime, integrating the end-of-life phase in the design and uses new ownership models where materials are only temporarily stored in the building that acts as a material bank
Rijksdienst Voor Ondernemend Nederland (2018)	Natural resources, living environment, ecosystems	The circular building represents all related activities such as construction, use and reuse, avoid incurring unnecessary depletion of natural resources, negative influence on living environment and ecosystems
Ronald Rovers (2020)	Using resources, speed	Circular building (or renovating) is using resources (and the energy for this) with a speed that assures that flows remain flowing. Alternatively, it can be regenerated and will be regenerated. This is first and for all a matter of space and time: how much resources per time period (volume speed, energy, restore capacity) are available, and how to optimize their use.
Jia et al. (2020)	The life cycle of building, new natural resources	The use of practices, in all stages of the life cycle of a building, to keep the materials as long as possible in a closed-loop, to reduce the use of new natural resources in a construction project.

Apart from a clear definition of a circular building, it is necessary to understand more characteristics of the circular building to assess whether a building is circular. van den Boogaard (2018) investigated various characteristics regarding the circular building from different literature and classified them into four primary categories, namely materials, design, energy, and value. Furthermore, As shown in **Table 1**, the gathered definitions from other literature reveal that materials and design are the most derived topics.

Due to the broad subject of the circular building, this project focusses explicitly on building materials and the design. The focus of this research is also compliant with the Loppies' study (2015), which proposed two important aspects from the perspective of technical properties of a circular building: circular material usage and circular design (Loppies, 2015).

- **Circular material usage**

Circular material usage refers to the selection of materials. In line with the material flow in the CE model (**Figure 5**), circular material usage is divided into biosphere and technosphere. The non-toxic materials in the biosphere are renewable and regenerated, whereas the materials and products in the technosphere are restored into the market after usage. It aims to prevent material degradation, provide opportunities for material regeneration, and protect and maintain the material value (Verberne, 2016; Amory, 2017).

- **Circular design**

The circular design is about designing the products and components so that they can be disassembled at the end of their use easily and can be applied in a new situation again. It intends to provide opportunities for tight restoration cycles, such as reuse and remanufacture, in favour of recycling (**Figure 8**). As a result, the highest amount of added value is maintained (Verberne, 2016; Amory, 2017).

Both circular material usage and circular design should consider the entire lifecycle of the building. Compared with the traditional building, which employs linear material-use model with the focus on design for one end of life, the circular building has the circular material-use model with an emphasis on design for multiple life and reuse options of material (**Figure 8**).

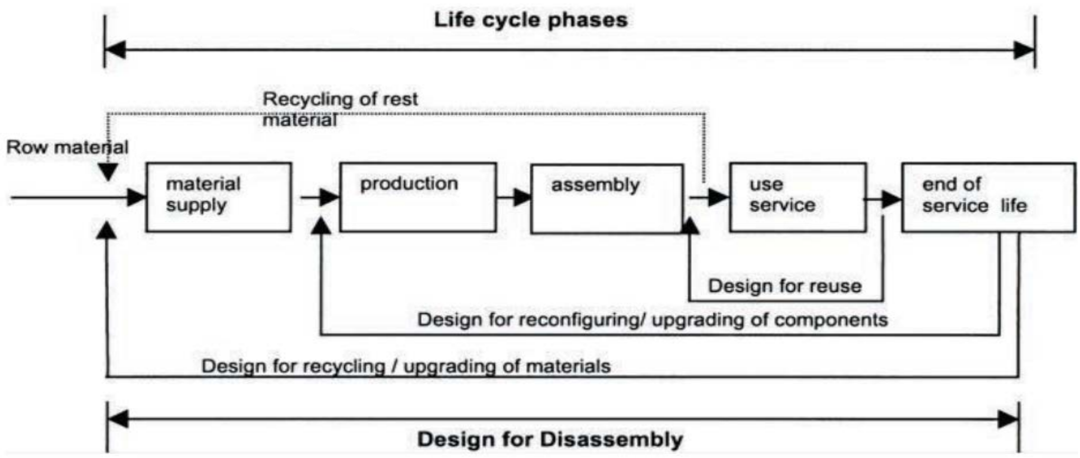


Figure 8: The lifecycle of a circular building (Durmisevic, 2019)

2.2.4 Circular building design principles

A circular building should be designed according to circular design principles (Bokkinga, 2018). Many studies contribute to providing various kinds of crucial design principles for circular building (Bakx et al., 2016; Nußholz, 2017; Amory, 2017; Rijkswaterstaat, 2015). With many identified design principles, there is a need to clarify the implementation stages of different design principles (Geldermans, 2016). **Figure 9**, which contains specific principles for circular material usage and the circular design, is structured by three vital lifecycle phases of building: (1) material and component production; (2) design; (3) end-of-life.

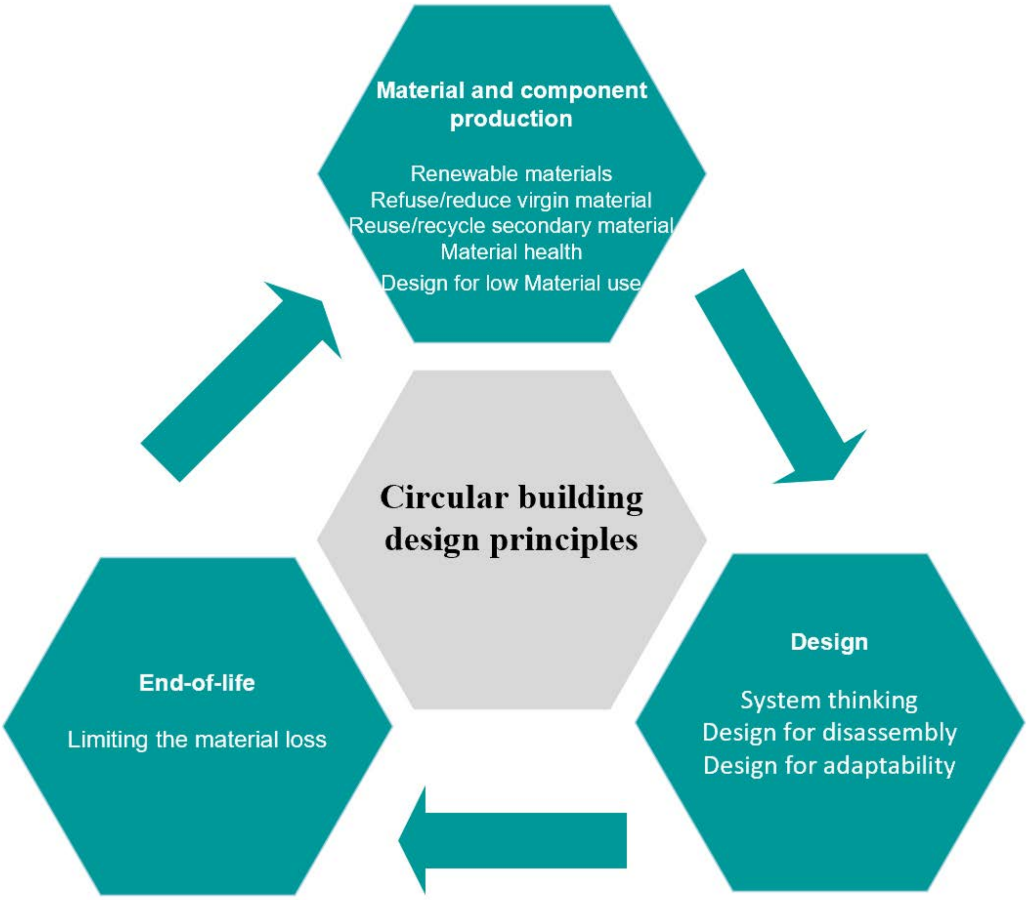


Figure 9: Crucial circular building design principles throughout building technical life cycle

2.2.4.1 Material and Component Production

Considering circular building as a temporary material depot, the stage of material and component production mainly decide the material inflows of the technical life cycle of the building. The materials input may consist of virgin materials and secondary materials. The following design principles aim to control the quantity, quality, and type of material inputs.

- **Shift to renewable materials**

Choosing renewable materials has been emphasized by many studies (Verberne,2016; Amory, 2017; Platform CB'23, 2019). It is noted that the renewable materials explicitly refer to the raw materials that are sustainably produced, which means the raw materials should be extracted, grown and/or managed in a demonstrably sustainable manner apart from the renewable sources (Platform CB'23, 2019).

- **Refuse/reduce virgin material**

Primary materials or virgin materials are extracted from natural resources and have not been previously used or consumed or subjected to processing other than for their original production (EMF, & Granta Design, 2019). The Dutch construction sector has a large-scale consumption of raw materials and displays a strong dependence on natural resources. The harvesting and processing generate a large amount of CO_2 emissions and require much primary energy. Thus, it is very urgent to refuse or reduce the demand for virgin material (Circle Economy et al., 2014). This can be achieved by using more secondary material, which is explained in the next design principle.

- **Reuse/recycle secondary material**

Different from new primary materials, the secondary material is re-used or recycled from discarded products and can be the alternative of primary materials. Fewer materials that consist of more secondary material and fewer primary materials could contribute to improving the circularity (Circle Economy et al., 2014). However, it should be noted that recycling may need more energy than the extraction process from the natural resource. Therefore, this principle aims to promote more secondary material use instead of virgin material under the premise of material health.

- **Material health**

The material health refers to toxicity, impairs the reuse of the components and their exposure during the intended use and end-of-use product phases. Products and materials containing toxic substances can be restricted to the current regulation and future horizons (EMF, 2015a).

- **Design for low materials use**

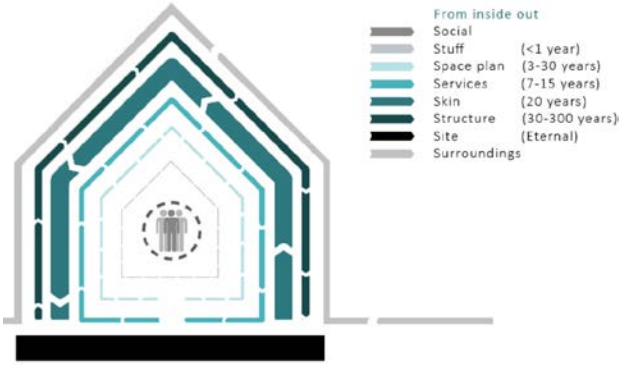
This principle aims to use fewer materials and can contribute to extracting less raw materials, generating less CDW and decreasing the negative influence on the environment (Rijkswaterstaat,2015). Castro et al. (2019) state that materials can be designed efficiently, such as optimal structural frames and prefabricated elements, to minimize the material used in production and the final building.

2.2.4.2 Design and Planning

The building is considered as a dynamic materials depot, while different buildings may share certain components over time. Applying the system thinking approach has the potential to create a dynamic structure based on the division of their parts and relations between those parts. To achieve the target, namely system thinking, design for adaptability (DFAD), design for disassembly (DFD) are three essential principles that should be considered (Bakx et al., 2016).

- **System thinking**

This principle emphasizes the importance of providing a 'systematic thinking approach' on a circular building. A building can be distinguished as different levels based on the hierarchy of materials composition. Brand (1994) proposed the 'six layers of change' model, which divides a building into six layers, namely stuff, space plan, service, skin, structure, and site (**Figure 10**). This model is employed by many circular initiatives and researchers (Verberne,2016, Bakx et al., 2016, Madaster, 2018b). Durmisevic (2006) distinguished five levels in hierarchical order: building, system, sub-system, component, and material (**Figure 11**). Furthermore, various studies have developed different approaches to distinguish building levels (Bakx et al., 2016). Their hierarchy models can be found in **Appendix I**. All in all, these approaches regarding the classification of circular building product levels share a similar concept; only the name and the level of detail are different.



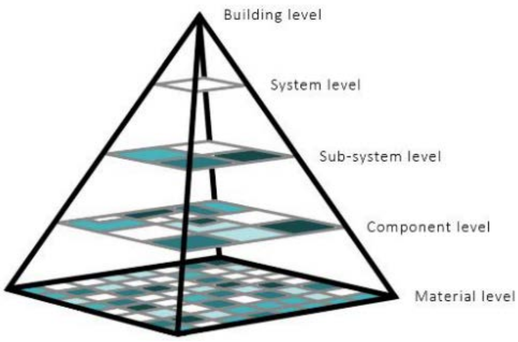


Figure 10: Six layers of change (Brand, 1994)
Figure 11: Hierarchy of material levels (Durmisevic & Brouwer, 2006)

- **Design for adaptability (DFAD)**

This principle ensures that the building can be amended to meet time requirements and have a longer useful life (Kasarda et al., 2007). It is assumed that the modular design can make the building use as long as possible, but the demolition is still inevitable when the building could not adapt to new functions (Rijkswaterstaat,2015).

- **Design for disassembly (DFD)**

DFD is defined as *"the concept of designing buildings in such a way to facilitate future dismantling, thereby reducing the generation of waste by guaranteeing the possibility, of all circular building product levels to undergo re-life options in a hierarchical way, achieved by the implementation of disassembly determining factors (DDF's) in building design (Bakx et al.,2016)".* This principle aims to extend the building's technical lifetime. At the end stage of building, brute force is often used to demolish its structure, resulting in the damage of building elements and less value for reuse. Therefore, DFD is applied to ensure the easy disassembly of building to maximize the value of secondary building components (Rijkswaterstaat,2015).

2.2.4.3 End-of-Life

Considering circular building as a temporary material depot, the stage of end-of-life mainly determines the output of this depot. This end-of-life design principle focuses on managing the building's end-of-life efficiently by limiting material loss and retaining the material value.

- **Limiting the material loss**

This principle aims to retain the material value in the technical cycles of building depot by reducing material loss. At the end-of-life stage, the technical materials should be designed to recover, reuse, or remanufacture rather than dispose of as waste (Platform CB'23, 2019).

2.3 Building Circularity Assessment

2.3.1 Definition and research dimensions

Similar to the concept of the circular building, there is no clarity about the definition of a building's circularity. However, it is often described as an approach that facilitates the close of material loops of the building (Geldermans & Jacobson,2015; Verberne, 2016). The research gives an explicit definition for building's circularity:

The building's circularity describes a way of designing and managing the circular building during its lifecycle. Being consistent with the circular building design principles, it aims to protect the materials stock of the building by reducing the use of raw materials, maximizing the reuse and recycle of materials, and eliminating the waste.

Gauging the building's circularity is essential in the transition to a circular building (Rahla et al., 2019). The framework created by Platform CB'23 puts the "Core method for measuring circularity in the construction sector" as one of the main topics in working towards a circular construction economy. The building's circularity needs to be measurable so that there will be a clear criterion which can be integrated into the procurement process. Furthermore, stakeholders (e.g., architect, structural engineer, project manager, and more) expect to have support on the choices made from the preliminary stages to enable the monitoring of the entire project performance regarding circularity. Also, the government wishes to assess their progress of promoting circular building (Rijkswaterstaat,2015). All of these requirements and expectations indicate the necessity to have the building's circularity measurable.

To measure the building's circularity, it is essential to figure out what domains are closely related to the transition to a circular building. Geldermans & Jacobson (2015) addressed seven interrelated domains, including social, technical, design, financial, legal, organization, and contextual. Verberne (2016) divided the research aspects into four groups: technical, functional, aesthetical, and economical. Pomponi & Moncaster (2017) defined six research dimensions of CE in the built environment, namely environmental, technological, economic, societal, governmental, and behavioural. Their classifications for research dimensions are various, but the contents are similar. After combining their findings, this research sorts out nine major research dimensions (**Figure 12**).

- **Technical:** It refers to the technical properties of building materials and components, such as the intrinsic properties (material and product characteristics) and relational properties (building design and use characteristics) (Geldermans,2016).

- **Social:** Social aspect is user-oriented (Geldermans,2016; Rahla et al., 2019)**.** It focuses on matching the building users' expectation since they play an essential role in managing the energy in the building (Rahla et al., 2019).

- **Behavioral:** Pomponi & Moncaster (2017) emphasized the significance of behavioural issues. For example, people tend to have a negative attitude towards reused materials because of the effects of attractiveness and aesthetic.

- **Legal:** To facilitate and organize the circular economic models, it is necessary to have a legal change, such as revising the regulation for procurement and distinguishing the ownership of two major clients: the investor and the user (Geldermans and Jacobson, 2015).

- **Economic:** Generating economic value is one of the key targets of the circular building. There is a need to develop a new paradigm for high profitability (Pomponi & Moncaster, 2017).

- **Environmental:** Positive environmental impacts are expected because of the circular building. Instead of only focusing on whole life energy and carbon of building, the consideration of environmental impacts should be comprehensive (Pomponi & Moncaster, 2017).

- **Technological:** The technological domain highlights the role of technology in data collection, sharing and management, which are the key elements to enable circular loops. For example, BIM has the potential to collect the information of the building, the online platform and web-based apps can offer support for resource sharing (Pomponi & Moncaster, 2017).

- **Perception:** The perception represents the attractiveness of the circular building, including aesthetical, exposure, comfort, acoustic, and light (Verberne, 2016).

- **Organizational:** The organizational dimension concerns the communication and collaboration in the building projects and among all involved stakeholders (Geldermans, 2016).

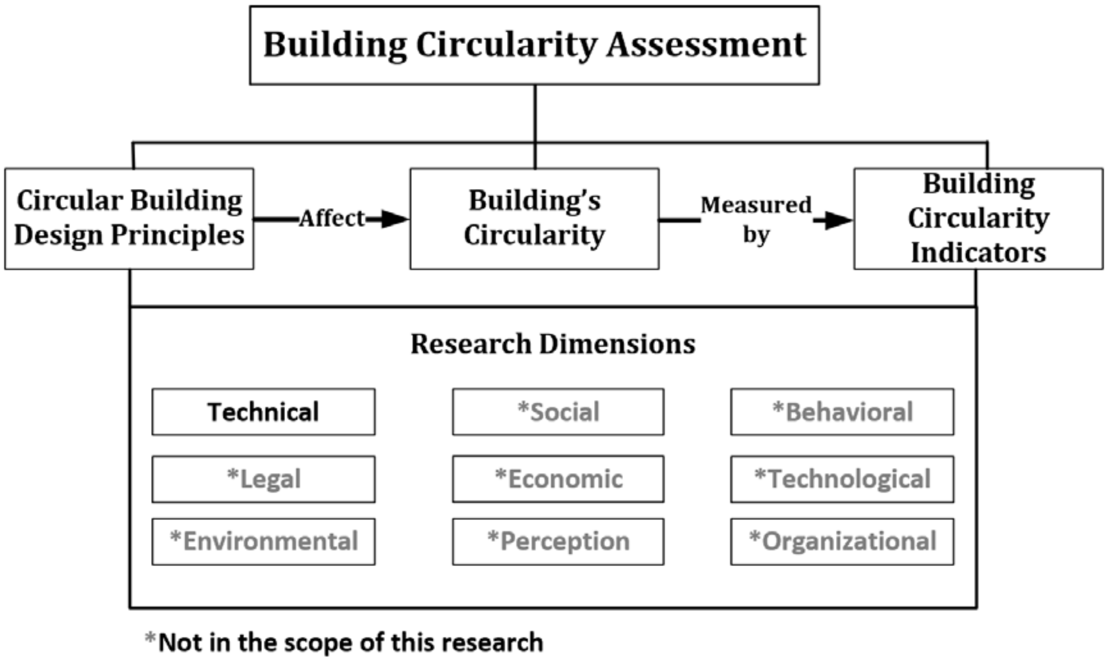


Figure 12: The research dimensions of building circularity assessment

This research creates the term 'Building Circularity Assessment (BCA)'. As shown in **Figure 12**, the building's circularity is affected by the defined circular building design principles, and its value is measured by building circularity indicators. The complete definition of BCA describes as:

Building circularity assessment measures the value of the building's circularity that is affected by various circular building design principles. It employs building circularity indicators to assess the impact of building's circularity on different domains such as technical, environmental, social, and economic aspects. The outcomes of BCA are utilized to see how well the circular building design principles perform and how far the progress is towards a circular building.

The nine research dimensions are interrelated and have influences on each other rather than independent. Currently, most measurements mainly focus on technical, environmental, and economic aspects and overlooked other aspects (Rahla et al., 2019). limited by the time frame of six months, this research focuses explicitly on the technical aspects of the BCA. Accordingly, the key technical building circularity indicators are investigated. Furthermore, this chapter reviews the existing assessment models for measuring the building's circularity in terms of the technical aspect. Finally, an evaluation of these models is given to describe their advantages and gaps.

2.3.2 Technical building circularity indicators

Technical building circularity indicators are related to the technical properties of building materials and components. Geldermans (2016) distinguished the technical parameters into two categories, namely intrinsic properties and relational properties. The former refers to the material and product characteristics, which are following the core of circular material usage. Intrinsic properties highlight that the building materials or components should have high quality, sustainable origin, be non-toxic, and be consistent with biological cycle and cascade, and one or more technical cycles. The relational properties, which are identical to the idea of the circular design, represent the building design and use characteristics. The building materials and components should consider the design and use of the building, including the dimensions, connections, and performance time (Geldermans, 2016). Furthermore, Geldermans (2016) highlighted that the real value of a building product is the intersection of intrinsic and relational properties from a circular design point of view. Gupta (2019) found that a building component affects the circularity of the overall building at two levels: the share of mass and its connection with other components, which can also be classified as intrinsic and relational properties.

2.3.2.1 Material and Component Production

- **The percentage by mass of virgin materials in the total material input**

This indicator refers to the degree of using primary raw materials (Platform CB'23,2019) and belongs to the intrinsic property. It is used to reflect the progress of the design principle "Refuse/reduce virgin material". Many studies and organizations like platform CB'23, Material Circularity Indicator (MCI), BCI have included this indicator into their circularity measurement (Platform CB'23, 2019; EMF,2015b; Verberne, 2016).

- **The percentage by mass of reused/recycled materials in the total material input**

This indicator represents the degree to which materials originating from previous use or residual flows are used and replace primary materials (Platform CB'23,2019). It can be classified as an intrinsic property and indicates the progress of applying the design principle "Reuse/Recycle secondary material". Same with the virgin material, EMF (2015), Verberne (2016), and Platform CB'23 (2019) take into account this indicator.

- **The percentage by mass of renewable materials in the total material input**

This indicator describes the degree of primary materials which are renewable (Platform CB'23, 2019). It belongs to the intrinsic property and reflects the design principle "Regenerate". This indicator is considered by Alba Concepts (2018), Madaster (2018b), and Platform CB'23 (2019) in their circularity measurement at the building level.

- **The total mass of materials**

This indicator is the total amount of material in the building and can be grouped as an intrinsic property. It serves the design principle "design for low material use". The value of the indicator aims to promote a more efficient design with fewer materials.

- **The toxicity of the material**

This indicator reflects the design principle of "Material health" and is an intrinsic property. It is equally important to consider this qualitative information when selecting materials (Heisel & Rau-Oberhuber, 2020). If materials contain toxic substances, their future use and potential future economic value are restricted (EMF, 2015b).

2.3.2.2 Design and Planning

- **Circular building product levels**

This indicator simply checks if the measurement of a building's circularity considers other different levels of a building's composition, such as system, components, materials. Both Verberne (2016) and Alba Concepts (2018) consider this indicator.

- **Disassembly factors**

This indicator aims to evaluate how well the design principle "Design for disassembly" is conducted. Durmisevic (2006) established seven essential DDF's with weighted variables, whose value ranges from zero to one (**Table 2**). Zero represents the worst impact on disassembly, while one means the best influence. The DDF's are adopted by many studies and organizations (Verberne, 2016; van Vliet, 2018; Alba Concepts, 2018).

Table 2: Fuzzy variables for DDF' s (E. Durmisevic et al., 2006)

DDF'S	Attribute	Score
Type of Connection	Accessory external connection or connection system	1.0
	Direct connection with additional fixing devices	0.8
	Direct integral connection with inserts (pin)	0.6
	Filled soft chemical connection	0.2
	Filled hard chemical connection	0.1
	Direct chemical connection	0.1
Accessibility to Connection	Accessible	1.0
	Accessible with an additional operation which causes no damage	0.8
	Accessible with an additional operation which is reparable damage	0.6

	Accessible with an additional operation which causes damage not accessible	0.4
	Not accessible - total damage of elements	0.1
Functional separation	Separation of functions	1.0
	Integration of functions with the same lifecycle into one element	0.6
	Integration of functions with a different lifecycle into one element	0.1
Functional dependence	Modular zoning	1.0
	Planned interpenetrating for different solutions (overcapacity)	0.8
	Planed for one solution	0.4
	Unplanned interpenetrating total dependence	0.2
	Total dependence	0.1
Technical life cycle / coordination	Long (1) / long (2) or short (1) / short (2) or long (1) / short (2)	1.0
	Medium (1) / long (2)	0.5
	Short (1) / medium (2)	0.3
	Short (1) / long (2)	0.1
Geometry of product edge	Open linear	1.0
	Symmetrical overlapping	0.8
	Overlapping on one side	0.7
	Unsymmetrical overlapping	0.4
	Insert on one side	0.2
	Insert on two sides	0.1
Standardization of product edge	Pre-made geometry	1.0
	Half standardized geometry	0.5
	Geometry made on the construction site	0.1

- **Adaptability potential**

This indicator indicates how different adaptable parts of the building structure are and reflects the design principle "Design for adaptability". It has been emphasized to be a vital indicator in the building circularity BCA by some studies (Verberne, 2016; Platform CB'23, 2019). This principle is based on a set of strategies, namely: adjustable, versatile, refitable, convertible, scalable and movable (Schmidt, 2011). Moreover, Bakx et al. (2016) and Platform CB'23 (2019) addressed that "Design for adaptability" should be determined separately on each of the building systems such as structure, skin, service. **Figure 13**, which shows the relationships between the building layers and the adaptability strategies, guides the determination of adaptability options for each building system (Bakx et al., 2016).

Figure 13: Adaptability strategies and building systems (Bakx et al., 2016)

2.3.2.3 End-of-life

- **The percentage by mass of reusable /recyclable materials/ material sent to landfill/ incineration in the total material output**

These indicators are used to reflect the design principle “limiting the material loss”. They represent four main future scenarios in which the building materials and components are at their end of life. Verberne (2016), Platform CB’23 (2019), Alba Concepts (2018) have included these indicators into their circularity measurement.

- **Recycling Process Efficiency**

This indicator represents the efficiency of the recycling process for a specific material and recycling process (EMF, 2015b). Both EMF (2015b) and the Madaster (2018b) consider this indicator in producing the recycled feedstock and recycling the product at the end of its use phase.

The identified technical building circularity indicators can be used in the design of buildings to take circularity into account as a criterion and input for design decisions. However, separate indicators without considering the characteristics of buildings result in insufficient assessment results. Thus, a rational assessment model is needed to link these individual indicators together.

2.3.3 Technical assessment model for building's circularity

Some studies and companies have explored the assessment models to measure building circularity such as BCI developed by Verberne and CI formulated by the Madaster Foundation (Verberne, 2016; the Madaster, 2018b). However, there is no research systematically gathered and analyzed them. This research aims to fill this gap by investigating six popularly applied assessment models for measuring the building's circularity. Then, these methods are compared from the aspects of input, output, advantages, disadvantages, and supported tools.

2.3.3.1 Material Circularity Indicator (EMF, 2015b)

MCI is a methodology that has been developed as a commercially available web-based tool to measure the circularity level at the product level (EMF, 2015b). The methodology measures the extent of a linear flow and restorative flow for the component materials of a product and compares its lifespan and intensity with similar industry-average products. A diagrammatic representation of material flow is given to show the material flow of a product (**Figure 14**). It is noted that MCI addresses the materials flow of a product or company, and it focuses exclusively on technical cycles, including materials from non-renewable sources like fossil fuels, coal, and natural gas. The methodology generates the main indicator MCI, which is mainly based on three product characteristics: the mass of virgin raw material, the mass of unrecoverable waste, and the utility factor. The value of MCI assigns a score between 0 and 1 to represent the circularity level of a product. 0 considers the product is fully "linear", with the feature of only using virgin feedstock and its only further scenario is landfill. On the contrary, 1 refers to a fully "circular" product, which contains no waste nor uses virgin material.

Figure 14: Diagrammatic representation of material flows (EMF,2015b)

2.3.3.2 Building circularity indicator (Verberne,2016)

Verberne (2016)'s BCI model builds upon MCI (EMF, 2015b) and the knowledge model for transformation capacity (Durmisevic, 2006). Specifically, The BCI model (Verberne, 2016) takes consecutive steps from the Material Circularity Indicator for a specific product (MCI_p) to a Product Circularity Indicator (PCI), System Circularity Indicator (SCI) until Building Circularity Indicator (BCI). The conceptual model of the BCI assessment model is displayed in **Figure 15**.

- **MCI:** The calculation of the MCI is to compute the fraction of material input (virgin/non-virgin), the material output (energy recovery/ landfill) and the technical lifetime for each product in the building. It is found that its calculation is similar to the MCI of Ellen Macarthur Foundation but relatively simplified in all parts. Furthermore, it should be noted that the significant difference lies in the calculation of the utility.

- **PCI:** The next step is getting the value of the PCI, which takes into account both MCI and interfaces and connections between products. In the purpose of Design for Disassembly (DFD), Verberne adopted seven disassembly determining factors (DDF's) from Durmisevic's study to assess the disassembly potentials. In his research, the DDF's are independent of each other and have the same impact, which was also argued by himself.

- **SCI:** This indicator aggregates all MCIs and PCIs of products, then categorizes these products based on the layers they belong to. The product mass is selected to determine a weighted average of each product for the SCI.

- **BCI:** Finally, the BCI is calculated by aggregating all values of SCIs into one score and additionally correct this value by multiplying the level of importance for each layer of the building.

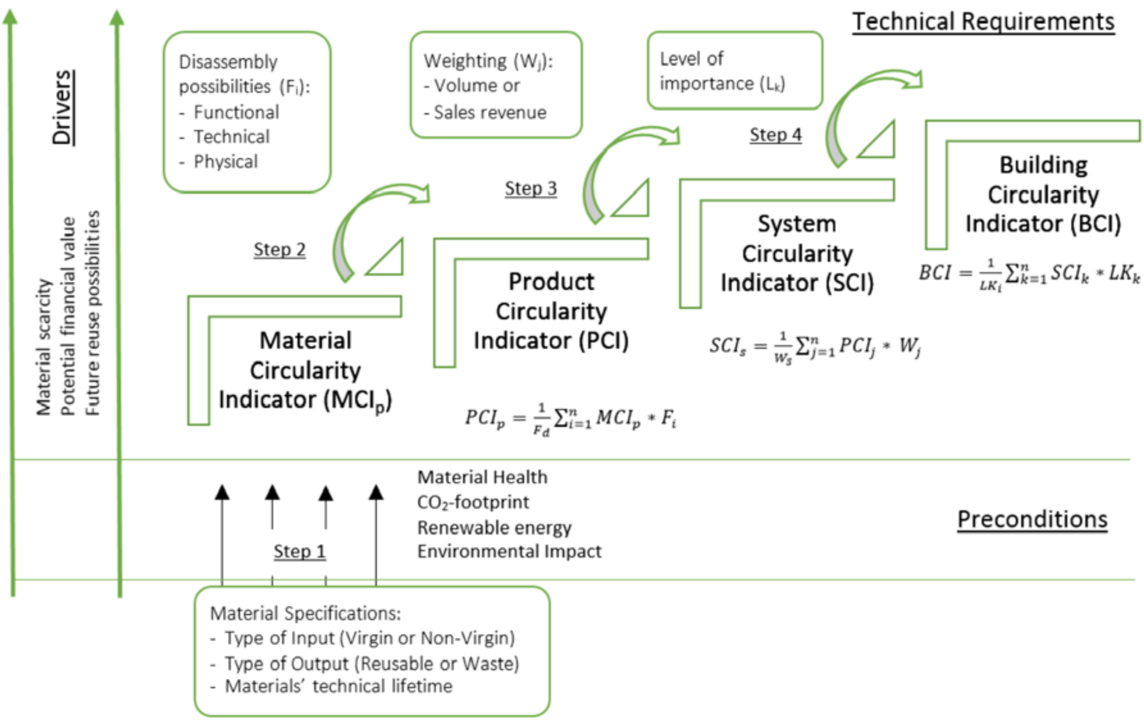


Figure 15: The hierarchy of the BCI model (Verberne, 2016)

2.3.3.3 Building circularity indicator (van Vliet, 2018)

van Vliet (2018) redeveloped the BCI model of Verberne (2016) after addressing its limitations, especially in assessing the disassembly potential. The BCI model of van Vliet (**Figure 16**) keeps the same hierarchy, but the calculation methods for PCI, SCI, and BCI change. Regarding the Although the model still utilizes equal weights for disassembly factors in the BCI assessment model based on the research results, there are significant changes in assessing ways and levels. The research uses a relational pattern of products to assess the disassembly. It identifies the relational patterns through the detailed drawing, which is a two-dimensional technical representation of a specific junction in a building. Furthermore, he distinguished the identified technical disassembly factors into the product disassembly potential and the connection disassembly factors. The former considers all surrounding products in the assembly, while the latter only considers the outgoing connection. Moreover, the calculation of SCI has entirely changed in the BCI model of van Vliet (2018). Instead of grouping products of per system (e.g., site and structure) and using the total product mass in each system as a normalizing factor, van Vliet (2018) categorized products in systems using either a disassembly potential threshold or reusability potential. As for the BCI, it consists of an aggregation of PCIp's and SCIs's. In conclusion, with this model, it is possible to determine on which building-level products, systems and the entire building can be disassembled, leading to a comparable result with each other (van Vliet, 2018).

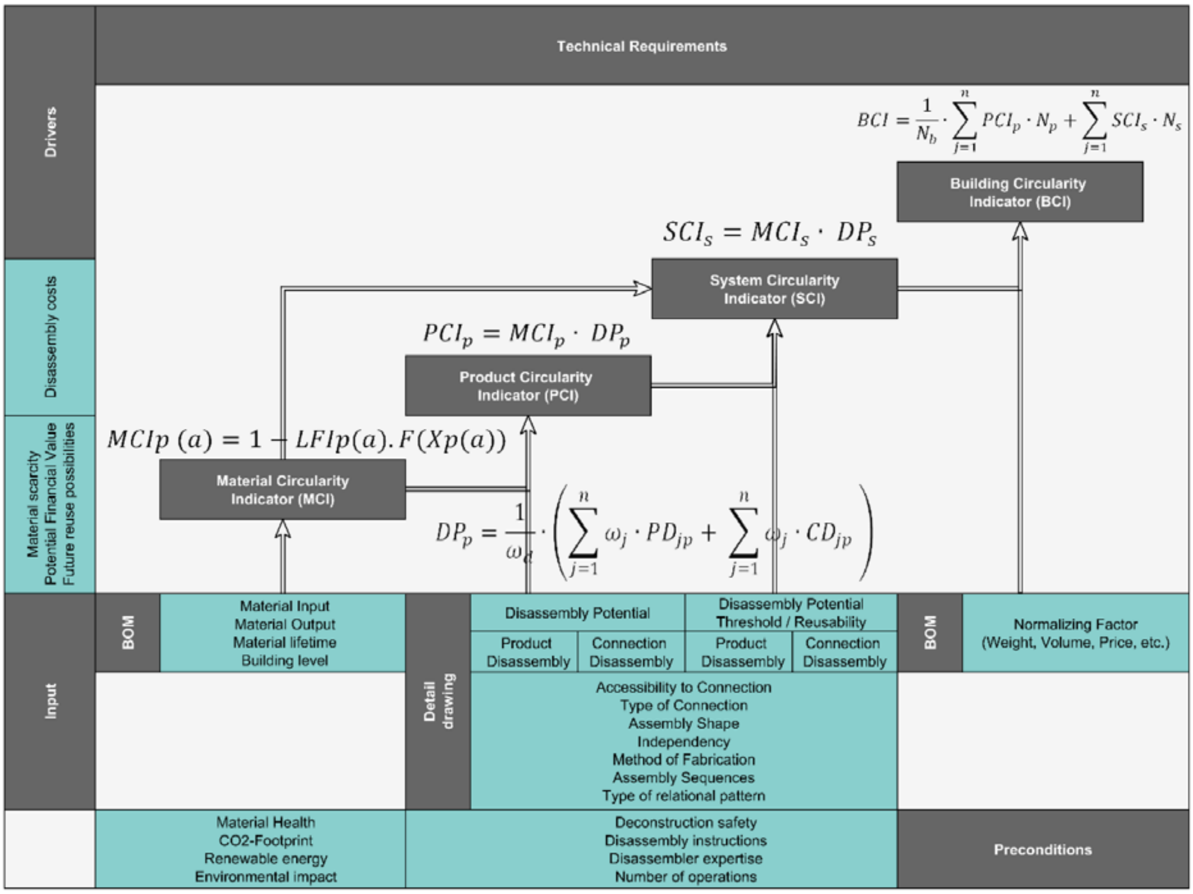


Figure 16: The hierarchy of the BCI model (van Vliet, 2018)

2.3.3.4 Building Circularity Index (Alba Concepts, 2018)

The Building Circularity Index (BCIX) model, which has been developed by Alba Concepts (2018), is an assessment model that makes it possible to determine the circularity level of the building. In the BCIX model (**Figure 17**), there are three vital KPI's, namely Product Circularity Index (PCIX), Element Circularity Index (ECI) as well as BCIX. PCIX is based on Material Index (MI) and Disassembly Index (DI). The calculation of MI is the same as that of Verberne (2016) and van Vliet (2018). It is based on the virgin material, future scenario, technical lifespan, and the mass of material. DI takes into account the two key disassembly factors, namely the type of connection and accessibility to connection, respectively. Instead of SCI, Alba Concepts has developed ECI, which is a significant distinction between Alba concepts' BCIX model and that of Verberne (2016) and van Vliet (2018). Similarly, ECI is obtained in the same manner as PCI through MI and DI. It is noted that Alba Concepts defines an element as a group of products that are inextricably linked and cannot be disassembled from each other. Only when a connection is detachable, and the damage is limited, does the cluster end, and forms an element. Thus, the building can be an entity that is composed of elements. Finally, mass is utilized as weight, and normalizing factors for each element are used to calculate the BCIX. In addition to assigning the score of PCIX, ECIX, BCIX, Alba Concepts also gives the value of the individual indicator for the overall building. For example, the percentage by mass of virgin material for the whole building. The related documents are in **Appendix II** Documents from Alba Concepts

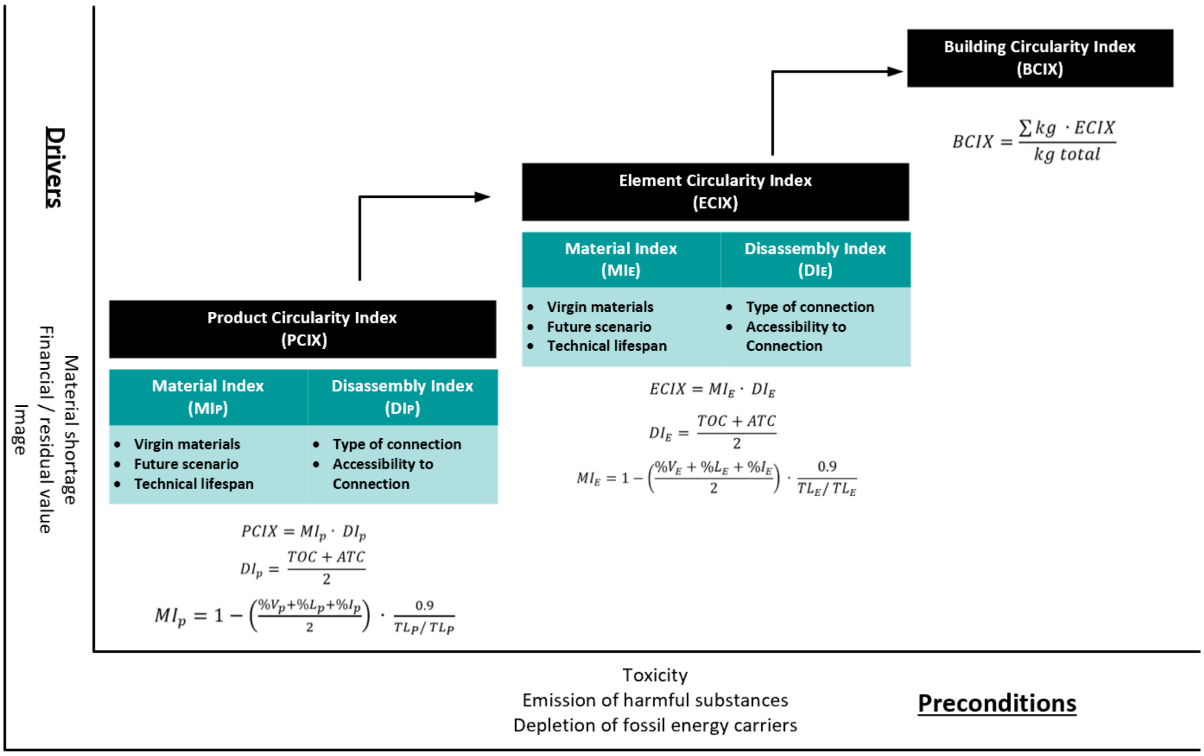


Figure 17: The hierarchy of BCIX model (Alba Concepts, 2018)

2.3.3.5 Circularity Indicators (Madaster, 2018b)

The Madaster Foundation developed Circular Indicators (CI) based on the MCI (EMF, 2015a) and adopts it specifically in the construction sector. Their CI assesses the circularity level of a building throughout the whole life stages. Similar to MCI, CI also assigns the value to each assessed building in the range of 0 and 100 per cent. 0 % means a building is considered as fully "linear". It is constructed entirely from virgin materials and sent to landfill after a use phase shorter than average. In contrast, when a building is constructed from reused, recycled or/and rapidly renewable materials that can be disassembled and easily re-used at the end of the use phase, it is considered to be a fully "circular" building and has the CI score of 100%. More specifically, a building and its components are measured in three essential life stages: the construction phase, the use phase, and the end of life phase. Each phase is given a CI score. The CI score with 100% in the construction phase refers to completely secondary material resources. Moreover, it takes into account the efficiency of the recycling process and the mass of waste generated during the recycling process, which are used to adjust the CI score in this phase. For the use phase, it aims to make the functional lifetime exceed the industrial average lifetime, while a 100% CI score in the last phase represents the fully recoverable materials in the building after its end of life. Finally, these three indicators in different life phases are aggregated to generate an overall CI building score.

2.3.3.6 Platform CB'23 (2019)

Platform CB'23 (2019) has been developing a core method to measure circularity in the construction sector. Its calculation is formulated mainly based on three primary goals of circular construction, namely protecting existing material stocks, protecting the environment, and protecting existing value. Following the established goals, a list of individual indicators that reveal the degree of circularity in the construction sector is created. These indicators are generally divided into six groups, namely the quantity of material used (input), the quantity of material available for the next cycle (output), the quantity of material lost (output), influence on the quality of the environment, the quantity of existing value used (Input), the quantity of value available for the next cycle (output), and the quantity of value lost (output). It is noted that the quantity of material means their percentage by mass of the total input or output. Currently, the first version of the calculation guide has been published and focuses exclusively on the material stock: the first three types of indicators. Apart from providing the value of individual indicators with the expression of percentage, the core measurement method is also expected to contain a report on the adaptive capacity of a building structure. The report illustrates some key principles regarding the qualitative description of the adaptive capacity. Following the guidance in this report, clients or other stakeholders could estimate the building's adaptive capacity. The use of this report is of importance to optimize the overall impact of material stock, the quality of the environment, and existing value.

The general idea behind these six technical assessment models is to consider the building as a material depot and focuses on the material input, usage, and output. Furthermore, the one developed by Platform CB'23 differs from others. It mainly provides a list of individual indicators (e.g., the quantity of primary materials used) rather than further connect them to measure the extent of transiting from "linear" to "circular".

2.3.4 Evaluation

Fourteen technical building circularity indicators and six existing technical assessment models have been reviewed. **Table 3** displays the range of covered technical building circularity indicators for each assessment model. Boxes are filled with a light blue to indicate that the related indicators are included in the assessment model. Notably, the indicators that are created to incorporate stakeholders' interests better without influencing the level of building's circularity are not considered in **Table 3**. For example, some complementary indicators like material scarcity and toxicity in MCI (EMF, 2015) and the indicators derived as drivers and preconditions (such as renewable energy usage, toxicity) in BCI(X) (Verberne, 2016; van Vliet, 2018; Alba Concepts, 2018) are excluded. % represents the percentage by mass of relevant material in the total material input or output.

Table 3: The covered technical building circularity indicators of six assessment models

Technical building circularity indicators	Technical Assessment Models for Building's Circularity					
	MCI:EMF (2015)	BCI(X)			CI Madaster (2018b)	Platform CB'23 (2019)
		Verberne (2016)	van Vliet (2018)	Alba (2018)		
% by mass of renewable materials						
% by mass of virgin materials						
% by mass of reused materials						
% by mass of recycled materials						
The total mass of materials						
The toxicity of the material						
Building circular product levels						
Disassembly potential						
Adaptability potential						
% by mass of reusable materials						
% by mass of recyclable materials						
% by mass of materials sent to landfill						
% by mass of materials sent to incineration						
Recycling process efficiency						

In **Table 3**, three key findings are revealed. Firstly, the six technical assessment models cover a similar number of technical building circularity indicators. The core measurement method formulated by Platform CB'23 is the most exhaustive, covering thirteen indicators, while MCI (EMF, 2015b) has the least number of nine indicators. BCIX developed by Alba concepts (2018), and CI established by the Madaster (2018b) have eleven indicators. This is followed by the model developed by Verberne (2016) and van Vliet (2018), which cover the same number of ten indicators. Furthermore, eight technical building circularity indicators concerning the effect of material stock are considered by all models. These are the percentage by mass of virgin materials, reused materials, recycled materials in the total material input, the percentage by mass of reusable materials, recyclable materials, material sent to landfill, materials sent to incineration in the total material output, and the total mass of material. Finally, no assessment model considers the toxicity of materials.

This section also conducts a further evaluation for the six assessment models regarding their features in input, output, advantages, disadvantages, and assessment tool (

Table 4). The input entails what kind of information is needed to calculate the level of building's circularity. It is found that all assessment models require the percentage by mass of material origins (feedstock sources) and material destinations (end of life scenario) despite slight differences in the needed information. Besides, the bill of materials (BoM), which contains a list of the parts or components and their precise type and amount of material, is also necessary for all measurement methods. Basically, the disassembly potential as a vital indicator is included in the input of most of the assessment models, but it is assessed in different manners. For example, Verberne (2016) and van Vliet (2018) consider seven disassembly factors, while Alba Concepts (2018) only considers two of them. Regarding the output, the type of BCA (quantitative or qualitative) and the expected assessment results are presented. As can be seen, all measurement methods tend to employ the quantitative assessment, assigning a specific value to the level of building's circularity. Besides, except for MCI (EMF, 2015b), others provide more than one indicator. For example, BCI(X) assessment models (Verberne, 2016; van Vliet 2018; Alba Concepts, 2018) give MCI(MI), PCI(X), SCI, (ECI), and BCI(X) scores based on different levels of a building's composition.

The advantages and disadvantages describe the most highlights and major drawbacks for each assessment model. The assessment models are assessed regarding the range of covered technical building circularity indicators, practical use, and universal application in the Dutch construction sector. An ideal measurement method for building's circularity should cover as many as possible indicators, become universally acknowledged, and has gained practical experience in the AEC industry. Moreover, the evaluation form provides information regarding the support tools for six assessment models. Except for Platform CB'23 that does not have an assessment tool, most tools employ either an Excel spreadsheet or an online platform.
In conclusion, the evaluation (

Table 4) indicates that six technical assessment models share many similarities. For example, they all focus on measuring the effect of material stock and utilize the quantitative assessment. These findings will contribute to determining a suitable assessment model for building's circularity in the research.

Table 4: Overview of evaluation for six assessment models

Assessment Models		Input	Output	Advantages	Disadvantages	Support Tool
MCI: EMF (2015)		-Percentages by mass of (reused, recycling) material origin and destination after use. -Utility during the use phase. -The efficiency of recycling. -BoM.	**Quantitative** The MCI, single score, gives a value between 0 and 1, where higher values indicate a higher circularity.	-It is universally acknowledged and adopted by many studies.	-It only focusses on technical cycle. -It does not assess the circularity from different levels of the building. -It only considers the effect of material stocks.	Excel Spreadsheet
BCI(X)	**Verberne (2016)**	-Percentages by mass of (non-virgin) material input and (reusable) material output. -Technical lifetime for the product. -Lifetime for building layers. -Disassembly potentials for the product (7 factors). -System dependency for layers. -BoM.	**Quantitative** The MCI, PCI, SCI, BCI scores for different levels of the building, gives a value between 0 and 1, where higher values indicate a higher circularity.	-It investigates the interconnection and physical interfaces at the assembly in a building. -It considers the circularity from different levels of the building.	-It only focusses on technical cycle. -It has not been recognized as a certification or labelling methodology in Dutch construction.	Excel Spreadsheet
	van Vliet (2018)	-Percentages by mass of (virgin and reused) material input, (landfill, energy recovery, and reuse) material output. -Technical & system lifetime for the product. - Disassembly potentials for the product (7 factors). -BoM.	**Quantitative** The MCI, PCI, SCI, BCI scores for different levels of the building, gives a value between 0 and 1, where higher values indicate a higher circularity.	-It considers the circularity from different levels of the building. -It has a comprehensive framework to assess the building's disassembly potential.	-It only focusses on technical cycle. -It has not been recognized as a certification or labelling methodology in the Dutch construction	Excel Spreadsheet
	Alba (2018)	-Percentage by mass of (virgin, reused, recycled, renewable) material input and	**Quantitative** -The MI, PCIX, ECI, BCIX scores for different levels of	-It has been put into practices.	- It has not been recognized as a certification or labelling	Excel Spreadsheet & Online Platform

	(reusable, recyclable, landfill, and incineration) material output. -Technical & functional lifetime for the product. - Disassembly potential for the product (2 factors). -BoM.	the building, gives a value of percentage, where higher values indicate a higher circularity. - The percentage by mass of individual indicator for the whole building	-It considers the circularity from different levels of the building. -It gives the percentage by mass of individual indicator for the whole building.	methodology in the Dutch construction	
CI: Madaster (2018b)	-Percentage by mass of (recycled, rapid renewables) material input and (recycled and reused) material output. -The efficiency of the recycling process raw materials and end of life. -Technical & functional lifetime for the product. - Disassembly potential for the product (3 questions). -BoM.	**Quantitative** CI scores for the construction phase, use phase, end of life phase, and overall building, gives a value of percentage**.**	- It has been put into practices -It considers the building's circularity in the perspective of whole life phases.	-It does not assess the circularity from different levels of the building;	Online Platform
Platform CB'23 (2019)	-Percentage by mass of (primary, secondary, renewable) material input and (reuse, recycle, energy generation, landfill) material output in an object or sub-object. -Fill in the list of adaptive properties of a building. -BoM.	**Quantitative** Individual indicators for every object or sub-object, give a value of percentage. **Qualitative** A list of adaptive properties of a building for users to pay attention to the important properties for each building layer.	-It covers the most investigated technical building circularity indicators. -It aims to be recognized as a certification or labelling methodology in Dutch construction.	-It is not complete and still be developing. -There are only separate individual indicators without an overall indicator for building's circularity. -It lacks practice.	No

2.4 Building Information Modeling and Building Circularity Assessment

A large amount of data is needed for the Building Circularity Assessment (BCA) (Rahla et al., 2019). However, the overabundant data consumes time and resources to gather and manage. In such a context, the role of BIM can be a supplementary tool to facilitate the assessment (Rahla et al., 2019). This section aims to describe the concept of BIM, its application in the AEC industry and which features of BIM makes it be capable of accelerating the BCA. Furthermore, this chapter explores how previous research integrate BIM and BCA.

2.4.1 Building Information Modelling

BIM is a very broad concept as it has various extensions: Building Information Model, Building Information Modeling, Building Information Management. On the one hand, BIM is often considered as a 3D model that digitally stores all building data (Aguiar et al., 2019). On the other hand, it refers to the process of creating digital building models and maintaining, using, and exchanging these models throughout the entire life of the building (Borrmann et al., 2018). This research adopts the concept of BIM that is defined by the US National Building Information Modeling Standard:

Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is a collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder (Borrmann et al., 2018).

Globally, the AEC industry has widely applied BIM due to its significant benefits in increasing the production efficiency in design and construction processes. The use of BIM enables designers to have the building 3D visualized during the design stages for project meetings or public relations. By employing this BIM technology, the clients have the chance to preview the building before the physical implementation takes place. Consequently, there is less reworking or remodelling (Borrmann et al., 2018). Moreover, BIM contributes to better collaboration among different disciplines and efficient building performance assessment. Because of the beneficial contribution of BIM in the AEC industry, most innovation, which includes the transition towards a CE, should be BIM compliant (Akanbi et al., 2018). As mentioned previously, one of the key actions ‘Virtualization’ in the ReSOLVE framework highlights the key role of BIM in the use of the tracking mechanism for materials. It would increase the information digitization; thereby, support transparency, storage, access, and exchange of information (Iyer-Raniga, 2019).

Akanbi et al. (2018) emphasized three core features of BIM, which make it suitable for assessing the building’s performance in the context of CE. The first one is object parametric modelling that uses parameters and rules to capture design. The second feature is the bi-directional associativity, which demonstrates the changes in the building model closely relate to the design. Lastly, intelligent modelling refers to the use of supplementary data for evaluation and analytical purposes (Akanbi et al., 2018).

2.4.2 The integration of BIM and building circularity assessment

Currently, no study has systematically investigated how BIM can be integrated into building circularity assessment. To fill this gap, this research has reviewed the state-of-the-art BIM-BCA integration approaches by gathering and analyzing five studies and tools. **Table 5** illustrates the brief description and key features of them. In conclusion, there are two main streams of BIM-BCA integration. The first one is to utilize a data exchange standard (e.g., Industry Foundation Classes (IFC), Construction Operations Building Information Exchange (COBie)) to hold the BoM and other properties of BIM model elements. Then, the exchanged files are processed in external building circularity assessment software like an online platform. The circular building assessment (CBA) prototype (BAMB, 2019) and the Madaster (2018c) belong to the first stream. The other one is to conduct the assessment within BIM software through creating custom parameters in A BIM tool like Revit to capture various attributes regarding building's circularity. The BIM-based Deconstructability Assessment Score (BIM-DAS) tool, BIM-based Whole-life Performance Estimator (BWPE) tool, and Steel Structure Deconstructability Assessment Scoring (SS-DAS) tool are grouped into the second stream.

Apart from the aforementioned two approaches, there is another integration possibility that is to establish an automatic and efficient link between the BIM model and external building's circularity database. This method learns from the studies about BIM-Life Cycle Assessment (BIM-LCA) integration. This is because the implementation processes between BIM-BCA and BIM-LCA share the similar characteristics: requiring accurate status and quality of the building materials throughout the whole life cycle. Moreover, the research and development of LCA-BIM integration are more mature so that they enable to provide the BIM-BCA integration with insights. The following paragraphs elaborate on these three BIM-BCA integration approaches by describing the examples and specify how different streams work.

Table 5: State-of-the-art BIM-BCA integration tools/methods

BIM-BCA Integration	Description	Features
BIM-DAS tool (Akinade et al., 2015)	Create custom parameters in Revit to capture various attributes to assess the performance of Design for Deconstruction	BIM-software (Autodesk Revit)
CBA prototype (BABM, 2020)	Upload COBie files that hold bill of quantity and material on the platform to undertake circular building assessment.	BCA-software (Online platform)
BWPE tool (Akanbi et al., 2018)	Create custom parameters in Revit for appraising the salvage performance of structural components of buildings right from the design stage and process them through Revit add-in.	BIM-software (Autodesk Revit add-in)
SS-DAS tool (Basta et al., 2020)	Create custom parameters in Revit for quantitative assessment of steel structures deconstructability and automate the assessment through Dynamo prototype.	BIM-software (Autodesk Revit Dynamo)
Madaster (Madaster, 2018c)	Upload IFC file that contains building data such as BoM on the platform to generate the Circularity Indicators.	BCA-software (Online platform)

2.4.2.1 Stream 1: Process an exchange file in external BCA software

Madaster (Madaster, 2018c)

Madaster is an independent digital platform offered by the Madaster Foundation. This platform enables users to register a new or existing building and generate the corresponding Madaster CI scores. To conduct the BCA on Madaster, the first step for users is to upload the relevant building data on the Madaster Platform by using an IFC or Excel file (**Figure 18**). The IFC is an open, standard format for the exchange of BIM data (Building Information Model) between various software packages, such as Autodesk Revit and SketchUp. It can be exported by all 3D CAD applications. Therefore, when a building is modelled in 3D, IFC is the primary choice to utilize. However, if a building or part of it is not modelled in 3D, users must import limited data sets in the Excel template. The data and information that originate from the uploaded IFC source files include:

- **Geometric information:** All geometric data, such as the quantities of materials.
- **Material dada:** The material data like material name and type, which is compared with the material database on the Madaster Platform.
- **NL-SfB coding:** NL-SfB coding is a naming convention that is widely applied in the Dutch construction and installation industry to code layers and elements in BIM and CAD systems. (BIM Loket-NL-SfB, 2020). It is adopted by Madaster to classify the materials.

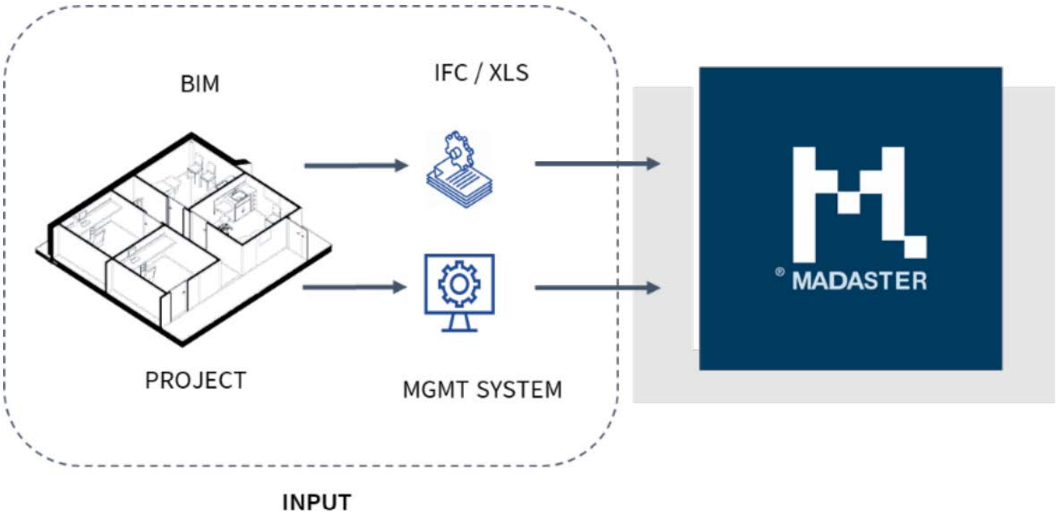


Figure 18: The input of Madaster Platform(Madaster, 2018a)

Circular Building Assessment Prototype (BABM, 2019)

The CBA Prototype is an online platform, which is being developed by the Building as Material Banks (BAMB) to quantify and assess different design approaches in the context of CE. Bearing a resemblance to Madaster, the CBA prototype also allows users to upload an information exchange file generated from authoring software (e.g., Autodesk Revit, Sketchup) to create a BIM model. **Figure 19** displays the process of sourcing information for the CBA prototype. As can be seen, it mainly differs from Madaster in utilizing COBie and IFC file to acquire building data. COBie is a spreadsheet data format that contains digital building information as complete and useful as possible (BABM, 2020). The data and information in the upload COBie source files include BoM.

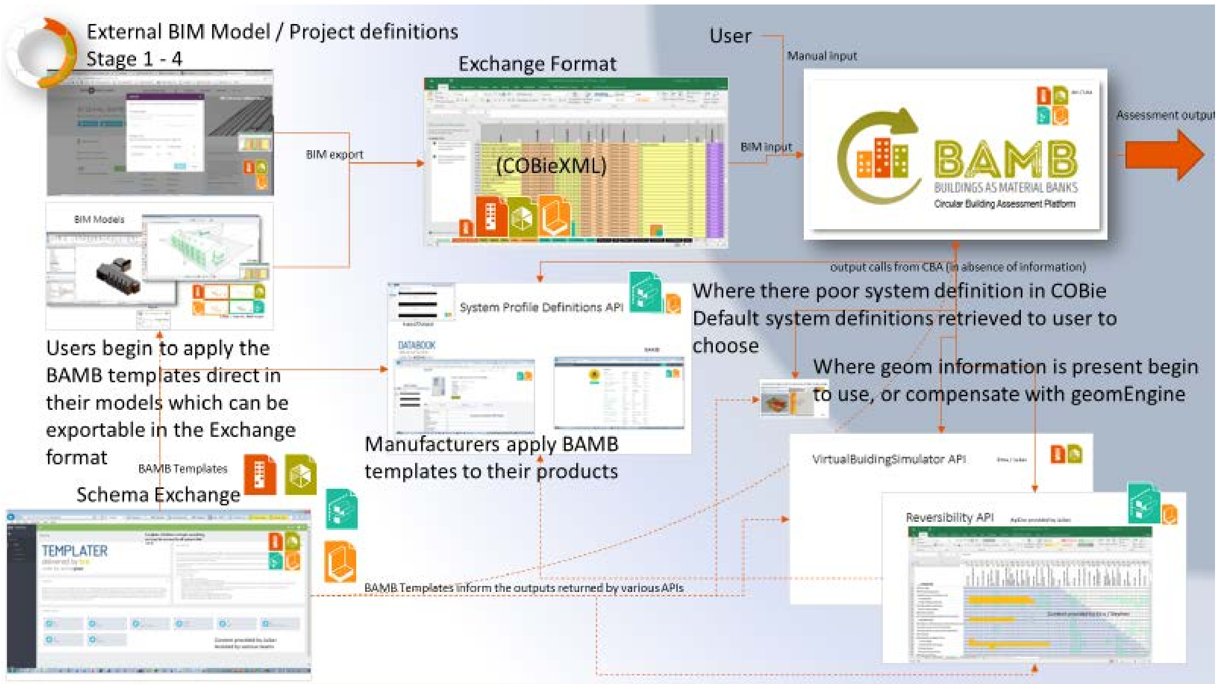


Figure 19: Vision of CBA information flow to assess the online portal (BAMB, 2019)

For the Madaster and CBA prototypes, the BIM model is central, and the integration with BIM mainly lies in using BIM-based information exchange files to obtain the input of the building data. Their combination helps to reduce the amount of data that needs to be input by the users.

2.4.2.2 Stream 2: Create and process circularity-related parameters in BIM software

BWPE / BIM-DAS /SS-DAS tool

To integrate BIM into building circularity assessment, an essential factor is BIM's ability to capture building elements' parameters automatically (Basta et al., 2020). The second stream realizes this funcation mainly by creating built-in parameters in BIM parametric modelling software such as Autodesk Revit. BWPE, BIM-DAS, and SS-DAS tools to create custom user-specific object parameters, which are related to the building's circularity. The assessment content and target of these tools are distinct; hence, different parameters are created (e.g., attributes for recyclability, reusability, lifespan, toxicity, connection type). Moreover, these tools utilize a different type of parameter value (e.g., Text, Integer, Yes or No). BWPE tool established four questions regarding material toxicity, and secondary finishes if the element is demountable and prefabricated. These questions are assigned the format of the checkbox, which represents yes or no. **Figure 20** shows a group of shared parameters for I-column in SS-DAS tool. The value of these parameters is restricted to the text value. In addition to the differences in the created parameters, these tools employ different means to capture and calculate the parameters. For example, the SS-DAS tool employs Dynamo for Revit, which is an open-source visual programming platform that allows users to customize the building information workflow and works as a Revit Plug-in. BWPE tool is implemented in the form of an add-in for Autodesk Revit, which is realised by the Revit Application Programming Interface (API), Visual Studio, and the C# programming language.

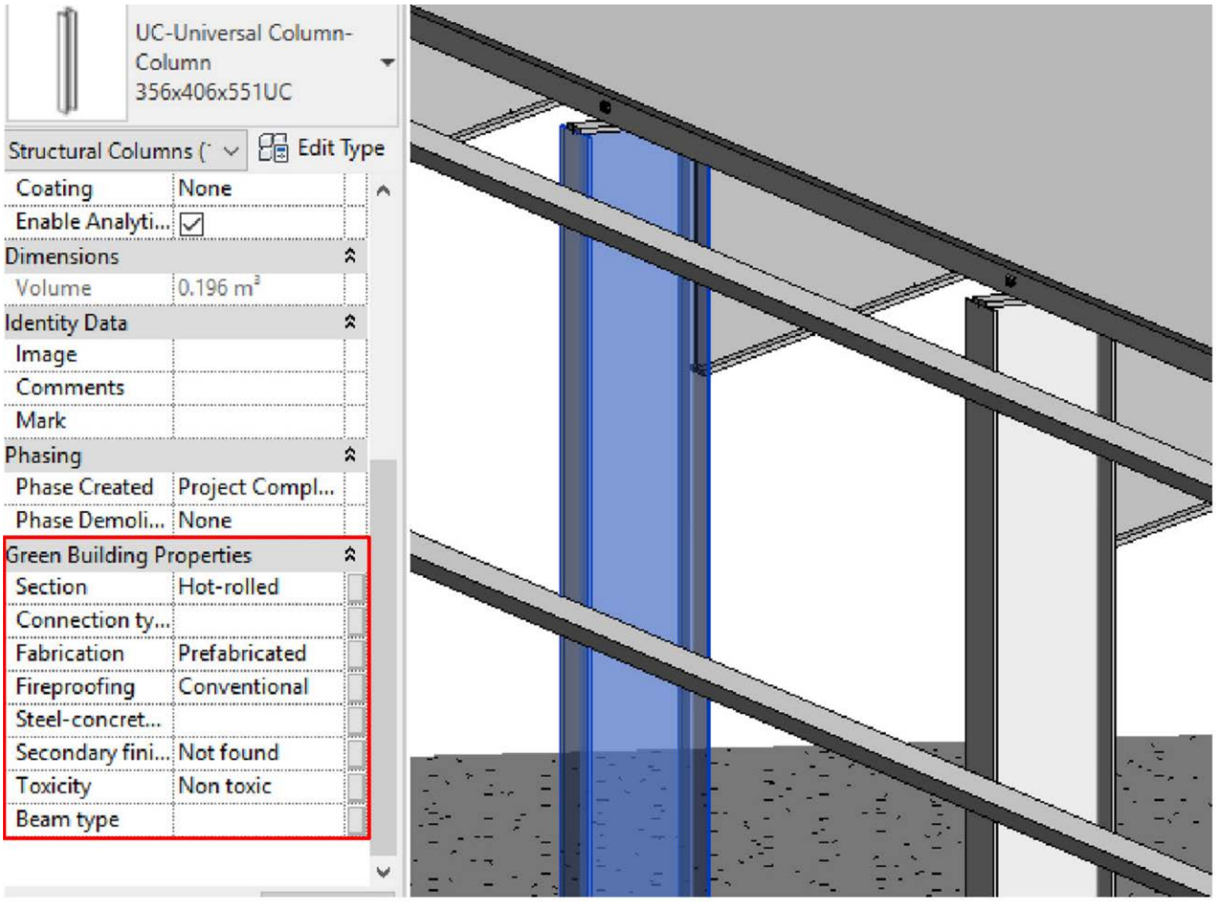


Figure 20: A group of shared parameters for I-column in SS-DAS tool (Basta et al., 2020)

2.4.2.3 Stream 3: Link BIM model and building circularity database that stores in an external database

As mentioned before, the third stream learns from the one of key BIM-LCA integration approaches: establishing an automatic and efficient link between the BIM model and required assessment information stored in external databases. Although it has not been implemented by studies or organizations yet in measuring building's circularity, it is considered to be feasible and enables to facilitate the assessment process.

The Integrated Dynamic model (Tsikos & Negendahl, 2017)

Tsikos & Negendahl (2017) developed an Integrated Dynamic Model (IDM), which employs Revit, Dynamo, and an external Life Cycle Impacts (LCI) database to realize the real-time assessment in a single BIM environment. By doing this, there is no need for an additional export to IFC (Tsikos & Negendahl, 2017). **Figure 21** displays how BIM is integrated into LCA in IDM. The basic concept of IDM is creating a permeant link between Revit material and the Database material, reducing the manual input when performing LCA for the building. After establishing the material linkage, the designed Dynamo script enables to obtain the BoM from the BIM model automatically and get Revit material's environment data from the LCI database. After that, it is possible to calculate the total life cycle environmental impacts, and finally, the assessment results are exported in an Excel sheet.

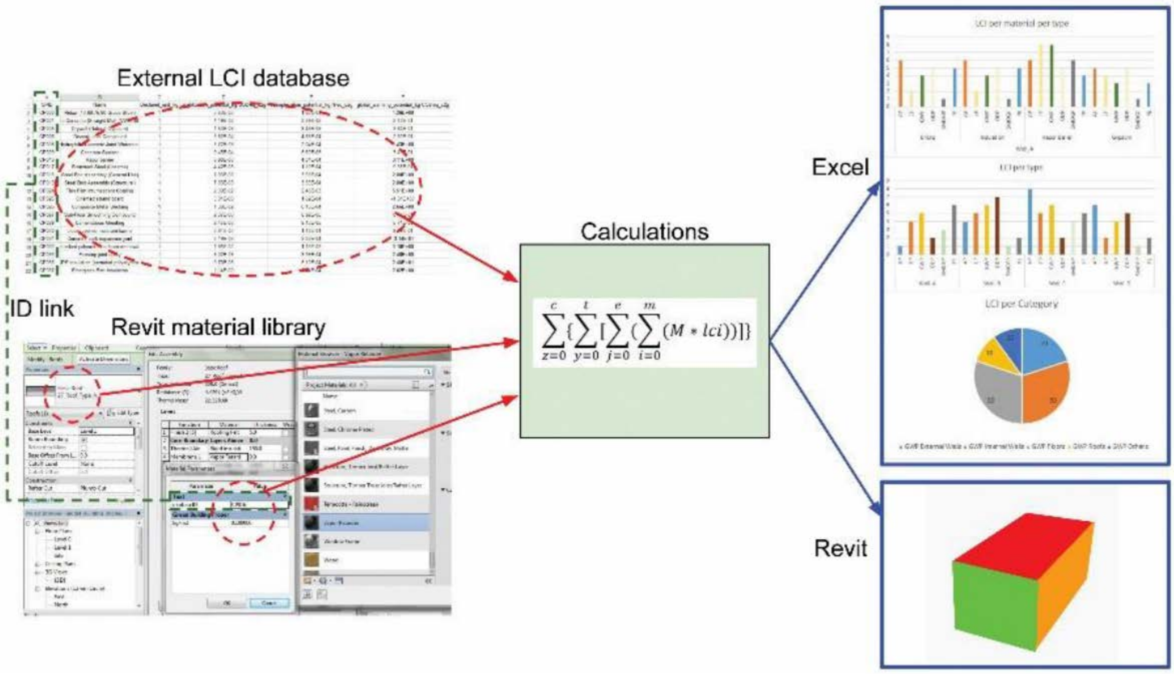


Figure 21: Overview of the IDM model. (Tsikos & Negendahl, 2017)

MPG-ENVIE (van Gemert, 2019).

MPG-ENVIE is a user-friendly application that was developed by Gemert to enable designers to comprehend the embodied impacts of their design quickly. **Figure 22** shows the system architecture diagram for developing this application. Users can import an IFC file that contains a bill of quantity in a BIM model into MPG-ENVIE. Then this application links the IFC file automatically with external LCA databases of building products through the NL-SfB code to calculate the whole life embodied impact of the proposed design. Finally, the assessment results are presented in the form of comprehensive tabular, graphical, and plotted outputs (van Gemert, 2019).

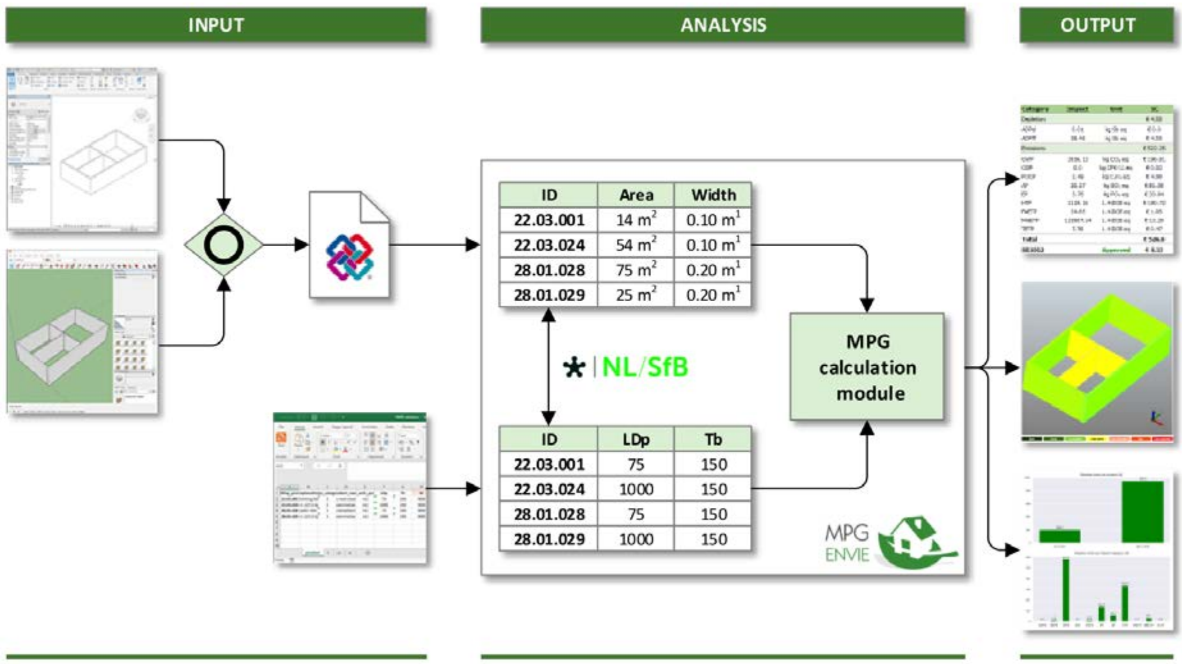


Figure 22: The system architecture diagram for MPG-ENVIE (van Gemert, 2019)

2.4.3 Evaluation

This section conducts a further evaluation for the main BIM-BCA integration streams and their support tools to conduct the assessment. **Table 6** illustrates the advantages and disadvantages of six possible approaches. According to this evaluation form, several key findings are discussed. Firstly, all of them enable to facilitate the BCA process and reduce users' manual input to a certain degree. Nevertheless, these BIM-BCA integration approaches realized through an online platform or external application still have overabundant manual procedures. Users have to export the information exchange file from BIM software and upload on such applications. Also, the second BIM-BCA integration stream (i.e., creates custom parameters in Autodesk Revit) is time-consuming. Users need to specify the parameter value for every building component. In such a context, only the third BIM-BCA integration method (i.e., connects the BIM model to the external database, then performs the BCA in BIM software) enables a more efficient assessment. This is because most data input has already been specified, and the assessment can be conducted in real-time. Secondly, compared with the tools that are compatible with open file formats such as IFC, a plug-in for specific software has restricted scope of application. For example, only Revit users have access to the Revit Plug-in. Apart from analyzing the integration methods from the perspective of users, for the application developers who are non-programmers or novice programmers, it is of importance to consider the difficulty in developing the application. Comparing with the online platform and Revit add-in, Dynamo is relatively easier to learn and understand.

Table 6: Evaluation of three BIM-BCA Integration approaches

BIM-BCA Integration	Tool	Advantages	Disadvantages
Upload BIM model into BCA software	The online platform (IFC/COBie exchange file)	-Automate the assessment. -Independent. -Applicable for all 3D CAD applications.	-Overabundant manual procedures. -Cannot assess the design in real-time. -Have a relatively high requirement for a developer's coding ability.
Create Revit Parameter for building's circularity and proceed them in BIM software	Dynamo for Revit	-Automate the assessment. -Instant/real-time assessment. -Easy to learn and revise. -Colour override.	- Overabundant manual procedures. -Only applicable for Revit users. -Limited format of creating parameters.
	Revit Add-in	-Automate the assessment. -Instant/real-time assessment.	- Overabundant manual procedures. -Only applicable for Revit users -Limited format of creating parameters. -Have a relatively high requirement for the developer's coding ability.
Establishing an automatic and efficient link between	External application (IFC)	-Automate the assessment.	-Overabundant manual procedures.

the BIM model external databases, then conduct BCA in a single BIM environment		-Applicable for all 3D CAD applications.	-Cannot assess the design in real-time.
	Dynamo for Revit	-Automate the assessment. -Instant/real-time assessment. -Easy to learn and revise. -Colour override.	-Only applicable for Revit users.
	Revit Add-in	-Automate the assessment. -Instant/real-time assessment.	-Only applicable for Revit users. -Have a relatively high requirement for a developer's coding ability.

2.5 Conclusion

The literature review provides five interesting findings, including several key terminologies, key circular building design principles, building circularity indicators, existing assessment models for building's circularity, and the BIM-BCA integration approaches.
Firstly, it is found that there is no commonly accepted definition for the CE concept, circular building and building's circularity. To prevent misunderstanding, this chapter gives an explicit description of these important terminologies after reviewing various existing definitions. The definition of the CE concept describes CE as an industrial system that is restorative or regenerative by intention and design. Moreover, it specifies three operation levels of CE (micro-level, meso-level, and macro-level), and the circular building is grouped as the meso-level in the research of built environment towards a CE. The term "circular building" represents a temporary and dynamic material depot, while building's circularity describes a new way of design and managing the circular building during its lifecycle.

Due to the broad scope of the circular building, this research focuses exclusively on the technical aspects, including circular material usage and circular design. After giving an explicit definition for circular building and specifying the research scope, nine fundamental design principles are identified and classified by three vital lifecycle phases of building:

(1) Material and component production stage (i.e., shift to renewable material, refuse/reduce virgin material, reuse/recycle secondary material, material health, and design for low material use).
(2) Design stage (i.e., system thinking, design for disassembly, and design for adaptability).
(3) End-of-life stage (i.e., limiting material loss).

Then, this chapter emphasizes the importance of gauging building's circularity. The term "building circularity assessment" is created to represent the measurement of building's circularity that is affected by circular building design principles. It uses building circularity indicators to assess the impact of building's circularity on different domains (e.g., technical, environmental, social, and economic aspects). As a result, based on the nine principles mentioned above, fourteen building circularity indicators that enable to assess how well these principles perform are identified. All these indicators are all related to the building's technical properties. They are further divided into two groups: intrinsic properties and relational properties.

In addition, this chapter has reviewed six existing technical assessment models for measuring the value of the building's circularity. These methods are MCI (EMF, 2015a), BCI(X) (Verberne, 2016; van Vliet, 2018; Alba Concepts, 2018), CI (Madaster,2018b) and core measurement method (Platform CB'23, 2019). This chapter gives a brief description of their main characteristics. Furthermore, an evaluation is conducted regarding the features of these models in input, output, advantages, disadvantages, and support tools.

The last part of the research review highlights BIM's significant role in facilitating the building circularity assessment. It focusses on exploring the existing and potential integration approaches. As a result, three main streams are identified, including uploading BIM model into BCA software, creating circularity related parameters, and processing them in BIM software, connecting two databases and processing them in a single BIM environment. Each of them can be realized by different tools, such as online platform, Revit Add-in, Dynamo for Revit. Additionally, this chapter evaluates three main BIM-BCA integration streams together with their support tools by listing their advantages and disadvantages. Despite all of them can automate the BCA and reduce users' manual input to a certain degree, the first two approaches still require overabundant manual procedures when they are compared to the third integration approaches. However, there is no study and organization that has ever tried the third stream. To fill this gap, the research aims to develop a BIM-based framework that enables to automate the BCA to a large extent by connecting two external databases and processing them in a single BIM environment. In conclusion, the results of this literature review help to determine the assessment model for building's circularity and BIM-BCA integration approaches in this research. Subsequently, the next chapter aims to describe what methodology is employed to reach the target of the study.

3. Methodology

To attain the research goal and address the research questions, it is of importance to have a suitable methodology. It helps to realize a better planned and smoother research process, thereby increasing the chances of obtaining valid data and generating useful results. This chapter focuses on describing the methodology in the research and discussing parts of the research results.

In this research, Design research methodology (DRM) is adopted, which is an approach with a set of supporting methods and guidelines to be used as a framework for doing design research (Blessing & Chakrabarti, 2009). This methodology consists of four main stages: Research Clarification, Descriptive Study I, Prescriptive Study and Descriptive Study II. The DRM framework **(Figure 23)** shows the essential link between these stages, the research methods of each stage, as well as the specific steps. The bold arrows between the stages illustrate the main process flow, while the dotted arrows represent many iterations. (Blessing & Chakrabarti, 2009). After introducing the DRM framework, the details of conducting the research are elaborated. This chapter describes the important research method: Case study regarding its target and the process. Moreover, data collection illustrates how the data is collected by listing the data sources clearly and giving a concise reason for choosing the data. Last but not least, Descriptive Study I is included in **Chapter 2**. Its outcomes affect the choices regarding the assessment model for building's circularity, and BIM-BCA integration approaches in the research. Thus, this chapter also discusses the results of the Descriptive Study I to prepare for the next stage.

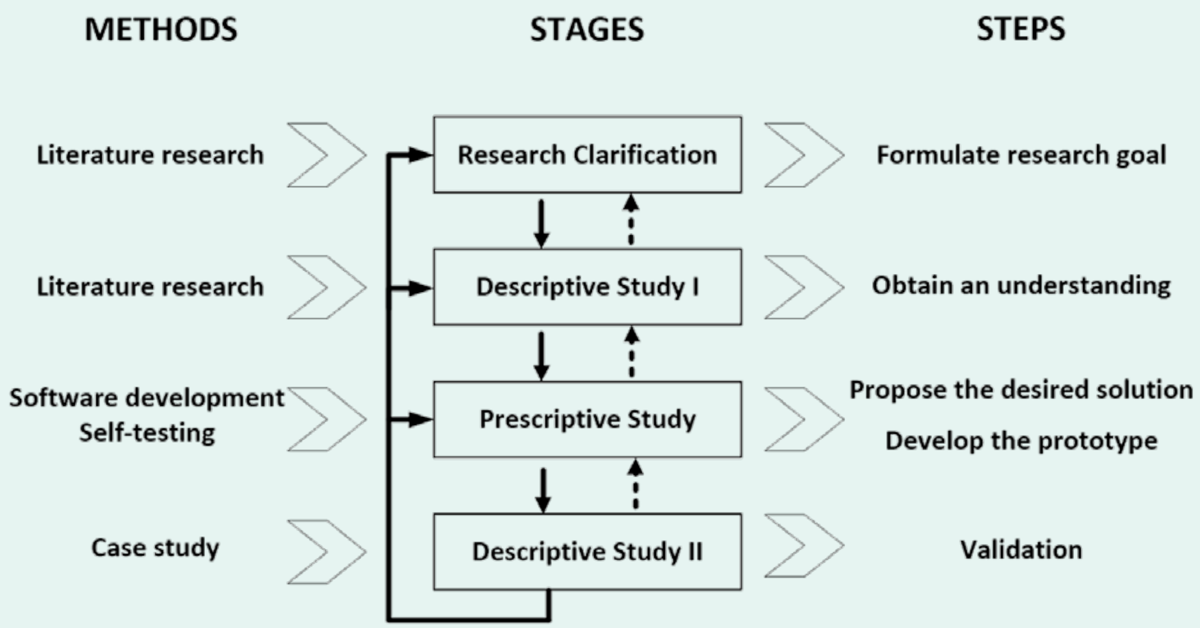


Figure 23: The DRM framework, Adopted from Blessing & Chakrabari (2009)

3.1 Design Research Methodology

Research Clarification

The research starts with the Research Clarification stage, which refers to the first chapter of this thesis: Introduction. Through literature research, the author formulates a realistic and worthwhile research goal that is to design a BIM-based building circularity assessment tool to promote the transition from a linear to a circular economy. Furthermore, the current situation regarding making circularity measurable is given. This is followed by the limitations of the existing measurement tools. Then an initial description of the desired situation that enables a more automated process with less manual procedures and instant analysis is provided. Thereafter, the key research questions are created to help reach this goal. At last, the author formulates the general criteria in both theoretical and practical perspectives to measure the outcomes of the research.

Descriptive Study I

After having a clear goal and focus, the next stage: the Descriptive Study I, which focus more on the “what” of the research subject, aims to obtain an understanding of the current situation, methods and its influencing factors to elaborate the description of the existing situation. The intention is to make the description detailed enough to determine which factor(s) should be addressed to improve task clarification as effectively and efficiently as possible (Blessing & Chakrabarti, 2009). During this stage, the building circularity indicator, the measurement methods, and the BIM-BCA integration approaches are investigated and evaluated to answer the **Sub-Q1**, **Sub-Q2**, **and Sub-Q3**. Besides that, all evidence from the literature research is collected.

Prescriptive Study

In the prescriptive study, based on the findings of the Descriptive Study I, the initial description of the desired situation in research clarification stage is corrected and elaborated to make it real (Blessing & Chakrabarti, 2009). Based on the results of the previous stage, and the BIM – BCA integration approach, the calculation method for building’s circularity is chosen. Thereafter, this research proposes a BIM-based framework that enables to facilitate BCA through an automated and real-time quantitative assessment. A prototype is developed to achieve this solution. During the development, firstly, the requirements for the functionality of the tool are formulated. Then the tool is developed. Hence, **Sub-Q4** about how BCA can be incorporated with BIM to automate the evaluation process is tackled.

Descriptive Study II

The purpose of Descriptive Study II is to investigate the impact of the support and its ability to realize the desired situation (Blessing & Chakrabarti, 2009). A case study is undertaken to gain an understating of the actual use of the proposed solution and the developed prototype, evaluate their usefulness against the success criteria. The result of Descriptive Study II addresses the last sub-question regarding how a BIM-based prototype enables to facilitate decision making about the design of the circular building from early design stages. This stage will answer **Sub-Q5**.

3.2 Case Study

The proposed BIM-based framework in Prescriptive Study stage is validated by a case study to realize the integration of practice and theory. The main target of conducting the case study is to illustrate how the developed tool promotes the design of circular design from early design stages. The selected case is a real project designed for circularity, which means the project stakeholders pay attention to the level of building's circularity while designing. Since the proposed BIM-based framework should enable the use of the tool from the early design stages, the validation involves different designed scenarios in three primary design stages of the project, namely Level of Development (LOD) 100, LOD 200 and LOD 300. LOD is used to represent the development level of BIM models at various stages in the design and construction process (Ikerd et al., 2013).

The case study starts with modelling the selected case from LOD 100 stage, where overall building massing indicative of the area, height, volume, location, and orientation may be modelled in three dimensions or represented by other data(Ikerd et al., 2013). However, due to the limited model information in LOD 100 stage, the BCA will not be conducted until the design develops to LOD 200 stage. During this stage, model elements are modelled as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation (Ikerd et al., 2013). Two different design are provided, such as timber structure and steel structure. Each of them is conducted with BCA. Based on the results, project statehooders can select the one with more circular potential. Lastly, during the phase of LOD 300, model elements are modelled as specific assemblies accurate in terms of quantity, size, shape, location, and orientation (Ikerd et al., 2013). Like LOD 200, two design options such as traditional timber column and renewable timber column, are created and used to have BCA.

3.3 Data Collection

Based on the research stages, data are collected by different means. During the stage of Research and Descriptive Study I, almost all evidence is collected from literature by inputting the keywords in ScienceDirect, Google scholar. Besides that, the cooperating company, Alba Concepts also provide some documents regarding the BCIX model, which is not published online. The relevant information has been put into **Appendix II**. In the Prescriptive Study stage, some documents about Nederlands Revit standard are used. For instance, NL-SfB classification schema. The author has provided the link for these files in the thesis. Lastly, in Descriptive Study II, there are two primary data sources, one is the BIM model that used in the case study, the other one is the relevant building's circularity data that is utilized to conduct the BCA. The original BIM model in Autodesk Revit 2020 is provided by the cooperating company Buro Kade and BIM-Optimaal, who is involved in the design of a circular building: The new Weener XL. With their permission, the author has taken representative parts and remodelled them, then implemented it in the case study. The circularity data of building element is offered by Alba Concepts, who is developing the database for building circularity index. This database builds upon two national product databases: Nederlands Instituut voor Bouwbiologie en Ecologie (NIBE) and Nationale Milieu Database (NMD). Compare with these two national databases, the database of Alba Concepts has the advantage that has more extensive circularity data. For example, NIBE mainly contains the data regarding the waste scenario (end-of-life scenario) without the origin scenario (NIBE.INFO site), whereas Alba concepts' database covers both scenarios. Besides, as described earlier in **Chapter 2.3.4**, most assessment models require both the percentage by mass of material origin and destination after use, so this research adopts Alba Concepts' database. It should be noted that this research only publishes the building circularity data related to the case study since Alba Concepts' database is for commercial use.

3.4 The Results of Descriptive Study I

Descriptive Study I investigated and evaluated six technical calculation methods and six BIM-BCA integration approaches (three main streams and support tools). The findings contribute to determining the calculation method and BIM-BCA integration approach.

3.4.1 Assessment model for measuring the building's circularity

The assessment model used in the research intends to integrate the most valuable part of six investigated models. Based on the evaluation results for MCI (EMF, 2015b), BCI (Verberne, 2016; van Vliet, 2018), BCIX (Alba Concepts,2018), CI (Madaster, 2018b), Core method (Platform CB'23, 2019), the technical calculation method for building's circularity should meet the five requirements.

First, the assessment should be quantitative, assigning a specific value to the level of building's circularity. Second, it should cover the identified technical circular indicators as much as possible (**Table 3**). Apart from the indicators that are included by all calculation methods (e.g., the percentage by mass of virgin material in the total material input), the indicators that are mostly covered should also be taken into consideration (e.g., the percentage by mass of renewable material in the total input, circular building product level, and disassembly potential). Besides, the measurement of building's circularity should follow the hierarchy of the BCI model (Verberne, 2016), consisting of BCI, SCI, PCI, MCI (**Figure 15**). The reason is that a building as an entity is often considered to be made up of six different systems (i.e., site, structure, skin, service, space, and stuff), and each of them is composed of a group of products and materials (Verberne, 2016). Moreover, the way of assessing the disassembly potential of products should be in line with the new BCI model (van Vliet, 2018), which adopts the relational patterns as a framework (**Figure 16**). Last but not least, learned from the calculation method of Alba Concepts, the assessment results should also include the value of the individual indicator for the whole building (**Figure 17**). For example, the percentage by mass of virgin material in the total material input for the overall building. These values are included because having the value of all individual indicators will help project stakeholders understand how the final BCI score is generated. Subsequently, according to these five points, the following paragraphs specify the circular building product levels and then describes the specific steps and equations of the determined calculation methods.

Circular building product levels

Circular building product levels describe the hierarchy of material composition in a circular building. The main target of specifying the number of product levels is to define the boundaries for independent circular building product levels (Bakx et al.,2016). Moreover, it influences the scale of input from Bill of Material (BoM) (van Vliet, 2018). After integrating several classifications introduced in **Chapter 2.2.4.2**, this research distinguishes a building into nine levels, which is shown in **Table 7**.

Table 7: A practical example of the defined circular building product levels

Level	Description
Building	-
System (Layer)	Space plan
Sub-system	Internal wall
Element group	Internal wall, non-load bearing
Element	Internal wall, non-load bearing, system walls; fixed
Product	Internal wall, non-load bearing, system walls; fixed; timber frame_hsb_100mm
Component	Internal wall, non-load bearing, system walls; fixed; timber frame_hsb_100mm; structure_softwood
Material	softwood
Raw material	wood

Material Circularity Indicator for the product (MCI_P)

The calculation of MCI_p is as the same with that of BCI (Verberne, 2016; van Vliet, 2018), and BCIX (Alba Concepts,2018), which all build upon on MCI (EFM, 2015b). The MCI for a product α is calculated as follows:

$$MCI_{p(\alpha)} = \max\left(0, \left(1 - \left(\frac{\%V_{p(\alpha)} + \%W_{p(\alpha)}}{2}\right) \cdot \frac{0.9}{\frac{TL_{p(\alpha)}}{FL_{p(\alpha)}}}\right)\right)$$

Equation 1: Material Circularity Indicator for product α

Where:

$MCI_{p(\alpha)}$ is the Material Circularity Indicator for product α,

$\%V_{p(\alpha)}$ is the percentage by mass of virgin material in the total material input for product α,

$\%W_{p(\alpha)}$ is the percentage by mass of total waste material in the total material output for product α(including material send to landfill and incineration),

$TL_{p(\alpha)}$ is the technical lifetime(year) for product α, which refers to the lifetime that the product meets the technical requirements,

$FL_{P(\alpha)}$ is the functional lifetime(year) for product α, which refers to the lifetime the product meets the user's requirements.

Product Circularity Indicator for the product (PCI_p)

The calculation of PCI_p builds upon that of van Vliet (2018), which is obtained by multiplying MCI_P and Disassembly Potential for the product (DP_p). van Vliet (2018) takes into account seven DDF's that are created by Durmisevic (2006) (**Table 2**), whereas this research only includes two of them due to the limitation of time. These two DDF's are Type of Connection (TOV) and Accessibility to Connection (ATC). The former assesses the type of connection between products and comprises six main types with different weights (**Table 8**). The other one assesses the connections between products that can be physically accessed without demolishing (parts) of the products. It consists of five variables with different weights (**Table 8**). The reason for choosing TOV and ATC is that these two factors are the most mentioned and essential to products disassembly (van Vliet, 2018). Also, the calculation method of Alba Concepts (2018) only consider two DDF's. The PCI for a product α is calculated as follows:

$$PCI_{p(\alpha)} = MCI_{p(\alpha)} \cdot DP_{p(\alpha)}$$

Equation 2: Product Circularity Indicator for product α

$$DP_{p(\alpha)} = \frac{TOC_{p(\alpha)} + ATC_{p(\alpha)}}{2}$$

Equation 3: Disassembly potential for product α

Where

$PCI_{p(\alpha)}$ is the Product Circularity Indicator for product α,
$DP_{p(\alpha)}$ is the disassembly potential for product α,
$TOC_{p(\alpha)}$ is the score regarding the type of connection for product α,
$ATC_{p(\alpha)}$ is the score regarding the accessibility to the connection for product α.

Table 8: The variables and their weight of TOV and ATC (Durmisevic, 2006)

Disassembly factor	Factor weight	Attribute	Score
Type of Connection	1.0	Accessory external connection or connection system	1.0
		Direct connection with additional fixing devices	0.8
		Direct integral connection with inserts (pin)	0.6
		Filled soft chemical connection	0.2
		Filled hard chemical connection	0.1
		Direct chemical connection	0.1
Accessibility to Connection	1.0	Accessible	1.0
		Accessible with an additional operation which causes no damage	0.8
		Accessible with an additional operation which is reparable damage	0.6
		Accessible with an additional operation which causes damage not accessible	0.4
		Not accessible - total damage of elements	0.1

System Circularity Indicator for a system (SCI_s)

The calculation of SCI_s is a systematic value by aggregating all PCI_p for the number (s) of products in the same system. The mass of the product is selected to be a normalized factor to determine a weighted average of a product for SCI_s. The SCI for layer β is calculated as follows:

$$SCI_{s(\beta)} = \frac{1}{W_{s(\beta)}} \sum_{\alpha=1}^{s} PCI_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 4: System circularity indicator for system β

$$W_{s(\beta)} = \sum_{\alpha=1}^{s} W_{p(\alpha)}$$

Equation 5: Total product mass for system β

Where:

$SCI_{s(\beta)}$ is the system circularity indicator for system β,
$M_{p(\alpha)}$ is the total mass of product α,
$W_{s(\beta)}$ is the total product mass for system β.

Building Circularity Indicator (BCI)

Similar to the calculation of SCI_s, the BCI is the aggregation of all PCI_p in the building, and the product mass is selected to be the normalized factor to determine a weighted average of product for BCI.

The BCI is calculated as follows:

$$BCI = \frac{1}{W_B} \sum_{\alpha=1}^{n} PCI_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 6: Building Circularity Indicator

$$W_B = \sum_{\alpha=1}^{n} W_{p(\alpha)}$$

Equation 7: Total product mass of the building

Where:

BCI is the Building Circularity Indicator,
W_B is the total product mass of the building.

Expect for MCI_p, PCI_p, SCI_s, and BCI, 12 individual circularity indicators for the overall building are calculated by aggregating relevant indicators for a product and selecting product mass as the normalized factor to determine a weighted average of product.

Origin of material

$$\%V = \frac{1}{W_B} \sum_{j=1}^{n} \%V_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 8: Percentage by mass of virgin material in the total material input for the overall building

$$\%Reused = \frac{1}{W_B} \sum_{j=1}^{n} \%Reused_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 9: Percentage by mass of reused material in the total material input for the overall building

$$\%Recycled = \frac{1}{W_B} \sum_{j=1}^{n} \%Recycled_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 10: Percentage by mass of recycled material in the total material input for the overall building

$$\%B = \frac{1}{W_B}\sum_{j=1}^{n} \%B_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 11: Percentage by mass of biological material in the total material input for the overall building

Where:

$\%V$ is the percentage by mass of virgin material in the total material input for the overall building,
$\%Reused$ is the percentage by mass of reused material in the total material input for the overall building,
$\%Reused_{p(\alpha)}$ is the percentage by mass of reused material in the total material input for product α,
$\%Recycled$ is the percentage by mass of recycled material in the total material input for the overall building,
$\%Recycled_{p(\alpha)}$ is the percentage by mass of recycled materials in the total material for product α,
$\%B$ is the percentage by mass of biological material in the total material for the overall building,
$\%B_{p(\alpha)}$ is the percentage by mass of biological materials in the total material for product α.

Future scenarios of material

$$\%L = \frac{1}{W_B}\sum_{j=1}^{n} \%L_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 12: Percentage of by mass material sent to landfill in the total material output for the overall building

$$\%I = \frac{1}{W_B}\sum_{j=1}^{n} \%I_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 13: Percentage of by mass material sent to incineration in the total material output for the overall building

$$\%Recycleable = \frac{1}{W_B}\sum_{j=1}^{n} \%Recycleable_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 14: Percentage by mass of recyclable material in the total material output for the overall building

$$\%Reuseable = \frac{1}{W_B}\sum_{j=1}^{n} \%Reuseale_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 15: Percentage by mass of reusable material in the total material output for the overall building

Where:

$\%L$ is the percentage by mass of material sent to landfill in the total material output for the overall building,

$\%L_{p(\alpha)}$ is the percentage by mass of material sent to landfill in the total material output for product α,
$\%I$ is the percentage by mass of material sent to incineration in the total material output for overall building,
$\%I_{p(\alpha)}$ is the percentage by mass of material sent to incineration in the total material output for the product α,
$\%Recycleable$ is the percentage by mass of recyclable material in the total material output for the overall building,
$\%\%Recycleable_{p(\alpha)}$ is the percentage by mass of combustion material in the total material output for the product α,
$\%Reuseable$ is the percentage by mass of reusable material in the total material output for the overall building,
$\%Reuseale_{p(\alpha)}$is the percentage by mass of reusable material in the total material output for the product α.

MCI for the overall building

$$MCI_B = \frac{1}{W_B}\sum_{\alpha=1}^{n} MCI_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 16: Material Circularity Indicator for the overall building

Where:
MCI_B is the Material Circularity Indicator for the overall building.

The lifetime of the overall building

$$TL_B = \frac{1}{W_B}\sum_{j=1}^{n} TL_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 17: Technical lifetime for the overall building

$$FL_B = \frac{1}{W_B}\sum_{j=1}^{n} FL_{p(\alpha)\ j} \cdot W_{p(\alpha)}$$

Equation 18: Functional lifetime for the overall building

Where:
TL_B is the technical lifetime for the overall building,
FL_B is the functional lifetime for the overall building.

Disassembly potential of the overall building

$$DP_B = \frac{1}{W_B}\sum_{j=1}^{n} DP_{p(\alpha)} \cdot W_{p(\alpha)}$$

Equation 19: Disassembly potential for the overall building

Where:
DP_B is the disassembly potential for the overall building.

3.4.2 BIM-BCA integration approach

Based on the Descriptive Study I, a BIM-based framework was designed. It establishes an automatic and efficient link between the BIM model and external databases. Then, the BCA is conducted in a single BIM environment. Moreover, to realize the designed BIM-based framework and the chosen BIM-BCA integration approach, the Descriptive Study I provides three tools, namely external application, Dynamo for Revit, and Revit Add-in. Their main strengths and drawbacks are also given below.

In this research Dynamo for Revit is utilized as the essential tool to integrate BIM and BCA. The main reason for selecting Dynamo is that it is easy to access the Revit model and Excel (Kilkelly, 2018). Relying on this ability, it can realize the creation of an automatic and efficient link between the BIM model and external databases. Moreover, Dynamo for Revit is often used to test and simulate building performance during the design stage since it works like a Revit Plug-in and enables a real-time and instant assessment for Revit Model (Kilkelly, 2018). Also, the capability of automating repetitive tasks makes Dynamo suitable to conduct unlimited times of BCA during the design stages (Kilkelly, 2018). Instead of opening the Dynamo interface, Dynamo Player provides a simple way to execute Dynamo scripts in Revit, which automates and hastens the whole process.

Another significant reason for choosing Dynamo is its visual programming languages, which is a kind of programming language that allows computer programs to be manipulated graphically rather than textually (Mousiadis & Mengana,2016). It enables a simplified and user-friendly way to realize the functions just by connecting small blocks of independent functionalities into a whole system or procedure (Mousiadis & Mengana,2016). For the non-programmers or novice programmers, Dynamo for Revit is much easier to learn and understand compared to the conventional programming languages such as C# and Java. Thus, it not only helps the author develop a new prototype more feasibly but also benefit the successor who intends to improve this Dynamo prototype.

3.5 Conclusion

Firstly, this chapter describes the working method of the research and the motivation of each step. DRM, which consists of four main research stages, is adopted to give clear guidance about how this research is conducted. In the first stage: Research Clarification, the main research question and five sub-questions are established, then **Sub-Q1**, **Sub-Q2**, and **Sub-Q3** regarding building circularity indicators, measurement methods, and BIM-BCA integration approaches are answered in the second stage: Descriptive Study I. Subsequently, the stage of Prescriptive Study proposes a promising solution: a BIM-based framework and develops a prototype to achieve the desired situation. **Sub-Q4** is addressed in this stage. Lastly, the stage of Descriptive Study II answers the **Sub-Q5** through the validation of the prototype.

In addition to explaining how DRM helps to achieve the research goal, this chapter describes one of the vital research methods: A case study. A real project is employed to show how the developed prototype promotes the design of circular design from early design stages. Moreover, this chapter also illustrates how data is collected. Based on the research methods, the four stages use a different way of collecting data. The stage of Research Clarification and Descriptive Study I mainly rely upon the literature, while Descriptive Study II contains two primary data sources from the cooperating companies.

The last part of the chapter focuses on discussing two essential research results in Descriptive Study I: the assessment model for measuring building's circularity of the research and the BIM-BCA integration approach used in this research. Regarding the calculation method, it starts with MCI per product, followed by computation of PCI per product calculated by multiplying MCI and disassembly potential score per product. Subsequently, to aggregate the PCI of all products, the product mass is used as the normalized factor to calculate the SCI per layer. Then, like SCI, BCI is also obtained by aggregating all products' PCI based on their product mass. Lastly, the calculation gives the value of individual circularity indicators for the overall building. About the BIM-BCA integration approach, this research intends to utilize Dynamo for Revit to establish an automatic and efficient link between the Revit model and external databases, then conduct the BCA in Autodesk Revit. After that, based on the outcomes of the Descriptive Study I, the next chapter begins with the Prescriptive Study and proposes the BIM-based framework.

4. BIM-based Building Circularity Assessment (BCA) Framework

In the previous chapter, the BIM-BCA integration approach used in the research project is described. A BIM-based BCA framework is developed to automate the BCA process and provide the project stakeholders with the decision-making support regarding the design of the circular building from early design stages to realize this proposed solution. Although Dynamo for Revit is quite essential throughout the whole process of the proposed framework, it is closely related to the BIM environment provided by Revit and has a series of information exchanges with Revit and external information.

This chapter illustrates how this BIM-based framework works and provides an overview of the proposed BIM-BCA integration. The main procedures to conduct the BCA, the necessary information, the working environment of the framework as well as the involved actors are all described in detail.

4.1 Framework Introduction

To clearly illustrate how the framework works, this section draws a process map to identify the performed activities, their sequence, the primary actors (e.g., designers, project managers), and the exchanged information within the process. Moreover, the process map enables to show the start and end events, the event where there is an information exchange, and decisions (**Figure 24**). As can be seen, the process map of BIM-based BCA framework consists of three swimming lanes, namely design team (the main actor that may include architect, structure designers, BIM modeller and more.), Autodesk Revit (the working environment), and exchanged information. The swimming pool of the design team contains three key objects: the activities that describe the work tasks such as “Create a conceptual design”, the event that shows the time of the notable event, and gateways that refer to the decision-making points. Besides, the other swimming pools only contain the data objects, which define the exchanged information.

The process starts when the designer team creates a conceptual model, which can be modelled either in Revit directly, or firstly in other authoring software like SketchUp and then imported or remodelled in Revit. Once the conceptual model is obtained, the design team continues the preliminary design phases, when there are various design options. For example, the choice of materials, building components, structure types, and more. Since these design options may have a different level of circularity, it is necessary to conduct BCA for them. Before the BCA, the design team needs to load tab-delimited text files of NL-SfB classification schema and disassembly potential classification into Revit through “Assembly code” and “Keynotes”, respectively. Then, each product of the BIM model has to be assigned with corresponding classification code and disassembly code. These procedures play a significant role in creating an automatic link between the BIM model and building circularity data stored in external databases. The details are elaborated in **Chapter 4.2.** Subsequently, the design team employ the BCAS tool, which is a Dynamo porotype, to conduct BCA for different design options. The outcomes of BCA are displayed in the Revit interface in the form of a 3D model or charts. Based on the assessment results regarding the circularity level of design, project stakeholders enable to make efficient decisions. After that, the design team goes on developing the design.

The primary working environment of the proposed BIM-framework is Autodesk Revit, so the proposed solution mainly servers the Autodesk Revit users. Two vital features of Revit used in the BIM-based framework are Phasing and Design option. Phasing allows the existence of the complete life cycle of a project, while Design option enables Revit to save multiple iterations of a concept in a single project file. Thus, through utilizing Phasing and Design option, the BIM models in different design stages with various design options can exist in one Revit file. Using these features contribute to avoiding the overabundant procedures like changing to diffident Revit files, leading to the improvements of BCA’s efficiency.

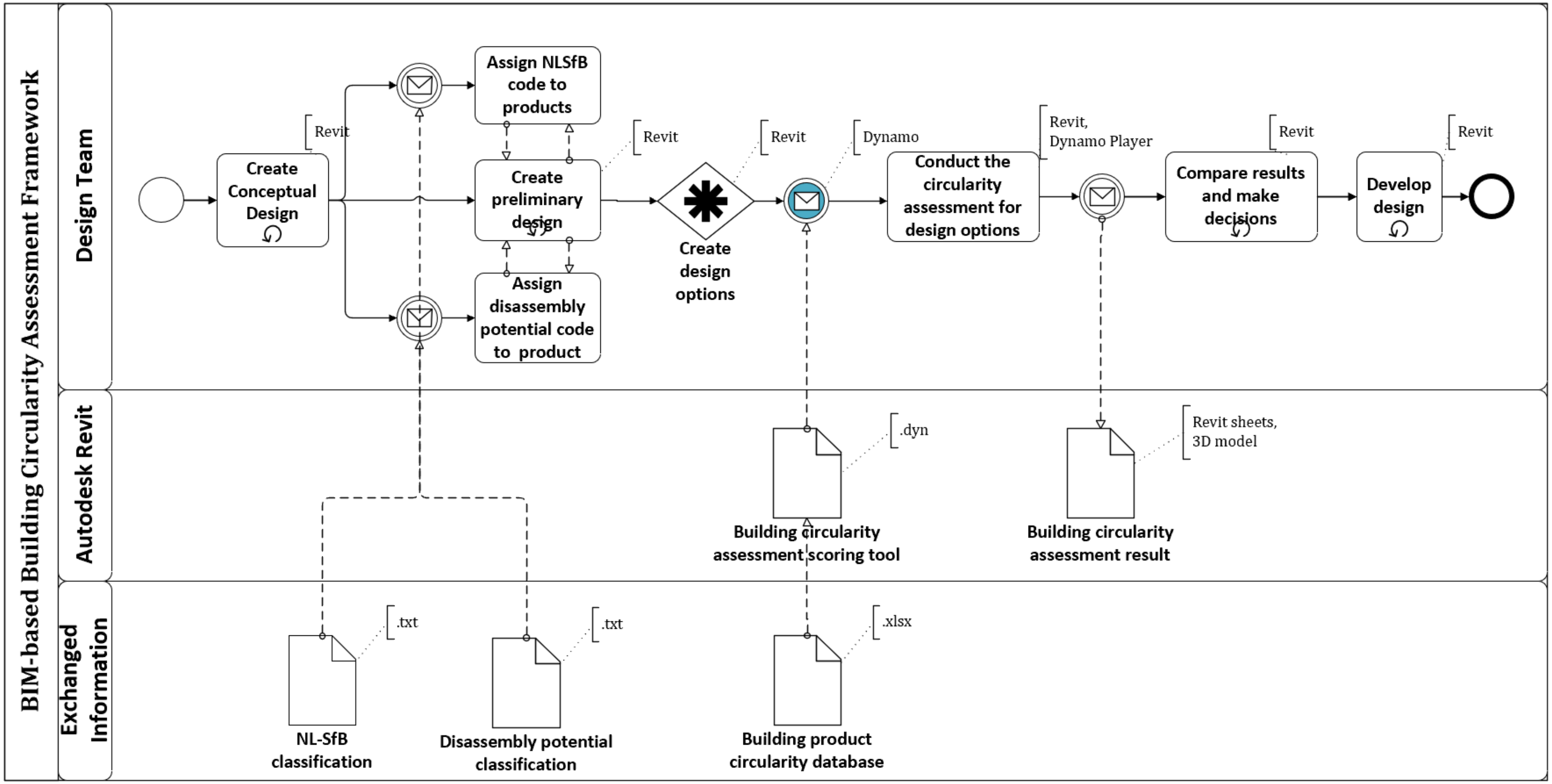


Figure 24: The process map of BIM-based framework

4.2 Exchanged Information

The third swimming lane: Exchanged information, contains three significant files that are exchanged between activities in the BIM-based BCA framework. These files are NL-SfB classification, disassembly potential classification, and building product circularity database. The first two files are the tab-delimited text file, and the database is stored in the Excel file. This section aims to describe the specific information with respect to the aforementioned files in detail.

4.2.1 NL-SfB

NL-SfB classification schema

It is of importance for the BIM-based BCA framework to utilize classification to identify building elements such as their type and location, as well as realize an automated and bidirectional link with the circularity data. The research adopts the NL-SfB classification schema since it is widely applied in the Dutch construction and installation industry to code layers and element in BIM and CAD systems (BIM Loket-NL-SfB, 2020). NL-SfB is derived from the Swedish committee (the abbreviation SfB comes from Samarbetskommittén för Byggnadsfragor), and consists of five tables, namely *Table 0* to *Table 4*, each of them contains different definitions. Table 0 represents the built environment of buildings, including the building types, residential areas, and spaces. Table 1 includes the codes that indicate the functional parts of the building and the location of products in the building, while the code in *Table 2* and *Table 3* represent different construction methods and building materials, respectively. Lastly, *Table 4* shows the building activities properties. These tables utilize a different number of digitals or the combination of letters and digitals to attach the information to building elements (BIM Loket-NL-SfB, 2020). As seen in **Figure 25**, they are filled into the boxes from left to right based on the sequence of *Table 0* to *Table 4*. For example, the NL-SfB code in **Figure 25** refers to an outer wall (21) of an office facility (32). This exterior wall is masoned (F) with baked clay (g2). P2 indicates that the performance of this wall is sound insulation (NL-SfB codering, 2020).

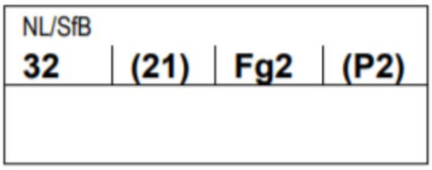


Figure 25: An example of NL-SfB format (NL-SfB codering, 2020)

Circular building product levels and NL-SfB classification code

Based on the needs of companies or organizations, it is flexible to adopt the NL-SfB classification schema. For example, the NMD uses NL-SfB code 21.02.001 to represent the systems' walls that are made of steel frame element and European softwood plywood (Nationale Milieudatabase Stichting Bouwkwaliteit, 2020). Based on the classification for circular building product levels, the research employs a customized NL-SfB coding system structure that is made of four groups. It is applied to indicate the different levels of the building. **Table 9** uses a specific example to illustrate the correspondence between circular building product levels and the customized NL-SfB coding system.

The classification starts from the sub-system level that represents a collection of an element group, using the first group of NL-SfB. For example, '22' means the internal wall. Then, the level of the element group and the element use the second group of NL-SfB to classify further and specify the building elements. So far, the above classification adopts the NL-SfB classification schema *Table 1*. For the product level, the classification code is customized in this research and used to distinguish different type of products in the building. For instance, '22.11.1' represents the 100mm timber frame internal wall that is non-load bearing and fixed. One step lower is the component level, which specifies the assemblies that are made of different materials. Together with material level and raw material level, the fourth group adopts NL-SfB classification schema *Table 3*.

Table 9: An example to explain the definition of building levels and classification system

Circular building product level	Classification code	Description
Building	-	
System(layer)	-	Space plan
Sub-system	22.XX.XX.XX	Internal wall
Element group	22.1X.XX.XX	Internal wall, non-load bearing
Element	22.13.XX.XX	Internal wall, non-load bearing, system walls; fixed
Product	22.11.1. XX	Internal wall, non-load bearing, system walls; fixed; timber frame_hsb_100mm
Component	22.11.1.i2	Internal wall, non-load bearing, system walls; fixed; timber frame_hsb_100mm; structure_softwood
Material	i2	softwood
Raw material	i	wood

The NL-SfB classification can be loaded into Revit through "Assembly Code" function in Revit, making it easy to choose from a list of available codes. The specific loading procedures are put in **Appendix III**. The latest version of the NL-SfB file is supplied by the Nederlandse Revit Standards (NLRS)2.5.2. The research builds upon this NL-SfB file and revises it based on the structure of the building product circularity database. The NL-SfB files can be found through the link provided below:

https://www.dropbox.com/sh/hqdxnloqzxoy3nh/AACcwHo0hbUNO-xJrooWg-U7a?dl=0

4.2.2 Disassembly potential classification

The main purpose of making the disassembly potential classification is to accelerate the assessment process. Like the NL-SfB classification, disassembly potential classification is also loaded into Revit but through the "Keynote" function. The specific loading procedures are put in **Appendix III**. Thereby, the design team can choose the most probable disassembly way for each product by choosing from a list of available codes. The following paragraphs explain how the disassembly potential classification is obtained.

Firstly, as mentioned in **Chapter 3.4.1**, this research involves two DDF's when assessing the disassembly potential for a product. One is TOC with six types, and the other one is ATC with five types. Based on their categories, the research gives each type a unique code (**Table 10**). For example, the code of "Direct chemical connection" is TOC6. Next, the research puts thirty possible disassembly types forwards after integrating TOC and ATC (**Table 11**). Each of them is assigned a unique disassembly code, which consists of two groups separated by a period. The first group represents the type of TOC, while the second group refers to the type of ATC. For example, if a product's TOC is "Filled soft chemical connection" and ATC is "accessible", its disassembly code is TOC4.ATC1. Moreover, according to **Equation 3**, the score of the disassembly types in **Table 11** is calculated by the average of the score of TOC and ATC. The file of disassembly potential classification that is loaded into Revit can be found through the link provided below:

https://www.dropbox.com/sh/hqdxnloqzxoy3nh/AACcwHo0hbUNO-xJrooWg-U7a?dl=0

Table 10: The types and codes for DDF's: TOC and ATC (E. Durmisevic et al., 2006)

DDF'S	Types	Score	Code
Type of Connection	Accessory external connection or connection system	1.0	TOC1
	Direct connection with additional fixing devices	0.8	TOC2
	Direct integral connection with inserts (pin)	0.6	TOC3
	Filled soft chemical connection	0.2	TOC4
	Filled hard chemical connection	0.1	TOC5
	Direct chemical connection	0.1	TOC6
Accessibility to Connection	Accessible	1.0	ATC1
	Accessible with an additional operation which causes no damage	0.8	ATC2
	Accessible with an additional operation which is reparable damage	0.6	ATC3
	Accessible with an additional operation which causes damage not accessible	0.4	ATC4
	Not accessible - total damage of elements	0.1	ATC5

Table 11: Disassembly potential code, description and score.

Disassembly Type	Disassembly Code	Score
Accessory external connection or connection system		
Accessible	TOC1. ATC1	1
Accessible with additional operation which causes no damage	TOC1. ATC2	0.9
Accessible with additional operation which is reparable damage	TOC1. ATC3	0.8
Accessible with additional operation which causes damage	TOC1. ATC4	0.7
not accessible - total damage of elements	TOC1. ATC5	0.55
Direct connection with additional fixing devices		
Accessible	TOC2. ATC1	0.9
Accessible with additional operation which causes no damage	TOC2. ATC2	0.8
Accessible with additional operation which is reparable damage	TOC2. ATC3	0.7
Accessible with additional operation which causes damage	TOC2. ATC4	0.6
not accessible - total damage of elements	TOC2. ATC5	0.45
Direct integral connection with inserts (pin)		
Accessible	TOC3. ATC1	0.8
Accessible with additional operation which causes no damage	TOC3. ATC2	0.7
Accessible with additional operation which is reparable damage	TOC3. ATC3	0.6
Accessible with additional operation which causes damage	TOC3. ATC4	0.5
not accessible - total damage of elements	TOC3. ATC5	0.35
Filled soft chemical connection		
Accessible	TOC4. ATC1	0.6
Accessible with additional operation which causes no damage	TOC4. ATC2	0.5
Accessible with additional operation which is reparable damage	TOC4. ATC3	0.4
Accessible with additional operation which causes damage	TOC4. ATC4	0.3
not accessible - total damage of elements	TOC4. ATC5	0.15
Filled hard chemical connection		
Accessible	TOC5. ATC1	0.55
Accessible with additional operation which causes no damage	TOC5. ATC2	0.45
Accessible with additional operation which is reparable damage	TOC5. ATC3	0.35
Accessible with additional operation which causes damage	TOC5. ATC4	0.25
not accessible - total damage of elements	TOC5. ATC5	0.1
Direct chemical connection		
Accessible	TOC6. ATC1	0.55
Accessible with additional operation which causes no damage	TOC6. ATC2	0.45
Accessible with additional operation which is reparable damage	TOC6. ATC3	0.35
Accessible with additional operation which causes damage	TOC6. ATC4	0.25
not accessible - total damage of elements	TOC6. ATC5	0.1

4.2.3 Building product circularity database

It is necessary to have the building's circularity data to conduct the BCA. Like the national database: NIBE and NMD, this research also constructs the building's circularity database at the product level. Thus, this database is called "Building product circularity database". The structure of the database is based on NL-SfB classification schema *Table 1*. **Table 12** gives an example to illustrate the basic structure of the database. As can be seen, the information in the left two columns derives from NL-SfB classification schema *Table 1*, and under each category, different types of products are listed with unique product ID and name in the right two columns.

Table 12: An example of the structured product circularity database

NL/SfB	Description	Product ID	Product name
16	Retaining walls, Foundations		
16.12	Foundations, footings and strips, foundation strips		
		16.12.1	Concrete, foundation beam.
		16.12.2	Brick, foundation beam
		16.12.3	Sand-line brick foundation
		…	

Except for the classifications, the database also includes the specific circularity data for each product. **Table 13** shows an example. As can be seen, the left part is the basic information of the product, including the product ID, product name, description, layers of Brand, weight. The right part contains all inputs that are used to calculate MCIp. Information includes the percentage by mass of material origin (i.e., virgin, reused, recycled, and biological), the percentage by mass of future scenario (i.e., landfill, incineration, recyclable and reusable), and the lifetime (i.e., technical lifetime and functional lifetime) of product.

Table 13: Example of product in circularity database

Product Information	
Product ID	16.12.1
Product Name	Concrete, foundation beam.
Description	Supplier Beton, poured in work, C20 / 25; incl. Reinforcement, Technical condition.
Layer of Brand	Structure
Weight(m3/kg)	2400

The Origin Scenario	
Virgin (%)	100%
Reused (%)	0%
Recycled (%)	0%
Biological (%)	0%
The Future Scenario	
Landfill (%)	1%
Incineration (%)	0%
Recyclable (%)	99%
Reusable (%)	0%
Lifetime	
Technical lifetime(yr)	75
functional lifetime(yr)	75
MCI*p*	0.55

4.3 Design for Changes

A significant precondition of this proposed BIM-framework is the building product circularity database. It is complete enough for the design team to choose from and assign relevant classification code for the element in the model. However, it is inevitable that the database lacks the circularity data for some products, making it impossible for the design team to assign relevant classification code to the product in the BIM model. In such a context, the building product circularity database and classification files must be updated. The updating process involves circularity experts, who provide the required product circularity data and relevant circular products by using their professional knowledge in building circularity. As can be seen in **Figure 26**, this update process is also displayed as a process map. Firstly, the design team sorts out the list of products categories that need to be added. Once circular experts receive the list, they will provide the circularity data for required products. Along with updating the building product circularity database, it is also necessary to revise NL-SfB files to be in line with the database. After finishing the update, the design team can continue assessing the circularity of their design and goes on developing BIM models.

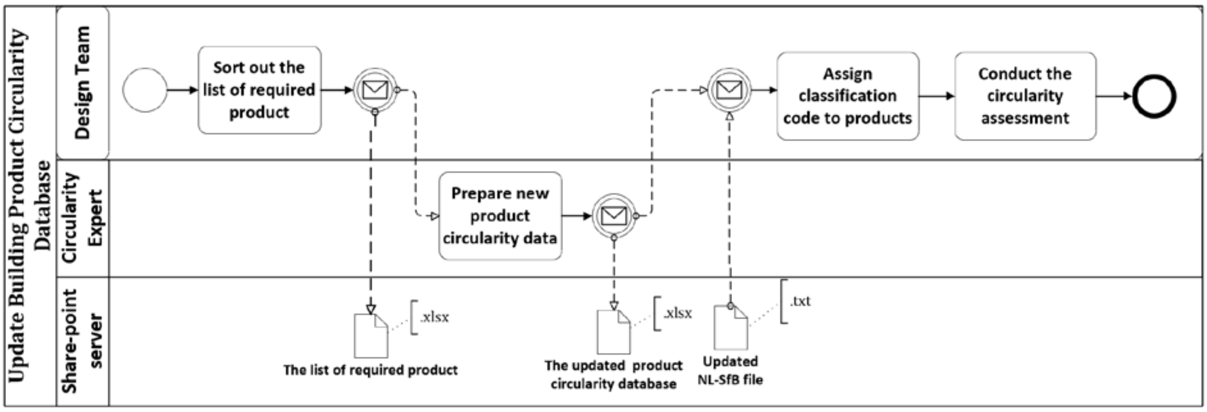


Figure 26: Update product circularity data process

4.4 Conclusion

This chapter describes the whole process of the proposed BIM-based BCA framework, its primary exchanged information, and the process when the update occurs during the BCA. There are three key points. Firstly, the research develops a customized NL-SfB classification schema, which falls under the defined circular building product levels. Additionally, a new disassembly potential classification, which involves thirty disassembly types and assigns each type a unique disassembly code and relevant disassembly score. Most importantly, the research makes the disassembly classification in a tab-delimited text file and load it into Revit through "Keynote". Then, it allows project stakeholders to choose the disassembly type for the product by selecting from a list of codes. Thereby, the assessment process could be accelerated. Last but not least, it is vital to follow the sequence of tasks that are defined in the framework. For example, NL-SfB code and disassembly code of the products in the BIM model must be provided before conducting the BCA. This is because they play a significant role in establishing linkage with the external database. Next, Chapter 5 will describe the design and development process of the BCAS too

5. Building Circularity Assessment Scoring (BCAS) Tool

The previous chapter described the BIM-based framework that aims to promote circular design from early design stages. The essential part of this framework is the use of BCAS tool to provide each design option with the quantitative assessment. This tool is a parametric design script, which has the advantages of instant analysis and feedback, as well as creating a permanent link between the Revit model and the external circularity data. This chapter focuses on describing the design and development process of this prototype, starting with the building blocks that are necessary to know. This part encompasses the functional requirements, technical setup and the hierarchy of the Revit model, followed by the system architecture to show the overview of the structure of the prototype, which mainly consists of three parts. Subsequently, these individual parts are elaborated.

5.1 Building Blocks

5.1.1 Functional requirements

Before developing the BCAS tool, its functional requirements should be specified. Learning from the literature, this section lists the essential requirements in the running environment, assessment content and graphical user interface (GUI) (**Table 14**). Also, the functions that should be achieved to meet the requirements are described. About the running environment, the Research Clarification and Descriptive Study I identified the need for tools that act as plugins for a specific BIM design software and allow an instant evaluation. Thus, the running environment of the prototype should be capable of performing real-time assessment and providing users with a single software environment. Furthermore, regarding the assessment content, it should be in line with the determined assessment model in the research (**Chapter 3.4.1**). Moreover, for the GUI, the way to visualize and interpret the results should be comprehensive and straightforward. The GUI is required to cover all assessment content. The design to meet the other requirement "straightforward" can learn from some existing BCA tools, such as the Madaster platform (Madaster, 2018a). They usually adopt the form of charts with annotation to display the results. Besides, Di Biccari et al. (2019) have visualized the circularity level of building through 3D geometry with a different colour, which is also easy to understand.

Table 14: The overview of requirements for the prototype and corresponding functions

Aspects	Requirements	Functions
Running environment	Real-time assessment	-The tool can update the analyzed results instantly once running the prototype. -The tool can remove users' manual procedures. -The tool can automatically obtain BoM;
	Single BIM software environment	-The tool can conduct the assessment in a single BIM software.
Assessment content	Circular flow of material	-The tool can analyze the material input and output, like the virgin, secondary materials, the material for reuse and recycle, and more.
	Disassembly potential	-The tool can assess the disassembly potential for product and building.
	Think in system	- The tool can calculate the building' circularity at a different level of composition.
	Complete	-The tool can calculate the value of the individual indicator for the overall building.
GUI	Comprehensive	-The tool can display all assessment contents.
	Straightforward	-The tool can generate the analysis results in the form of a chart. The tool can generate the analysis results in the form of a 3D model.

5.1.2 Technical setup

As mentioned before, the BCAS tool utilizes Dynamo for Revit, a visual programming language (VPL) platform. It can be downloaded and run as a plug-in for Revit. Using Dynamo to create the visual program, it is important to apply the nodes with different functions. Those nodes are located in the library. They include the default nodes that come with the installation as well as any additionally loaded custom nodes or packages. **Table 15** provides an overview of used Dynamo packages and their area of application in the research. Furthermore, Python script is available in Dynamo's visual programming environment. The use of Python can extend the capabilities of Dynamo and simplify the cluttered visual program. During the development of the BCAS tool, the author created some python script nodes apart from the loaded Dynamo packages. All customized Python script nodes are in **Appendix IV**.

Table 15: Used Dynamo published packages in the BCAS tool

Packages	Version	Description
Archilab_Bumblebee	2020.2.1	An Excel and Dynamo interoperability plugin that vastly improves Dynamo's ability to read and write Excel files.
Clockwork	1.0.3	Clockwork contains many Revit-related nodes, but also lots of nodes for various other purposes such as list management, mathematical operations, string operations, geometric operations and panelling.
LunchBox	2019.11.11	LunchBox is a collection of computational design tools for Grasshopper and Dynamo.
Archi-lab	110.0.2	Archi-lab is a collection of over 50+ custom packages that vastly extend Dynamo's ability to interact with Revit. Nodes contained in Archi-lab package vary from basic list operations to advanced analysis visualization framework nodes for Revit.
Rhythm	2017.1.8	Rhythm primarily consists of out of the box Dynamo nodes used in creative ways as they apply to the Revit environment.
Springs	110.0.2	The main focus of Spring Nodes is to improve the interaction between Dynamo and Revit. The larger goal is to explore all methods that help speed up the BIM priority workflow. Many nodes use IronPython or DesignScript, which are a good starting point for learning specific syntax and the best starting point for both.
Bakery	2019.5.8	The bakery is a real mixture. Some completely custom jobs, such as XML reader with ElementTree, and many derived jobs, which rely heavily on other packages such as Clockwork, Lunchbox and archi-lab.

5.2 System Architecture

This section gives an overview of the prototype's development process. **Figure 27** depicts its system architecture through a diagram, which consists of three primary parts: data preparation, data analysis, and data visualization. Firstly, during the process of input, data are collected from two primary sources:(1) The BIM model in Autodesk Revit and (2) Building circularity product database in Excel. This BIM model not only provides the geometric data such as the volume and the area which are necessary to calculate the building circularity but also include the classification code to identify building elements. The external database contains the building product circularity data, which is stored in an excel file. It should be noted that this database shares the same classification system as the Revit model: the customized NL-SfB classification schema. The type of data in the database is displayed in **Table 13**.

After preparing two primary data sources, the next step is to create the scripts in Dynamo VPL environment. (3) The information (e.g., NL-SfB, area, volume, disassembly code) from the BIM model is extracted. In the Meantime, the Dynamo script (4) imports the external database into Dynamo VPL environment. Subsequently, it is significant to (5) link the data from the BIM model with the external database by NL-SfB code. Also, Dynamo scripts match disassembly scores to disassembly types through disassembly codes. Next, (6) the calculation is conducted with the help of Dynamo. Lastly, the assessment results of the design are visualized through (7) automatically generating a pop-up window in the Revit interface, and (8) representing the 3D model with different colours. The specific description for three individual parts is elaborated in the next chapter.

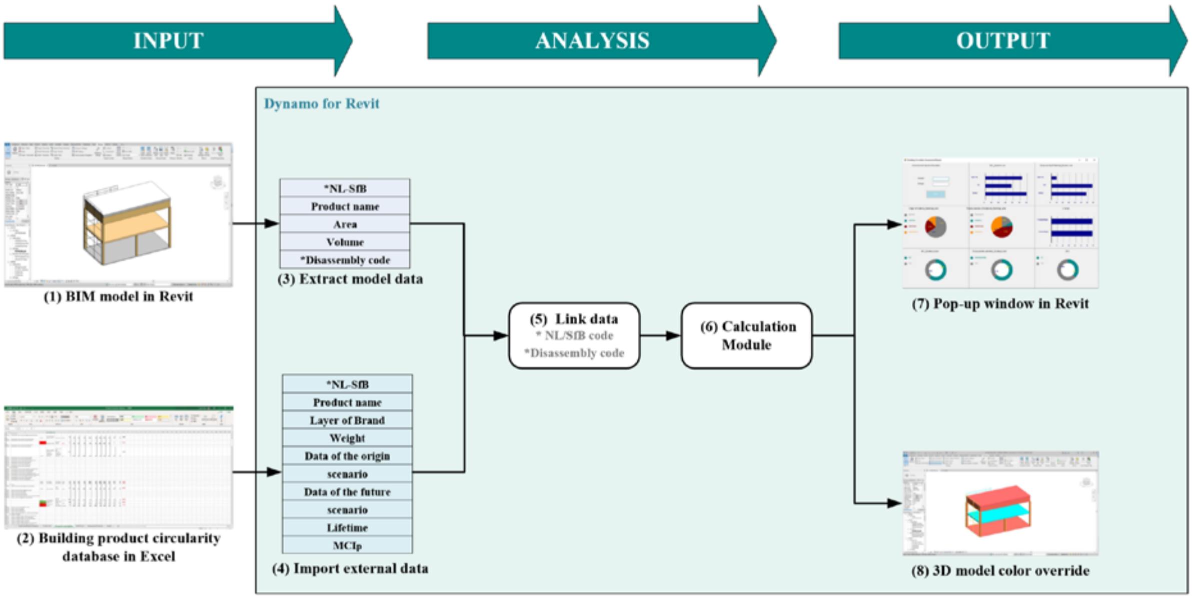


Figure 27: System architecture of the BCAS tool

5.3 Dynamo Script

Following the structure of the system architecture (**Figure 27**), the Dynamo scripts are created. They consist of four main parts, namely, import data, link data, calculation, and visualization (**Figure 28**). Each part contains a group of nodes to perform the required task.

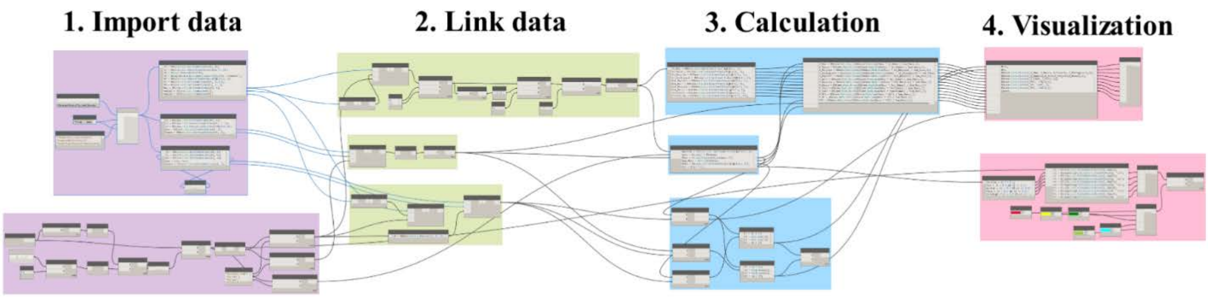


Figure 28: Full graph of the BCAS Dynamo scripts

5.3.1 Import data

Exact data from the BIM model in Revit

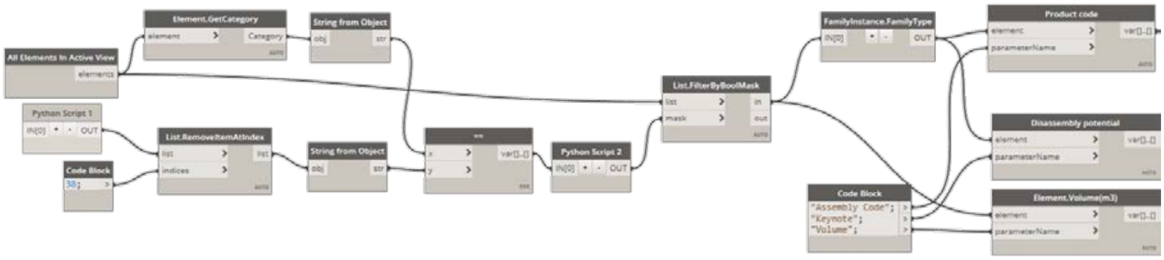


Figure 29: Dynamo scripts to exact data from the BIM model in Revit

This part extracts the data stored in the BIM model (i.e., the NL-SfB code, disassembly potential code, volume, and area). First, it utilizes the 'All Elements in Active View' node to select all elements in the active view of Revit. With this node, the BCAS tool is capable of capturing any design change. It should be noted that all types of elements in Revit (i.e., model elements, datum elements, and view-specific element) are chosen. However, only the model element, which is the 3D geometry of the design (e.g., wall and window), is needed. Thus, the 'Element.GetCategory' node, 'List.FilterByBoolMask' node, 'Python Script 2 (i.e., true for any)', and more are used to filter out the unnecessary elements (i.e., datum elements and view-specific element). Finally, the 'Parameter.ParameterByName' node is employed to get the values of determined parameters, including assembly code, Keynote, and the volume.

Import data from product circularity database in Excel

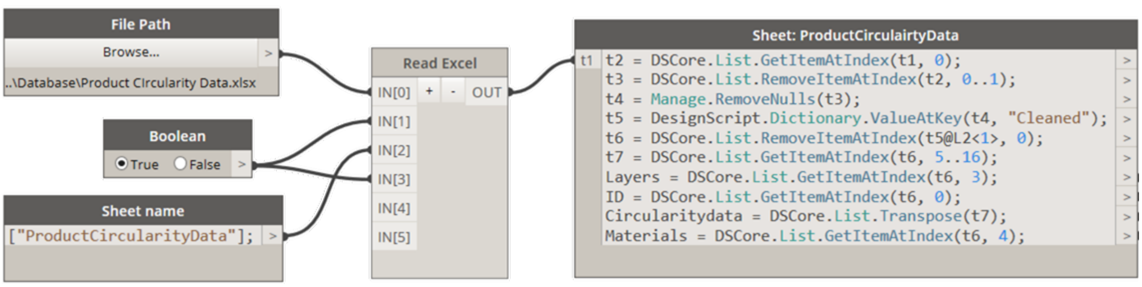


Figure 30: Dynamo scripts to import data from excel

This part imports the building product circularity data from the Excel into Dynamo VPL environment. The 'Read Excel' node plays an essential role in reading an external excel file. After connecting it with the 'File Path' node, the 'Boolean' node, and the 'Sheet name' code block, the Excel sheet of building product circularity database can be loaded into Dynamo by column. Next, the 'Sheet: ProductCircularityData' code block contains a series of scripts. It is used to categorize the circularity data based on their types (e.g., layers, NL-SfB code, circularity data).

5.3.2 Link data

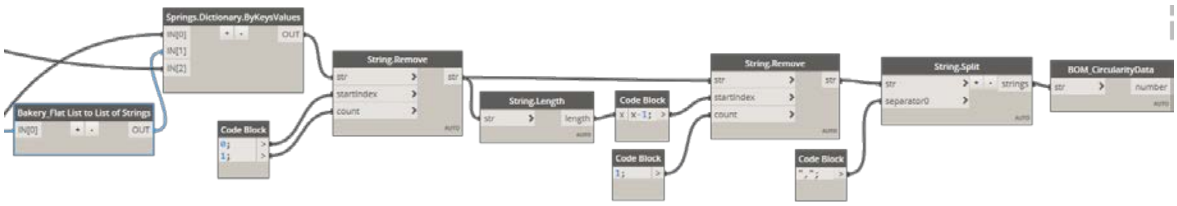


Figure 31: Dynamo script to link two databases by NL/SfB code

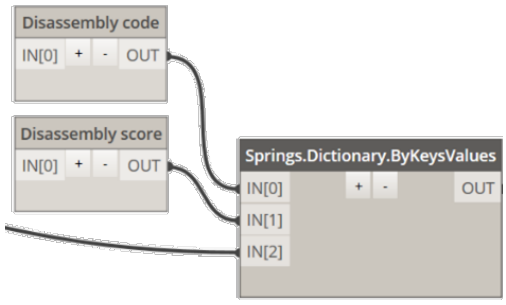


Figure 32: Dynamo script to link two databases by disassembly potential code

This part contributes to linking between all products in the BIM model and their corresponding circularity data. It consists of two components, which are displayed in **Figure 31** and **Figure 32**, respectively. The former intends to connect the BIM model with the circularity data from Excel file by NL-SfB code. The other one links between products' disassembly types in the BIM model and the disassembly scores. It creates two customized python nodes, which stores all disassembly codes and disassembly scores in **Table 11.** Similarly, the Dynamo scripts in **Figure 31** and **Figure 32** both utilize the key 'Spring.Dictionary.ByKeysVaules' node to realize the linkages.

5.3.3 Calculation

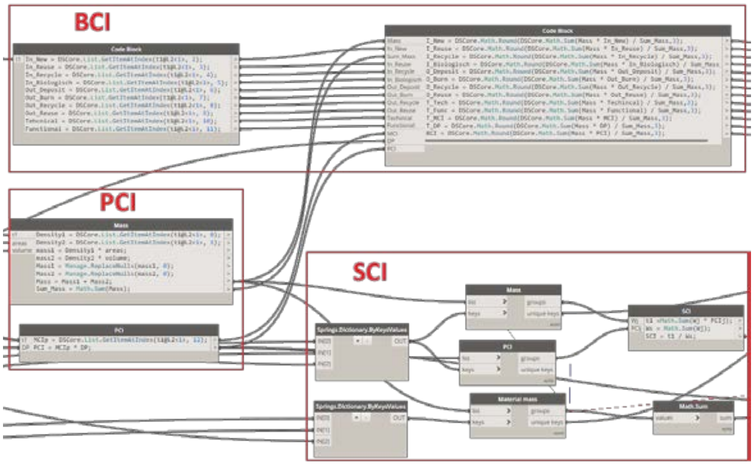


Figure 33: Dynamo scripts of the calculation module

This part performs the calculation of building' circularity from different levels (i.e., product, system, and building). As shown in **Figure 33**, the Dynamo scripts consist of three primary components, namely the calculation for PCI, SCI, BCI. Firstly, based on **Equation 2**, all PCIs are calculated in the 'PCI' code block, which also includes the calculation of the total mass of products. This is followed by the calculation of SCI of per system. It mainly employs a key 'Group.ByKey' node to classify products into different systems based on the layer they belong to. Then, according to **Equation 4** and **Equation 5**, the SCI of per system is calculated. Lastly, the Dynamo scripts for BCI utilize two code clocks to compute **Equation 6** to **Equation 16**.

5.3.4 Visualization

Pop-up window

Figure 34: Dynamo scripts of the pop-up window

This part designs the GUI of the pop-up window. As shown in **Figure 34**, the Dynamo scripts only contain two nodes. The 'Input' code block sorts out the values of indicators, which is visualized through the 'Window design' python node. As a result, the GUI of the pop-up window displays in **Figure 35**. It is composed of nine components: (i) Assessment report information, (ii) Material mass, (iii) SCI, (iv) Overall origin of the material, (v) Overall future scenarios of material, (vi) Overall lifetime, (vii) Overall MCI, (viii) Overall disassembly, (ix) BCI. These parts are elaborated in the following paragraphs.

- **Assessment report information**

This component gives users access to save the assessment results into the draft view of the Revit interface. The textbox *Vision* enables users to define the save path, name, and the format of saved image, while the textbox *Changes* enables users to distinguish different assessment of design options by brief input description such as steel structure. The *Save* button allows users to achieve the functionality of screenshotting the pop-up window and save it as an image.

- **Material mass**

This component is a horizontal bar graph that shows the type of raw materials and their total usage(mass) in the design. For instance, **Figure 35** shows there are three types of material, namely glass, concrete, and wood. Concrete is the dominant materials in the model with more than 40,000 kg, whereas glass the least material. The usage of the material is a significant indicator that affects the measurement of circularity, and this chart is designed to help users to know which materials have the most potential to influence the building' circularity.

- **SCI**

The panel is a horizontal bar chart that reflects the SCI of per layer (e.g., Skin). The value of the SCI ranges from 0 to 1, where the higher value means a higher level of circularity. As seen in **Figure 35**, the structure of the design has the highest SCI with the value of over 0.4. This is followed by the space plan with around 0.4, while there is the lowest SCI in the site. Based on this graph, users enable to know the circularity level of each layer. Thus, they can focus on improving these layers with lower SCI.

- **Overall origin of the material**

This component is a pie chart that shows the percentage by mass of the overall origins of the material. The chart presents the percentage by mass of four types of material in the total material input, namely the virgin material, reused material, recycled material, and biological material. As shown in **Figure 35**, the virgin material has the largest proportion (68.88%), followed by recycled material (22.09%). Furthermore, there is no reused material. As described prior in **Chapter 2.3.2**, more secondary materials and fewer primary materials could contribute to a higher circularity, and vice versa. Hence, this pia chart intents to provides users with more insights about the reason behind the BCI score.

- **Overall future scenarios of material**

This panel is also a pie chart but displays the percentage by mass of the overall future scenarios of materials, which encompasses landfill, incineration, recycle, and reuse. As shown in **Figure 35**, around 60% of materials will be sent to the landfill, and 4% of materials will be incinerated. Moreover, there are only around 36% of the materials will be reused and recycled after the end-of-life. Based on this pie chart, it can be concluded that more materials will be identified as waste after the end-of-life, lowering the BCI score of the design. Thus, these statistics can also give users some ideas about the reason behind the final BCI score.

- **Overall lifetime**

This component is a horizontal bar chart that shows the overall lifetime of the design. The technical lifetime and functional lifetime are computed. As shown in **Figure 35**, the technical lifetime and functional lifetime of the design both are around 32 years.

- **Overall MCI, disassembly potential, and BCI**

This last row of GUI consists of three doughnut charts, which represent the overall scores of MCI, disassembly potential, and BCI, respectively. As displayed in **Figure 35**, the assessment results show that the overall MCI is 42.3%, the overall disassembly potential is 34.8%, and the overall BCI is only 17.5%. These figures can provide users with a straightforward summation of assessment results.

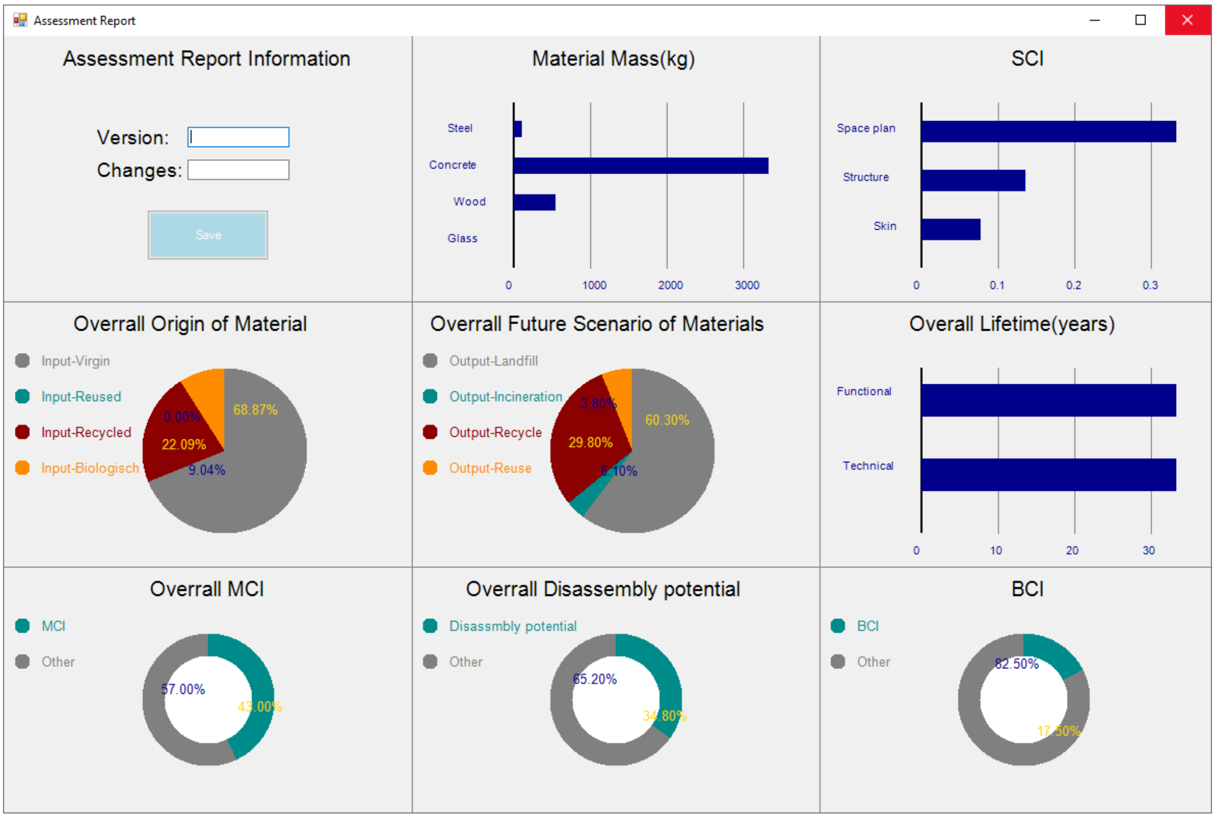


Figure 35: GUI of the BCAS tool

3D visualization

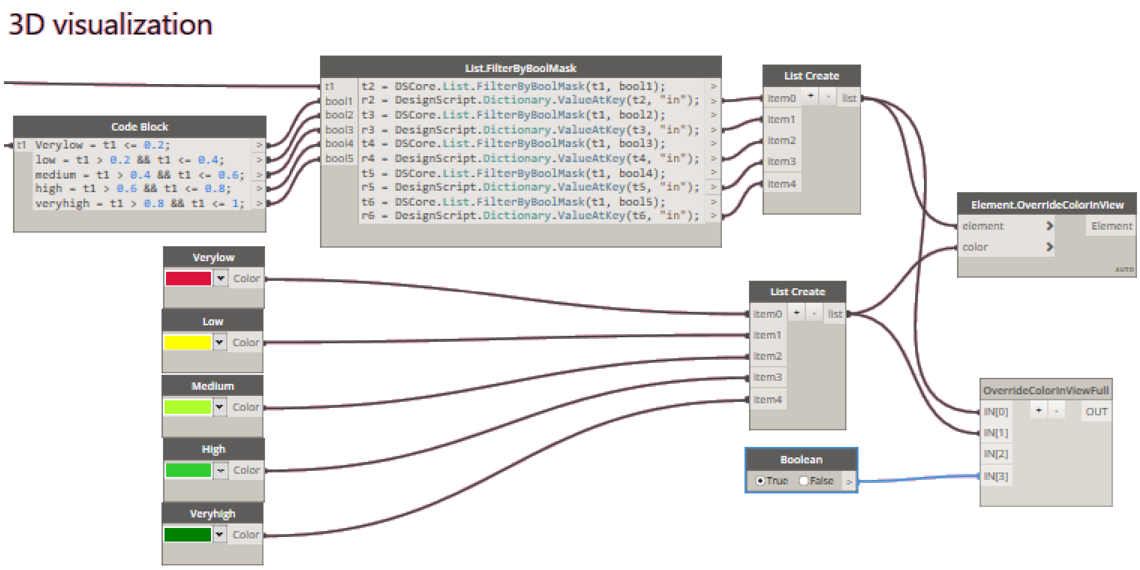


Figure 36: Dynamo scripts of 3D visualization

Figure 36 gives a rank to each element in the BIM model based on its value of PCI and overrides it by different colours. Firstly, a custom code block puts PCI into five levels, and each level has a different range of values, which is defined in **Table 16**. Furthermore, five 'Color Palette' nodes, which represent dark green, light green, yellow, orange, and red, respectively, are assigned from Class 1 to Class 5. Next, the 'List.FilterByBoolMask' code block categories all identified products based on the defined PCI classification. Finally, the key 'Element.OverrideColorInView' node achieves the function of overriding elements by colour. Also, the 'OverrideColorInViewFull' node controls the switch between regular 3D Revit model and the override 3D Revit model. **Figure 37** shows an example of the override 3D Revit model. As can be seen, the floors have very low PCIs. Therefore, users should improve the circularity level of the floors, maybe by replacing them with more circular floors.

Table 16: Five PCI classes with their range of value and colour

Class	Description	PCI	Colour
1	Very high	0.8 – 1.0	
2	High	0.6 – 0.8	
2	Medium	0.4 – 0.6	
4	Low	0.2 – 0.4	
5	Very low	0.0 – 0.2	

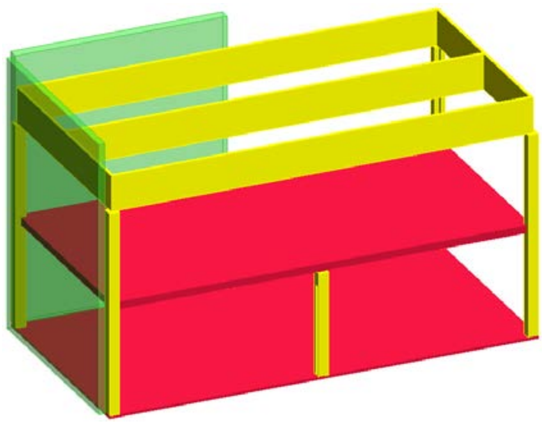


Figure 37: An example of a 3D BIM model overrode by different colours

5.4 Evaluation and Conclusion

This chapter describes the design and development process of the BCAS tool and gives a detailed illustration for every part of the Dynamo scripts. Furthermore, an evaluation is performed to test the functionalities of the tool from the author's point of view. **Table 17** is the evaluation form, which lists all required functions in **Table 14** and uses the answer 'Yes/No' to represent if these functions are achieved or not. As a result, only the 'Remove users' manual procedure' function is not realized by the BACS tool. This is because the BCAS tool requires users to assign the NL-SfB code and disassembly code for all elements in the BIM model before performing the BCA.

Table 17: The evaluation against the functional requirements of the BCAS tool

Criteria (Functions)	Yes/No
Can the BCAS tool update the analyzed results instantly once running the prototype?	Yes
Can the BCAS tool remove users' manual procedures?	No
Can the BCAS tool automatically obtain BoM?	Yes
Can the BCAS tool conduct the assessment in a single BIM software?	Yes
Can the BCAS tool assess the circular material flow?	Yes
Can the BCAS tool assess the disassembly potential for product and building?	Yes
Can the BCAS tool calculate the building' circularity from different levels?	Yes
Can the BCAS tool calculate the value of the individual indicator for the overall building?	Yes
Can the BCAS tool display all assessment contents?	Yes
Can the BCAS tool generate the analysis results in the form of a chart?	Yes
Can the BCAS tool generate the analysis results in the form of a 3D model?	Yes

Based on the development process of the BCAS tool, and its evaluation, several key findings of utilizing Dynamo are underlined. First, it is a powerful tool that has easy access to obtain the BoM from the BIM model and links it with the external product circularity database. Also, Dynamo enables to establish an automatic linkage between Excel and BIM model, leading to an efficient information updating process. Furthermore, the creation of pop-up window reveals Dynamo's potential in designing the GUI and its capability of conducting the real-time assessment.

Nevertheless, there are some drawbacks of the BCAS tool because of the limitations of the designed Dynamo scripts. The *Save* function of GUI, which is supposed to save the assessment results (i.e., the pop-up window) into the Revit interface, fails to work. Also, the Dynamo scripts utilize some Dynamo packages (e.g., Clockwork), which must be download before running the BCAS Dynamo scripts.

6. Validation

The previous two chapters describe the proposed solution of the research in detail. In this chapter, a case study is adopted through a real design in the Netherlands to validate how this solution facilitates the design of the circular building by providing decision-making support from the early design stages.

The validation involves the design in LOD 100, LOD 200 and LOD 300. It starts with modelling the selected case from LOD 100 stage. However, due to the limited model information, the BCA will not be conducted until the design develops to LOD200 stage. During this stage, two different design are provided, and each of them is undertaken with BCA. The results are analyzed in this chapter. Then, Like LOD 200, LOD 300 also contains two different design options for BCA.

This chapter starts with an introduction about the case to provide the necessary information of the project and the reason why it is utilized to validate the proposed solution. Besides, the general categories of the model element are listed. Subsequently, the validation starts based on the steps in the BIM-based framework.

6.1 Introduction

6.1.1 Case description

Weener XL in 's-Hertogenbosch is a sustainable work development company in the Netherlands, whose new building is planned to be constructed in Oude Vlijmenseweg. The new Weener XL identifies circularity as one of the main ambitions and takes circularity into account from the beginning of the design. Buro Kade, which is one of the primary design teams, aims to improve the circularity of this building from the design phases by utilizing circular building materials without loss of design quality, which is consistent with the target of the proposed solution in this research. Another vital feature of this project is that it applies an intensive BIM modelling process across all disciplines, making it suitable to be the case to validate the proposed solution.

The new Weener XL is designed to be a sustainable building with around 15,000 square meters of gross floor space for the 1,000 people who can work there every day, and 17,000 people who can visit there annually. It will be a multi-functional building, consisting of offices, a production hall, a warehouse, and supporting facilities. In terms of the appearance, it will have an industrial appearance with the wooden structure and gazed biobased facade. Its roofs will be covered green sedum roof, where CO_2 and rainwater are collected, providing a biodiverse environment. Moreover, it has the main characteristic of modular design, making the layout of the building be easily adaptable to varying activities.

The building consists of many modules with standard size (**Figure 38**). Since the new Weener XL is too large, it is decided to study only one standard module from the building in this research. This module is a two-storey office (**Figure 38**), which is located at the corner of the building's middle area. In the case study, the original BIM model of the chosen module is provided by Buro Kade and BIM-Optimaal. The Axial views of the chosen module are put in **Appendix V**. Moreover, the circularity data used to calculate all the building circularity indicators are obtained from Alba Concepts. As mentioned prior, Excel is used to save all needed circularity data with a standardized form, which can be found in **Appendix VI**.

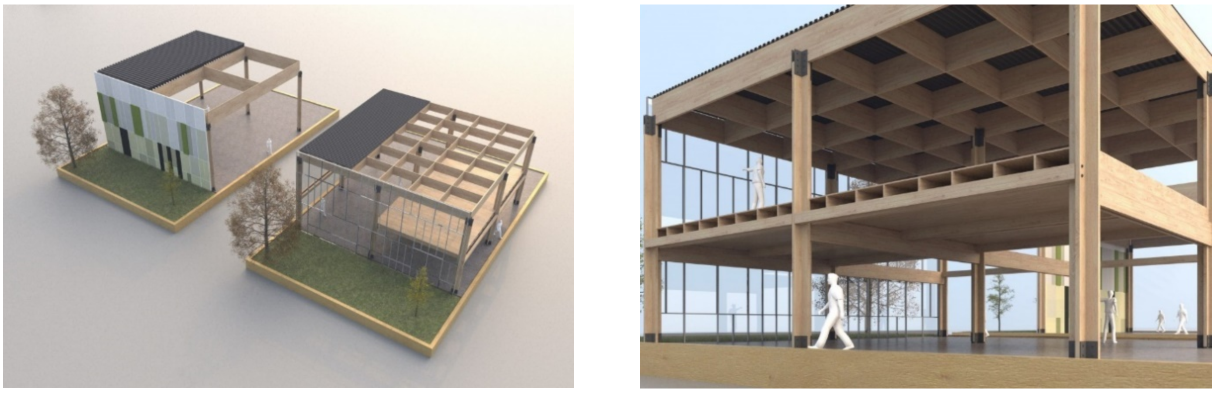
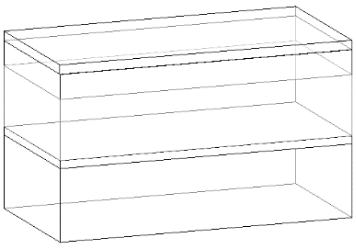
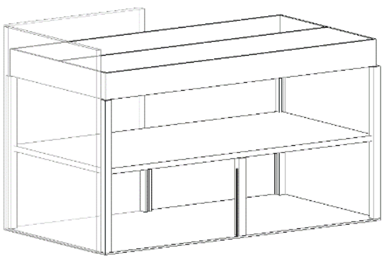
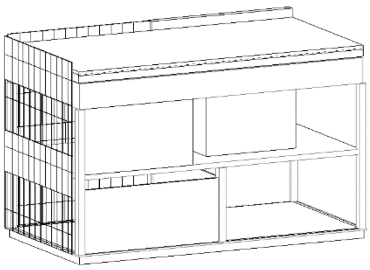


Figure 38: Examples of modular design (Buro Kade)

6.1.2 Model elements

Firstly, the general categories of the model element are listed. The first stage is LOD 100 (**Figure 39**), which only present the overall building massing indicative of the area, height, volume, location, and orientation may be modelled in three dimensions. **Table 18** shows the 3D model of the module in LOD 100. As can be seen, the module is around 7.5m in length, 15m in width, and 10m in height. In addition to giving an exterior shape of the module, designers can further specify its interior by dividing overall building massing into different functional areas, including roof, structure, floor. There is no specific element in this stage, resulting in the difficulty in conducting the building circularity assessment, but this stage would provide designers with some insights about the primary materials choices. Then, designers create the LOD 200 model (**Figure 40**) that specifies the approximate quantities, size, shape, location, and orientation of some model elements, including the curtain wall, structural beams, structural columns, and floors. The last stage LOD 300 (**Figure 41**), the elements with a higher level of detail are developed further, and some new products are added.

Table 18: The design model and model elements in different design stages

Design Stages	Design model	Model elements
LOD 100	 **Figure 39:** 3D model of chosen modular in LOD 100	-
LOD 200	 **Figure 40:** 3D model of chosen modular in LOD 200	• Curtain wall • Structural beams • Structural columns • Floors
LOD 300	 **Figure 41:** 3D model of chosen modular in LOD 300	• Curtain wall • Structural beams • Structural columns • Floors • Interior wall • Exterior wall • Roof insulation • Finish layer of roof • Finish layer of floor

6.1.3 Revit setup

Revit works with the concept of families. A family is a group of elements with a standard set of properties, called parameters, and a related graphical representation. Revit offers a range of predefined families, such as the Basic Wall family, but they can also be created from scratch. Each family can have multiple types that hold the same or different parameter values, such as width or 'Assembly Code' parameter values, but they always share the same set of parameters. This research utilizes two essential parameters of type properties: "Keynote" for disassembly potential classification and "Assembly Code" for NL-SfB classification (**Figure 42**).

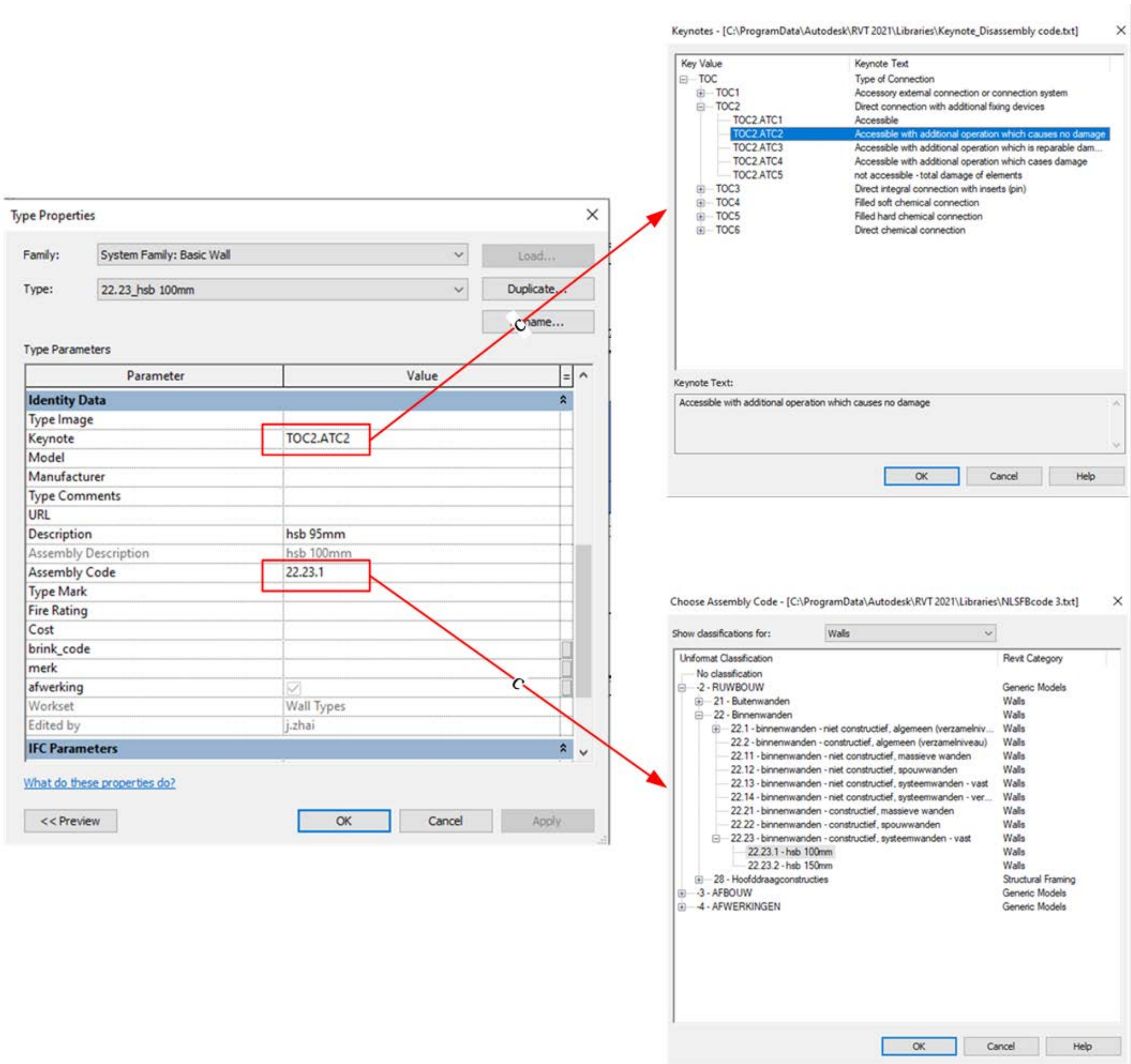


Figure 42: The parameters in the property of family type in Autodesk Revit

6.2 Circularity Assessment: LOD 200

In LOD 200, two design scenarios with different products that are performed the BCA. The first one is the basic scenario, which will be firstly measured by the BCAS tool. Based on the assessment results, to improve the overall circularity level of design, some of the products with low PCI value will be replaced by more circular products, which formulate the alternative scenario. After comparing and analyzing their assessment results, a decision is made to choose the design with better performance in circularity.

6.2.1 Basic scenario

Table 19 shows the model elements of the basic scenario in LOD200, including their NL-SfB code and the product name. The building circularity assessment results are displayed in **Figure 43** and **Figure 44**. As shown in **Figure 43**, the BCI score of the basic scenario is low, with only 13%. The overall MCI is relatively high (41.6%), compared to the overall disassembly potential (29.2%). Furthermore, other charts are analyzed to investigate the reasons why this design has a low circularity level. The 'Overall Origin of Material' pie chart shows the virgin material has the largest proportion, account for 71.87%, while the percentage by mass of recycled material is much lower (23.12%), followed by that of the biological material (5.01%). Also, the 'Overall Future Scenario of Material' pie chart indicates more than half of the materials in the design will be waste (52.5% of the landfill and 5.3% of incineration) in the future. Based on the three key defined circular building design principles in **Figure 9** (i.e., refuse or reduce virgin material, reuse or/and recycle secondary material, and limiting the material), a large number of virgin materials and material loss may result in a poor circularity performance.

Furthermore, the 'SCI' horizontal bar chart reveals that the structure of the design has a low SCI value (0.1), compared to the layer of skin (0.68). Hence, more improvements should be made for the layer of the structure. Moreover, the 'Material Mass (kg)' horizontal bar chart shows that the concrete is the most used materials in the design, may affecting the building's circularity.

Figure 44 presents the PCI classes of model elements in a more straightforward way. It shows that the colour of the floors are red, which means they have a very low SCI score. Furthermore, the structural beams and columns have a medium level of PCI, while curtain wall is relatively high. It can be concluded that floors should be focused on improving their circularity level.

Table 19: The products of the basic scenario in LOD 200

NL-SfB code	Product
21.14.1	Aluminium curtain wall with solar control glazing
23.20.1	Druklaag (concrete)80mm
28.11.1	Hardwood beam structures
28.11.3	Hardwood column structures
23.20.3	Concrete floor 200mm

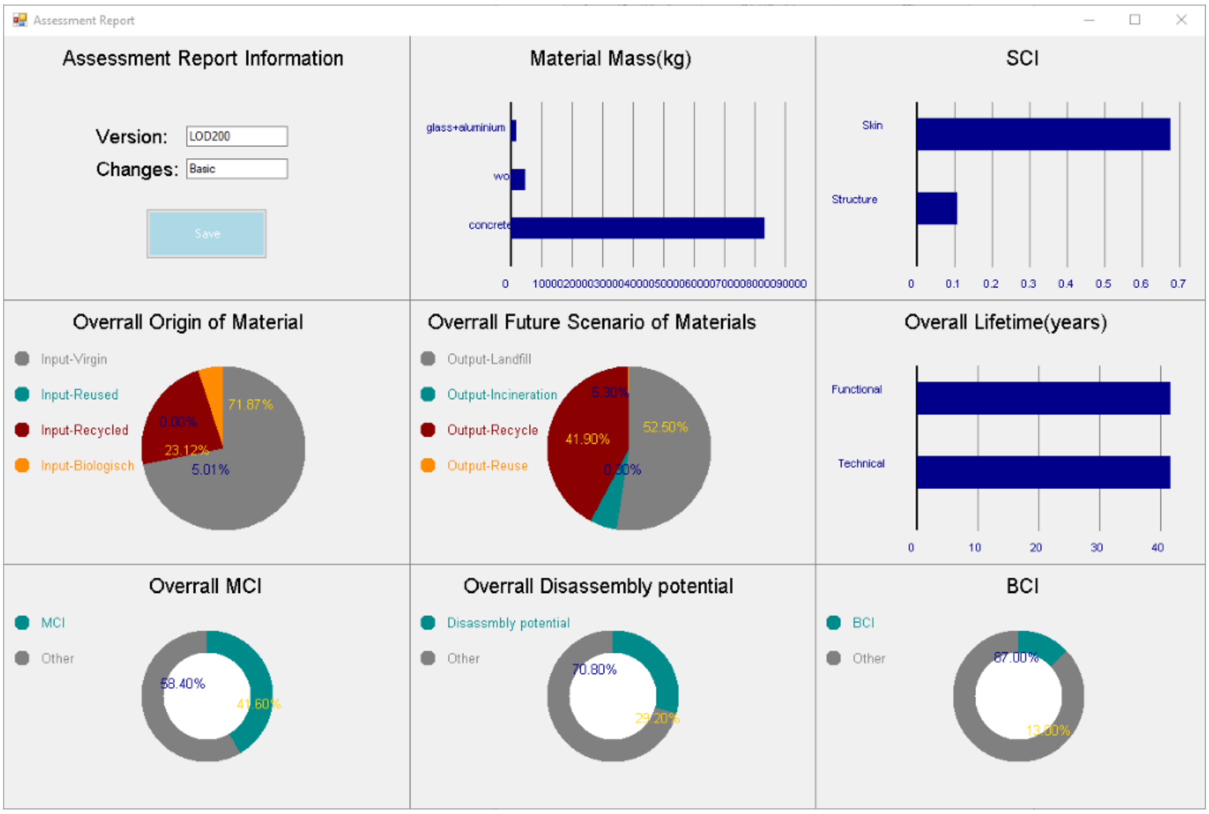


Figure 43: The pop-up window of basic scenario in LOD 200

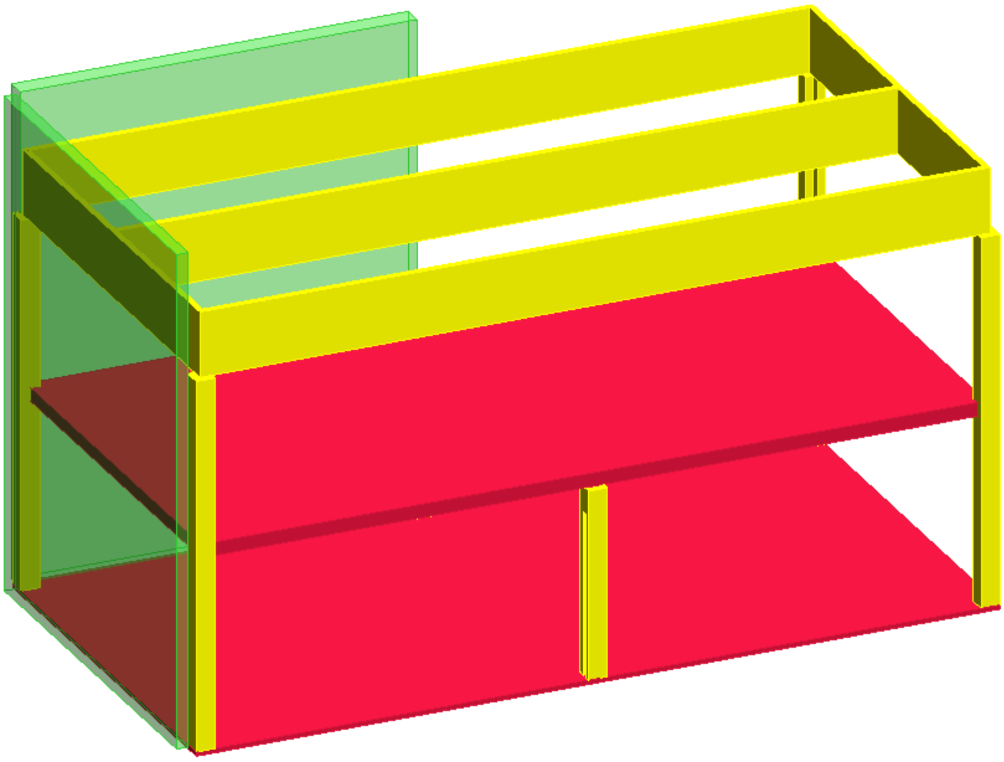


Figure 44: 3D visualization of basic scenario in LOD 200

6.2.2 Alternative scenario

Based on the assessment results of the basic scenario in LOD 200, the alternative scenario changes some products in the design. As listed in **Table 20**, the “23.20.1: Druklaag (concrete) 80mm” and “23.20.3: Concrete floor 200mm” were replaced by “22.20.4: Loose floor” and “23.20.2: Wooden floor 200mm”, respectively. Moreover, the structural beams and columns changed to reusable products.

Table 20: The products of the alternative scenario in LOD 200

Basic scenario			Alternative scenario	
NL-SfB code	Product		NL-SfB code	Product
21.14.1	Aluminium curtain wall with solar control glazing		21.14.1	Aluminium curtain wall with solar control glazing
23.20.1	Druklaag (concrete) 80mm	->	23.20.4	Loose floor
28.11.1	Hardwood beam structures	->	28.11.2	Hardwood beam structures (reusable in the further)
28.11.3	Hardwood column structures	->	28.11.4	Hardwood column structures (reusable in the further)
23.20.3	Concrete floor 200mm	->	23.20.2	Wooden floor 200mm

Figure 45 and **Figure 46** display the BCA results of the alternative scenario in LOD 200. As shown in **Figure 45**, the BCI is 55.5%, which increases 42.5% compared with that of the basic scenario. Also, both the overall MCI and the overall disassembly potential see a significant rise, from 41.6% to 83.1% and from 28.2% to 80.9%, respectively. Moreover, compared with the basic scenario, the ‘Overall Origin of Material’ pie chart reveals there are fewer virgin material and more biological material. The ‘Overall Future Scenario of Material’ indicates there will be less material loss and more reusable materials. These figures might explain why the overall MCI increases.

Furthermore, the ‘SCI’ horizontal bar chart shows that the value of skin keeps constant, while the layer of the structure has increased the SCI by 0.4 (0.5-0.1) compared with the basic scenario. In this alternative scenario, wood becomes the most material, while there is no concrete (See the ‘Material Mass’ horizontal bar chart). These indicators indicate the wood has a better performance than concrete in terms of circularity. Lastly, the 3D model visualization shows the colours of floors change from red (very low PCI) to yellow (medium level of PCI) and the PCI value of columns and beams both increased to the level of good.

All in all, compared with the basic scenario, the alternative scenario performs better in the aspect of building’s circularity. Hence, the design in the alternative scenario should be developed further in the next design stage.

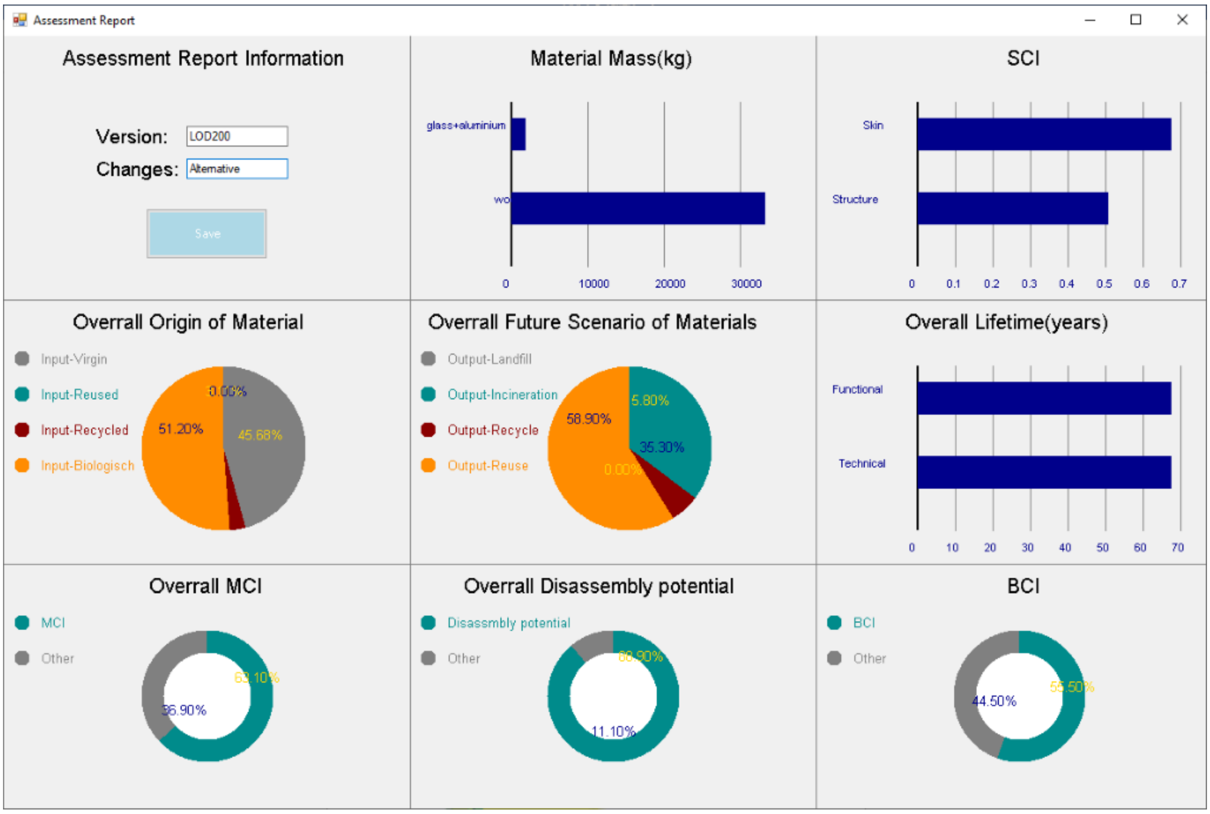


Figure 45: The pop-up window of alternative scenario in LOD 200

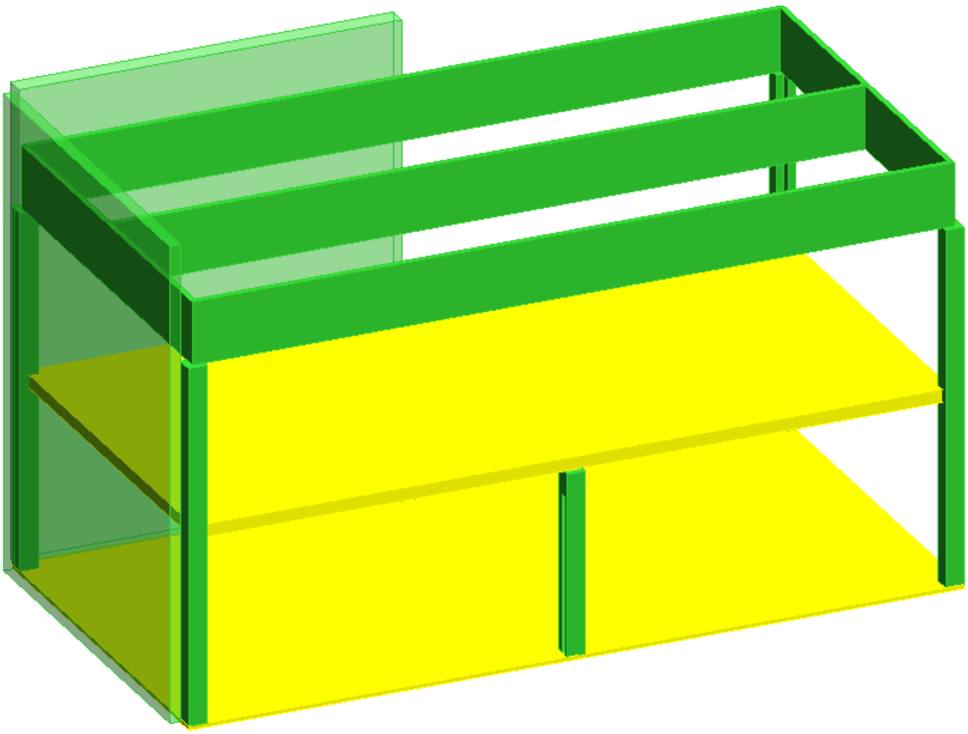


Figure 46: 3D visualization of alternative scenario in LOD 200

6.3: Circularity Assessment: LOD 300

LOD 300 develops the model elements in the previous stage to a higher level of detail. In terms of the assessment model, the building's circularity is affected by disassembly potential and circular material flow. Hence, as long as the NL-SfB code and disassembly code of the product are decided, any other changes will not impact the product's circularity. Furthermore, apart from the selected products in LOD 200, some new products are added in LOD 300 (**Table 18**). Same as the LOD 200, LOD 300 performs the BCA twice, one is for the basic scenario, and the other one is for the alternative scenario. Their specific products are listed in **Table 21**.

Figure 47 and **Figure 48** show the BCA results of the basic scenario in LOD 300. As seen in **Figure 47**, both the score of the BCI and the overall disassembly potential are low, namely 19.9% and 31%, respectively. Furthermore, it is noted that the concrete is the dominant materials, may result in a low overall BCI score. Moreover, **Figure 48** shows two roof elements have a very low PCI score, affecting the overall level of building's circularity.

After replacing two roof elements with low PCI (**Table 21**), the BCA results of the alternative scenario display in **Figure 49** and **Figure 50**. As can be seen, the BCI, overall disassembly potential, overall MCI all increase, representing a better building's circularity. Furthermore, it should be noted that wood becomes the dominant materials instead of concrete. It reveals that the building's circularity can be improved by using more wood and less concrete. Moreover, as seen in **Figure 50**, two new roof elements have low PCI classes, but still, they improved the building's circularity compared to the basic scenario.

Table 21: The products of the basic scenario and alternative scenario in LOD 300

Basic scenario			Alternative scenario	
NL-SfB	Product		NL-SfB	Product
21.14.1	Aluminium curtain wall with solar control glazing		21.14.1	Aluminium curtain wall with solar control glazing
22.20.4	Loose floor		22.20.4	Loose floor
28.11.2	Hardwood beam structures (reusable in the further)		28.11.2	Hardwood beam structures (reusable in the further)
28.11.4	Hardwood column structures (reusable in the further)		28.11.4	Hardwood column structures (reusable in the further)
23.20.2	Wooden floor 200mm		23.20.2	Wooden floor 200mm
27.11.2	Concrete roof	->	27.11.1	Green plant roof
27.21.2	Concrete roof insulation	->	27.21.3	Steel roof
22.23.1	HSB 100mm		22.23.1	HSB 100mm
22.10.1	Kantplant 175mm		22.10.1	Kantplant 175mm
21.10.1	HSB basis 378mm		21.10.1	HSB basis 378mm

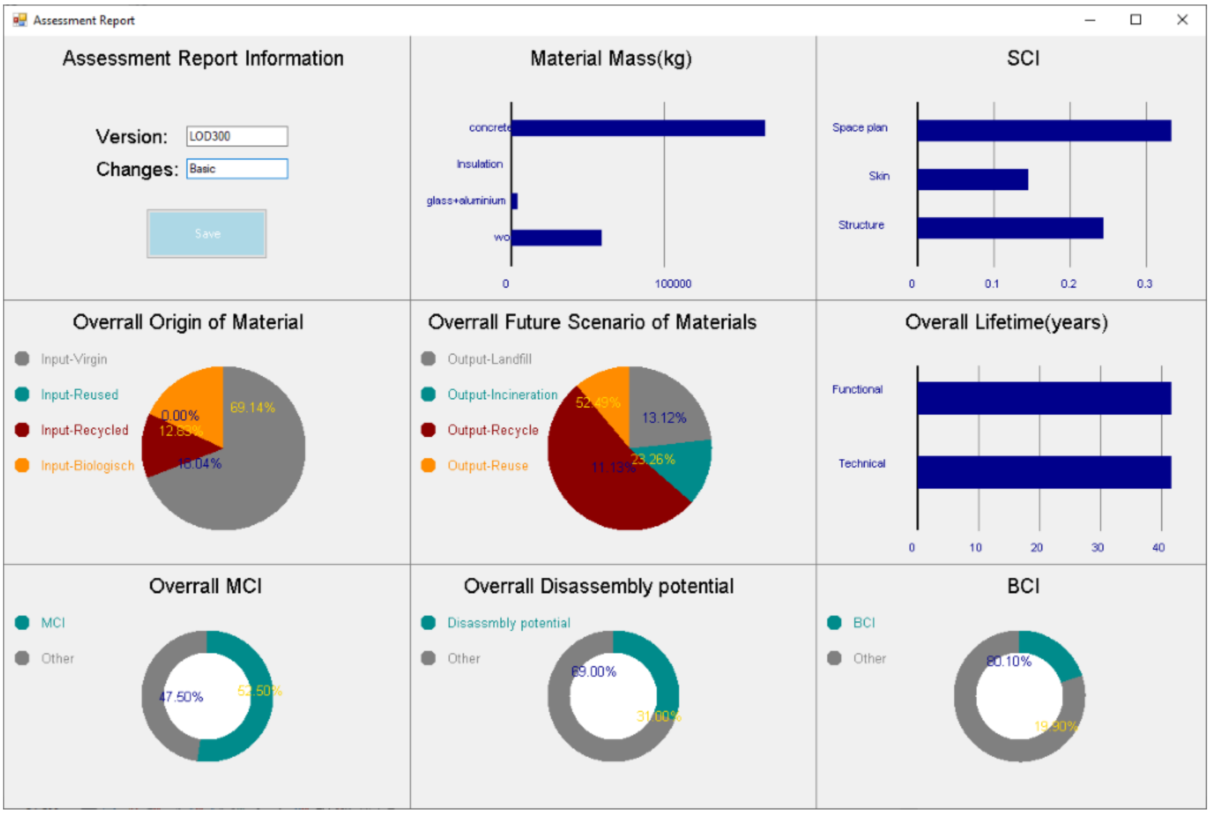


Figure 47: The pop-up window of basic scenario in LOD 300

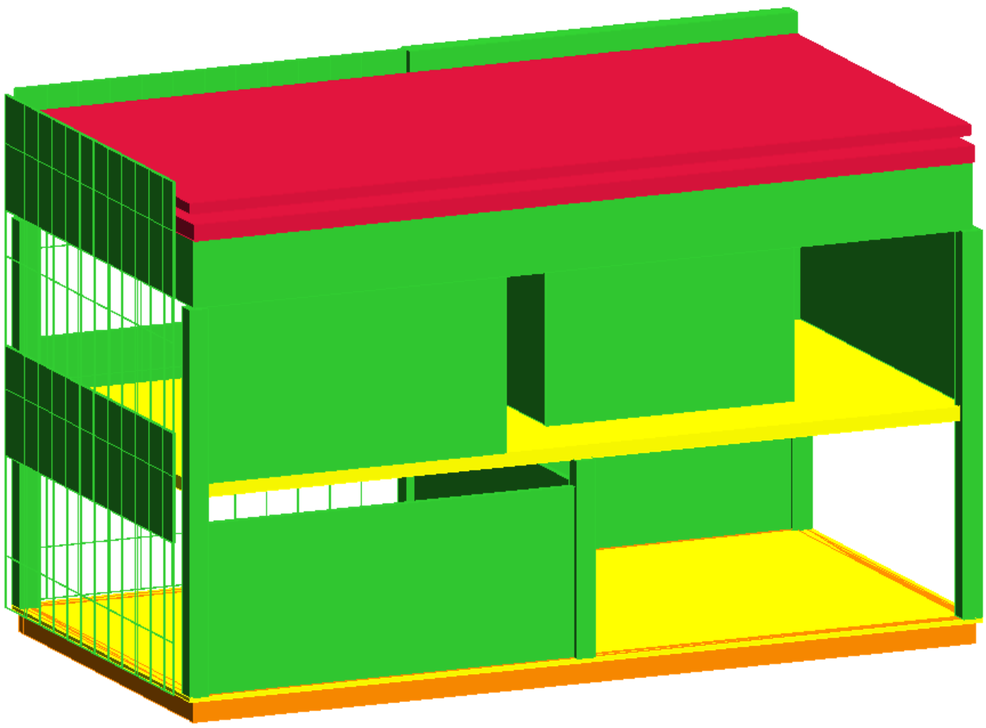


Figure 48: 3D visualization of basic scenario in LOD 300

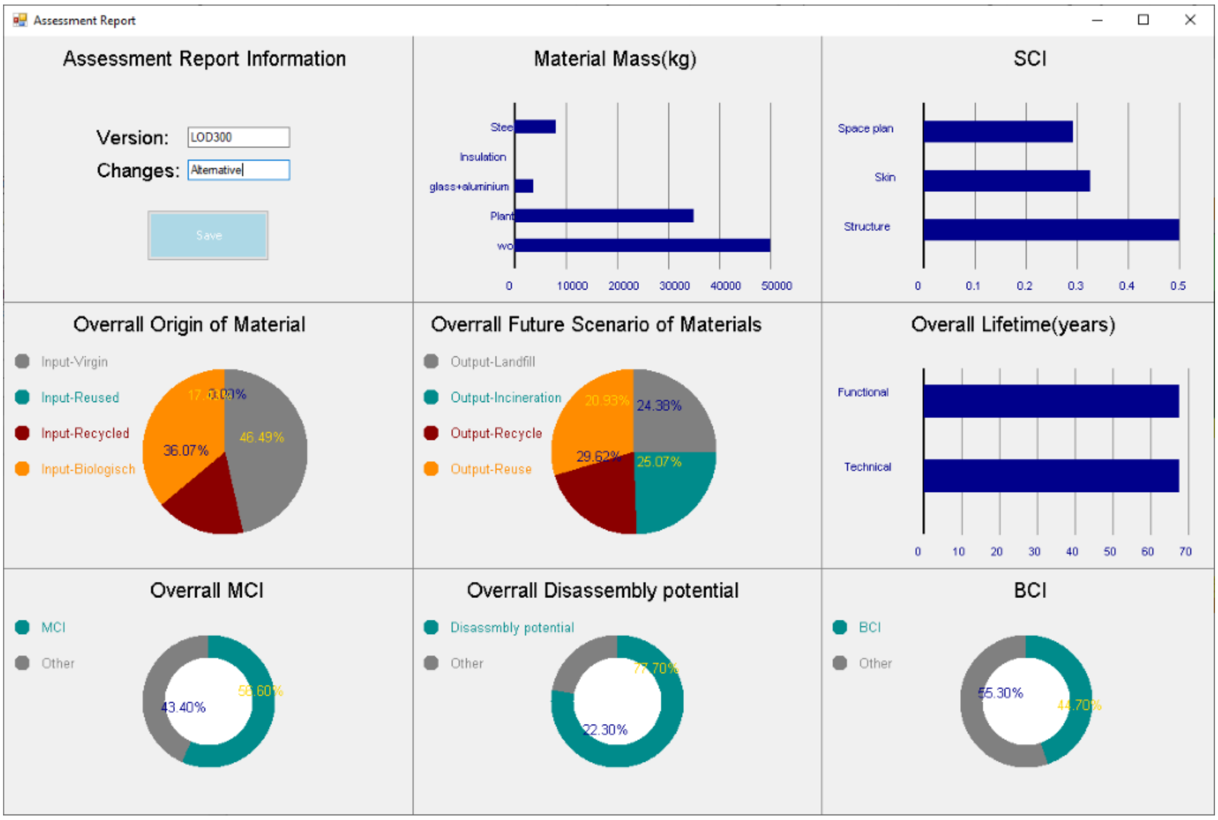


Figure 49: The pop-up window of alternative scenario in LOD 300

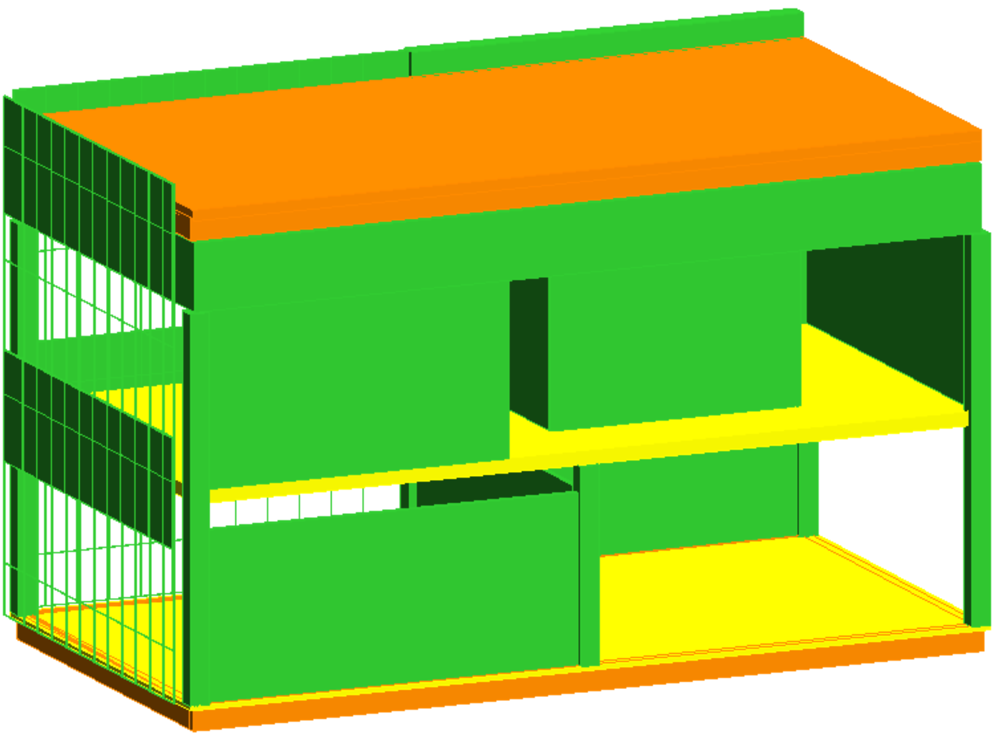


Figure 50: 3D visualization of alternative scenario in LOD 300

6.4 Conclusion

The BCA outcomes indicate the level of building's circularity and reflect how well the circular building design principles perform. This chapter conducts BCA twice for each stage in LOD 200 and LOD 300. The obtained results demonstrate that significant effect of using the wooden product in the design to enhance the value of the building circularity indicators. As can be seen in **Figure 51**, the results also revealed that utilizing the BCAS tool provides decision-making support regarding the design of the circular building.

Moreover, several key points are highlighted. First, it is possible to have the BCA from an early stage by creating the simple model elements or the mass of elements and assigned them with hypothetical NL-SfB code and disassembly code. This is because the building's circularity is only affected by disassembly potential and circular material flow based on the assessment tool. Nevertheless, it is hard to give the model in LOD 100 such a hypothesis due to the limited information. Besides, when analyzing the BCA results, the value of BCI and PCI are mainly considered, while other indicators play a role in giving the reason for each BCI score.

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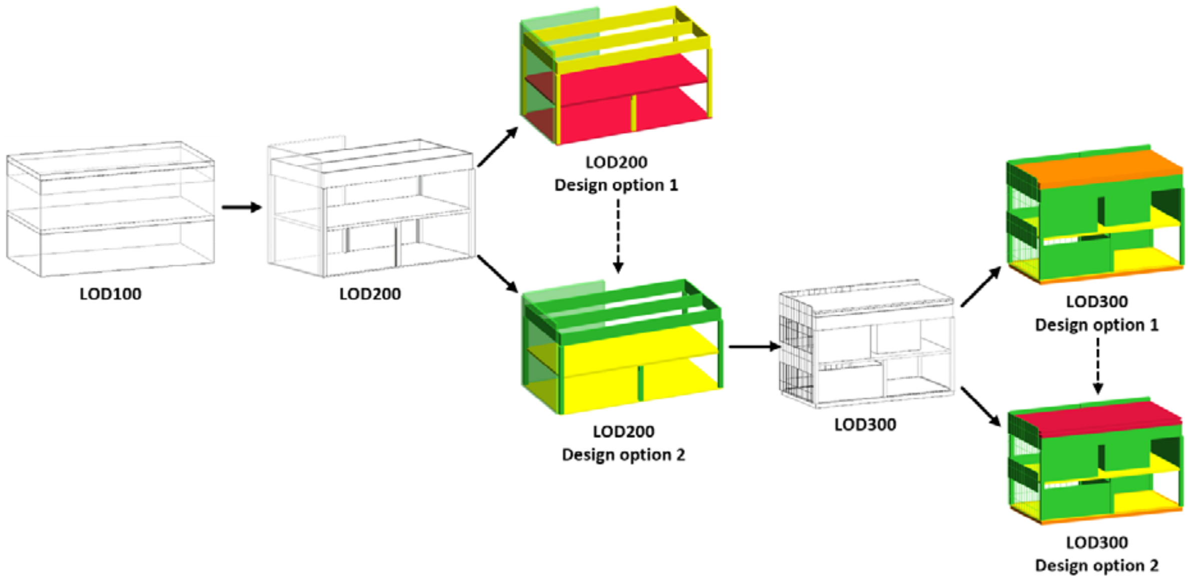

Figure 51: The decision-making process about the design of the circular building

7. Conclusion

Making the building circularity measurable is essential to promote the transition from a linear economy to a circular economy in the construction industry. The work of this thesis targets at improving the assessment process by reducing its limitations. This chapter, as the final part of this thesis, aims to give a conclusion for the whole research project. It starts by answering the research question:

How can the integration of building circularity assessment with BIM enable an automated assessment on different levels of building and provide the decision-making support on the design of the circular building from the early stage?

This main research question will be answered by discussing each sub-question individually. Then, the next part highlights the contribution of this research. Finally, the limitations are identified, followed by providing the corresponding recommendations for further research.

7.1 Research Questions

The primary objective of this study is to explore how a BIM-based building circularity assessment can give designers the freedom to focus on the design while at the same time keeping track of the potential effects of material and design decisions from the early design stages. The main research question and five sub-questions were posed to achieve the objective. Firstly, the chapter answers the sub-questions, followed by the main research question.

Sub-Q1: What indicators can reflect the progress towards a circular building?

Circular building design principles affect the progress towards a circular building, and the degree of this transition can be reflected by building circularity indicators. Thus, design principles play a crucial role in deciding the range of indicators. When considering different principles, the explored indicators differ. This research focuses on the building's technical aspects throughout its entire lifecycle, and eventually define nine important circular building design principles. Then, based on these principles in three key life phases, fourteen indicators are found as well as their corresponding technical property (**Table 22**).

Table 22: Circular building design principles and their technical building circularity indicators

Lifecycle phases	Circular building design principles (technical)	Technical building circularity indicators	Technical properties
Material and Component Production	Shift to renewable material	The percentage by mass of renewable materials in the total material input	Intrinsic properties
	Reduce virgin materials	The percentage by mass of virgin materials in the total material input	
	Reuse/recycle secondary materials	The percentage by mass of reused materials in the total material input	
		The percentage by mass of recycled materials in the total material input	
	Design for low materials	The total mass of all materials	
	Material health	The toxicity of the material	
Design	Think in system	Circular building product levels	Relational properties
	Design for disassembly	Disassembly potential	
	Design for adaptability	Adaptability potential	
End-of-life	Limiting the material loss	The percentage by mass of reusable materials in the total material input	Intrinsic properties
		The percentage by mass of recyclable materials in the total material input	
		The percentage by mass of materials sent to landfill in the total material input	
		The percentage by mass of material sent to incineration in the total material input	
		Recycling Process Efficiency	

Sub-Q2: What assessment models are used to measure the building's circularity?
This research has investigated six existing assessment models that precisely measure the technical aspect of building's circularity. These methods are MCI (EMF, 2015b), BCI (Verberne,2016; van Vliet, 2018), CI (Madaster, 2018b), BCIX (Alba Concepts, 2018), core method (Platform CB'23, 2019). After reviewing six existing assessment models for building's circularity, this research proposes an assessment model that tries to integrate the valuable parts of each method. **Figure 52** shows the hierarchy of the BCI model, which has the following key features:

- It is a quantitative assessment, giving a specific value to indicators.
- It covers eleven investigated indicators in **Table 22**, but does not include three indicators as follows:
    - The toxicity of the material.
    - Adaptability potential.
    - Recycling Process Efficiency
- It assesses the building's circularity from four different levels of a building's composition, namely material, product, system, and building.
- It provides the value of individual indicators for the whole building.

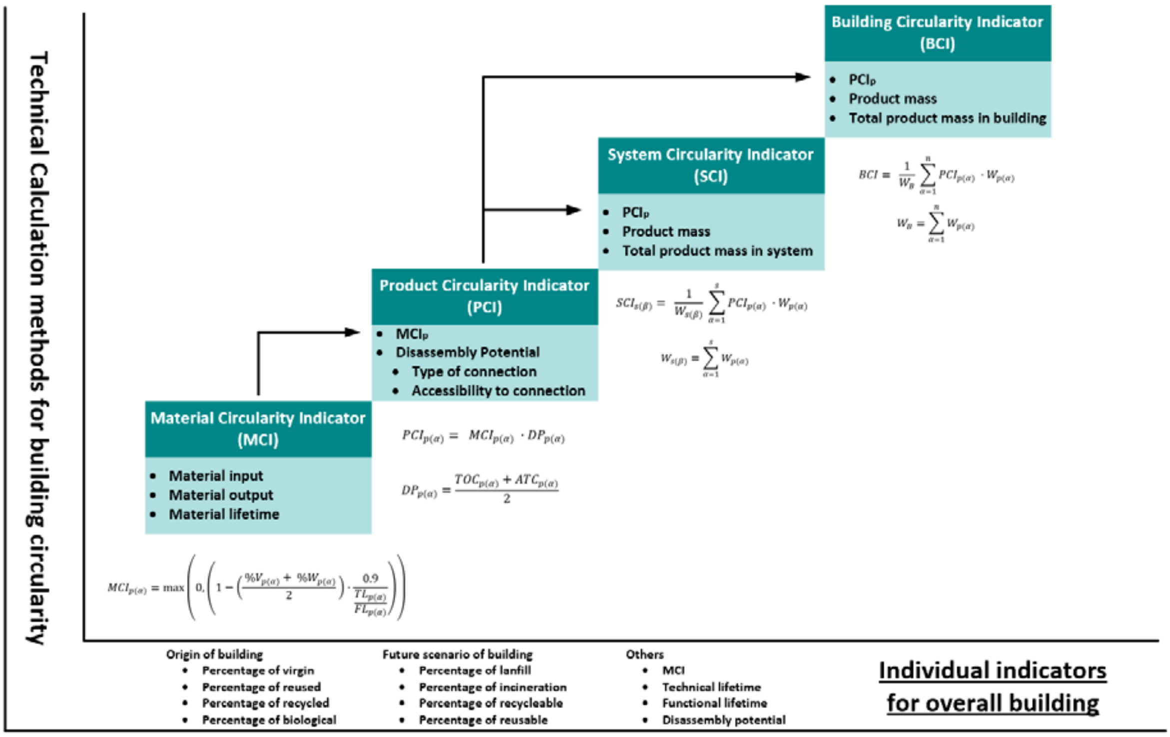

Figure 52: The hierarchy of the new BCI model that applied in the research

Sub-Q3: What are the integration approaches between BIM and building circularity assessment?
Two BIM-BCA integration approaches are identified from the previous studies. One of them utilizes a data exchange standard (e.g., IFC, COBie), to hold the BoM and other properties of BIM model elements, which are then processed in the external BCA software like an online platform. The other one is to conduct the assessment within BIM software like Revit by creating custom parameters to capture various attributes regarding building's circularity. Apart from these two approaches, another integration possibility is to establish an automatic and efficient link between the BIM model and external building's circularity database, then

conduct the BCA within BIM software. Other studies never tried the third method to the best of my knowledge.

Sub-Q4: How to integrate BIM into the building circularity assessment to automate the process?
This research creates a BIM-based framework, which uses Autodesk Revit and Dynamo for Revit to conduct the BCA for building' design. In this framework, BIM's capability in parametric modelling, classifying data and visualization makes it applicable to automate the BCA. Firstly, the feature of parametric modelling makes the BIM object have parametric attributes attached, holding useful information for BCA such as dimension. Thereby, BIM can automate the extraction of BOM, reducing the need for manual data input. Secondly, BIM's ability in classifying data makes it possible to connect the BIM model with the external database. In this framework, the customized classification system: NL-SfB code is the key to realize this linkage. In this way, BIM facilitates data collection. Thirdly, BIM's feature of visualization accelerates the process for assessing the disassembly potential. BIM model displays the relational patterns of products in a more comprehensive way when it is compared to a detailed drawing, leading to an efficient and time-saving assessment.

Sub-Q5: How does a BIM-based prototype provide decision-making support about the design of the circular building from early design stages?
The BCAS tool is validated by a case study, which follows the steps in the BIM-based framework. The selected case is modelled and assessed in different LOD. The results show that it is possible to have the BCA from an early stage schematic design by creating the simple model elements or the mass of elements and assigning them with projected NL-SfB code and disassembly code. Moreover, except for the very early stage when there is little information, other stages are provided with more than one design option to validate. The results indicate that the design of a circular building can be promoted by comparing the BCA outcomes. Moreover, the BCAS Dynamo prototype, which is the essential tool of the BIM-based framework, can present the assessment results in the form of charts and override the Revit model elements with different colours.

In conclusion, this research focused on the building's technical aspects throughout the entire lifecycle through a quantitative assessment while giving a specific value to indicators. An automatic link between the BIM model and external building's circularity database is created to automate the BCA. It assessed the building's circularity on four different levels of a building's composition, namely material, product, system, and building and provided the value of individual indicators for the whole building. This research created a BIM-based framework, which utilizes BIM's capability in parametric modelling, classifying data and visualization to automate BCA. A case study validates the framework, and the results proved that it is possible to assess the building circularity from an early stage schematic design and subsequently promote the circular design based on the assessment results of different design options

7.2 Contribution

The main contributions of this research include:

(i) The provision of an assessment model for the technical aspects of the building's circularity. This is the first research that integrates the valuable parts from the exiting methods.

(ii) The design of the BIM-based BCA framework. It not only supports an automated assessment but also enables to provide an estimated appraisal for the building in the early design stages.

(iii) The development of the BCAS tool (a Dynamo prototype). It creates a linkage between the BIM model and external database, conducts the assessment, and generate the outcomes. This is the first research that utilizes Dynamo to generate a Dashboard with charts within the interface of the Revit and displays the level of circularity by overwriting the 3D model.

(iv) The establishment of the building product circularity database for setting up a standard data collection. Its structure is built upon the NL-SfB classification to establish a more efficient link with the BIM model.

(v) The creation of the disassembly potential classification system for accelerating the assessment of product' disassembly. This is also the first research that tries to load this classification into BIM software to the best of my knowledge.

This research has significant influences on both academic and practical fields. For academic, it provides some key terminologies with clear definitions for (e.g., circular building, building's circularity, BCA) and improves the understanding of CE's transition in the built environment. Furthermore, it emphasizes the indicators that must be considered when measuring the building's circularity in terms of the technical aspect. From a practical point of view, since the application of BIM software, especially the Autodesk Revit is becoming popular in AEC industry, the BCAS tool (Dynamo prototype) can be widely implemented in the future.

7.3 Limitations and Recommendations

Despite the contributions of this research, there are certain limitations as follows:

The limited scope of the research

Building's circularity is related to many domains (e.g., social, economic, environment in **Figure 12**). This research only focuses on the technical aspect of the circular building. The relevant circular building design principles, the building circularity indicators, and the assessment models for measuring building's circularity are limited to technical domain. Hence, it is recommended to extend the research scope to other aspects.

The excluded indicators in the assessment model

Fourteen indicators are identified to reflect the progress towards a circular building, but the research fails to include all of them in the determined assessment model. The excluded indicators are the toxicity of material, the adaptivity potential, and recycling process efficiency. Moreover, regarding the disassembly potential, only two DDF's are considered. Thus, future research should address these unconsidered indicators.

The unrealized functions of the BCAS tool

The recommendations are given based on the identified technical drawbacks of the BCAS tool. Firstly, the *Save* function of GUI does not work, resulting in the pop-up window unable to be saved to the draft view in Revit. Furthermore, it is recommended for the prototype to generate a straightforward comparison of different assessment results. Also, a more user-friendly interface should be designed to directly import the external building circularity data and remove the override colour of the element.

The way of loading disassembly potential classifications system into Revit

This classification is loaded into Revit through the function of "Keynote"; hence, the users can select the disassembly type for a product from a list of codes. However, the 'Keynote' was used to tag elements or materials in Revit; the replacement by disassembly potential classification system results in the loss of the actual usage of the 'keynote'. Thus, an alternative way to load this classification system into Revit is suggested in future research.

Building product circularity database

The external building circularity data is stored in Excel, which is suitable for a limited amount of data and a minimum number of labels. An SQL database is recommended for a complete and centralized circularity database. Also, It has the advantage to create the relationships between various components easily. Furthermore, this database utilizes 'product' as a unit, missing considering how its components assemble.

Lack of verification for the assessment model and BCAS tool

The determined assessment model should be verified to have a better interpretation of the assessment result. It is suggested to validate it by comparing its calculation results with other assessment models (e.g., the BCI model (Verberne, 2016)). Also, it is necessary to validate the accuracy of the assessment result generated by the BCAS tool, especially whether the BoM extracted by Dynamo is accurate.

Lack of validation for the BIM-based BCA framework and BCAS tool from users' point of view

For the design and development of software or application, it is of importance to identify its drawbacks through users' feedback. However, the research only tested the designed BCAS tool from the author's point of view. Hence, it is suggested to conduct further research like a survey, questionnaire, or interview to acquire the users' experience. Then, the tool can be improved or elaborated further.

Other authoring software

The BCAS tool is restricted to Revit users. Therefore, future research can try other applications like SketchUp, which also allows adding information to components or Rhino that also has a visual programming tool: Grasshopper.

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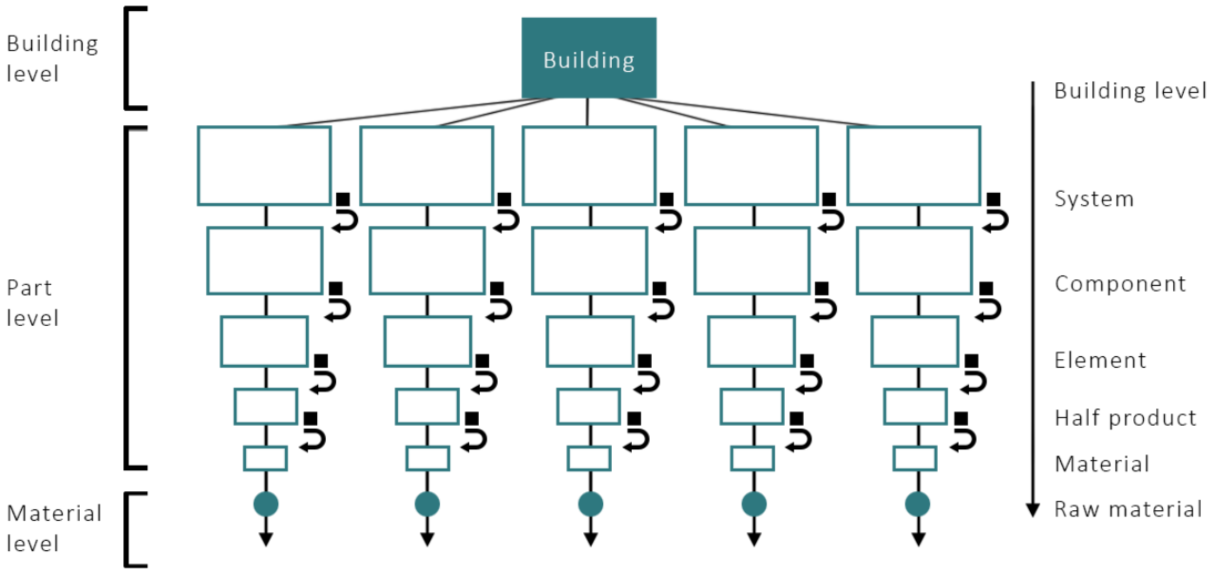
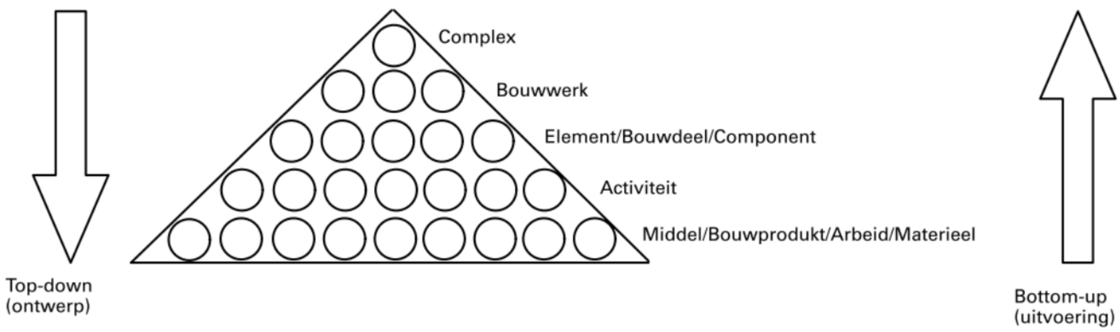
Appendices

Appendix I Define Building Levels

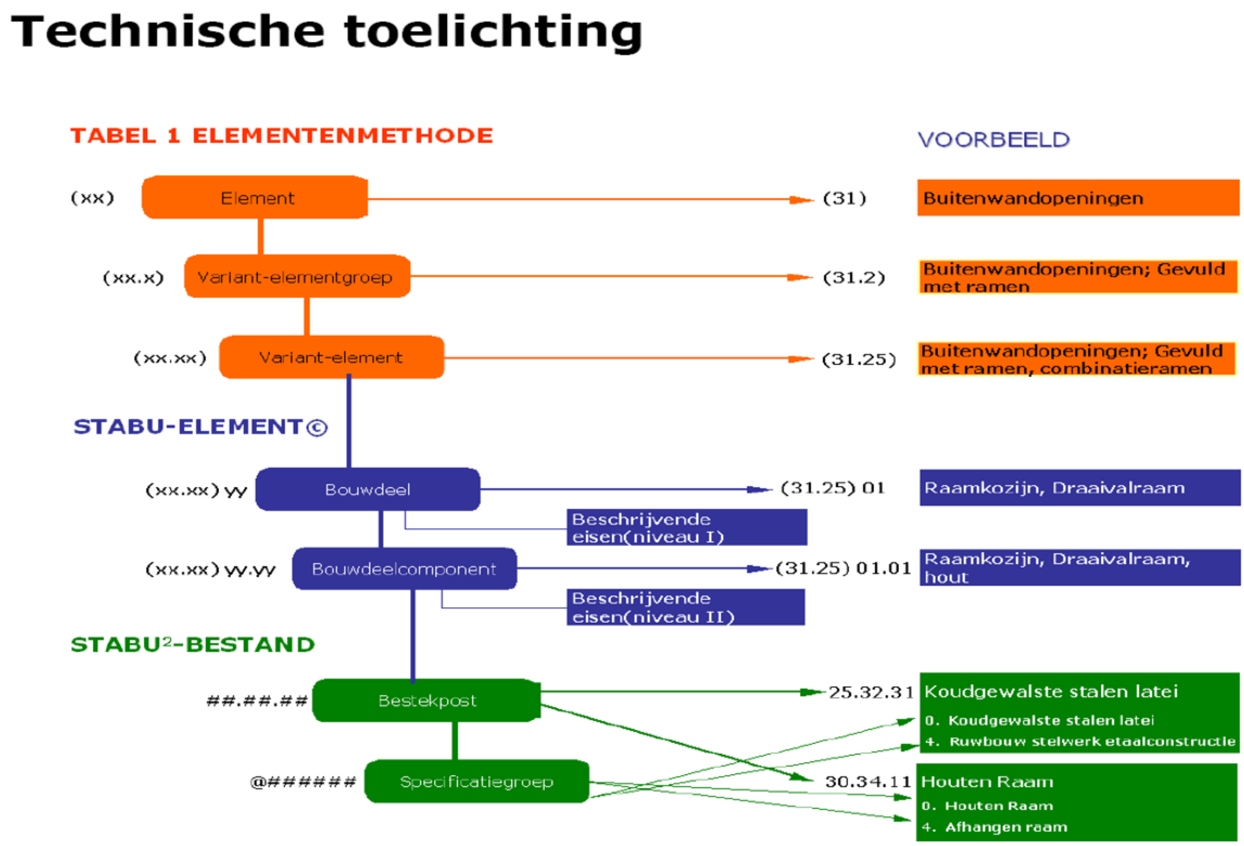
Theory of material levels (Durmisevic, 2006)



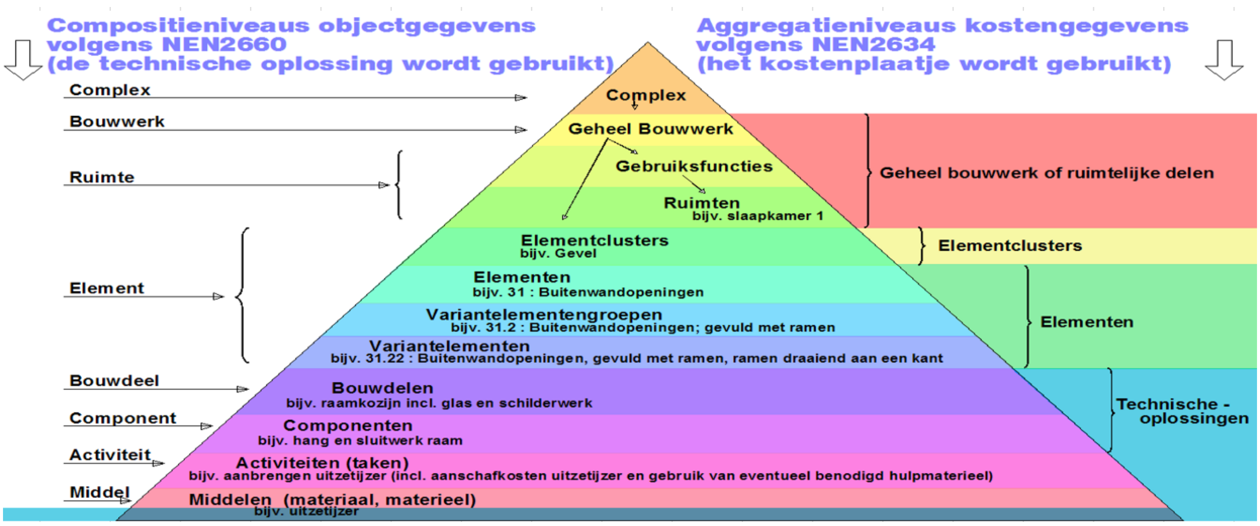
Information carriers for classifications (NEN, 1996)



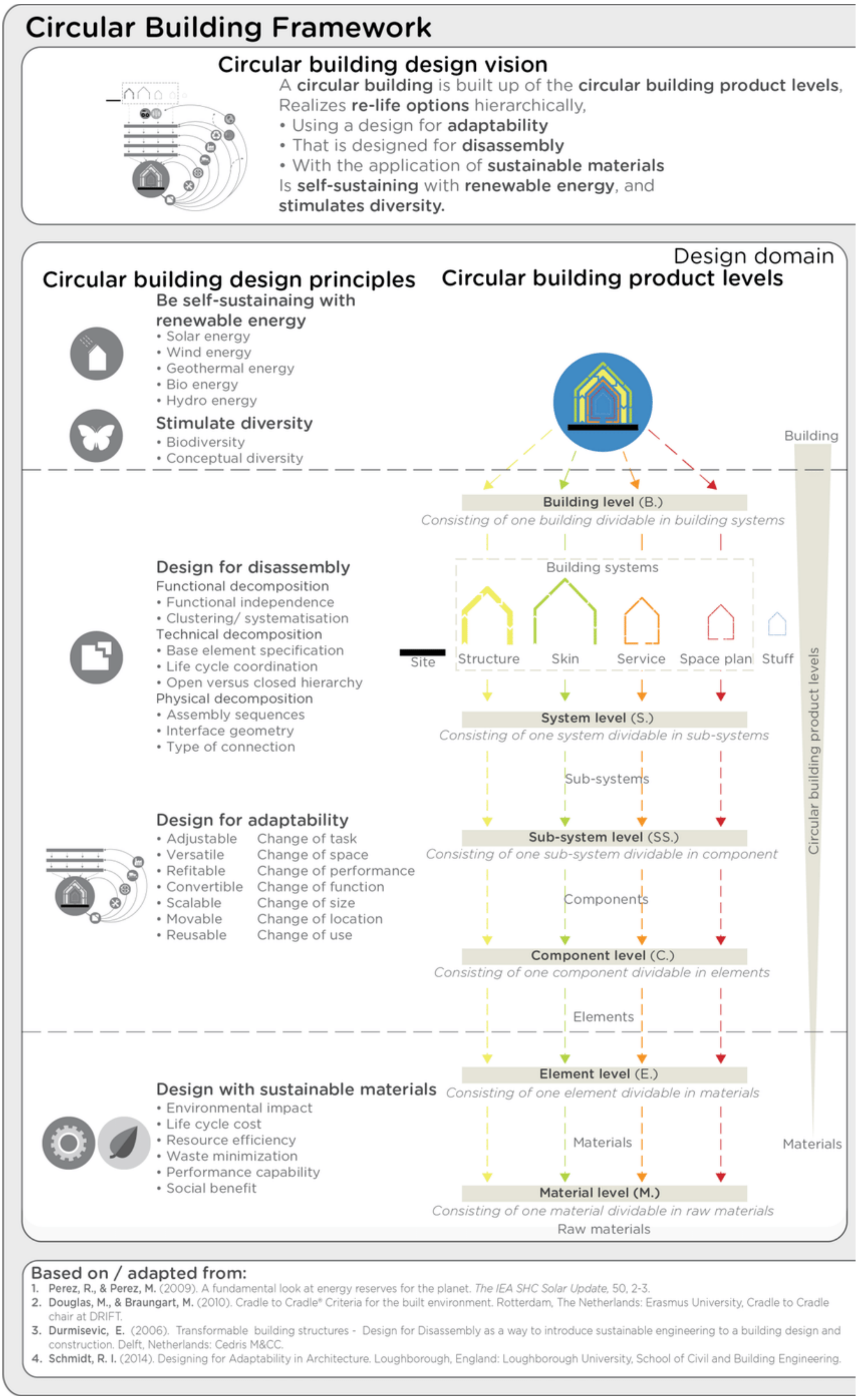
Comparison Elementenmethode, STABU-Element and STABU2-Bestand



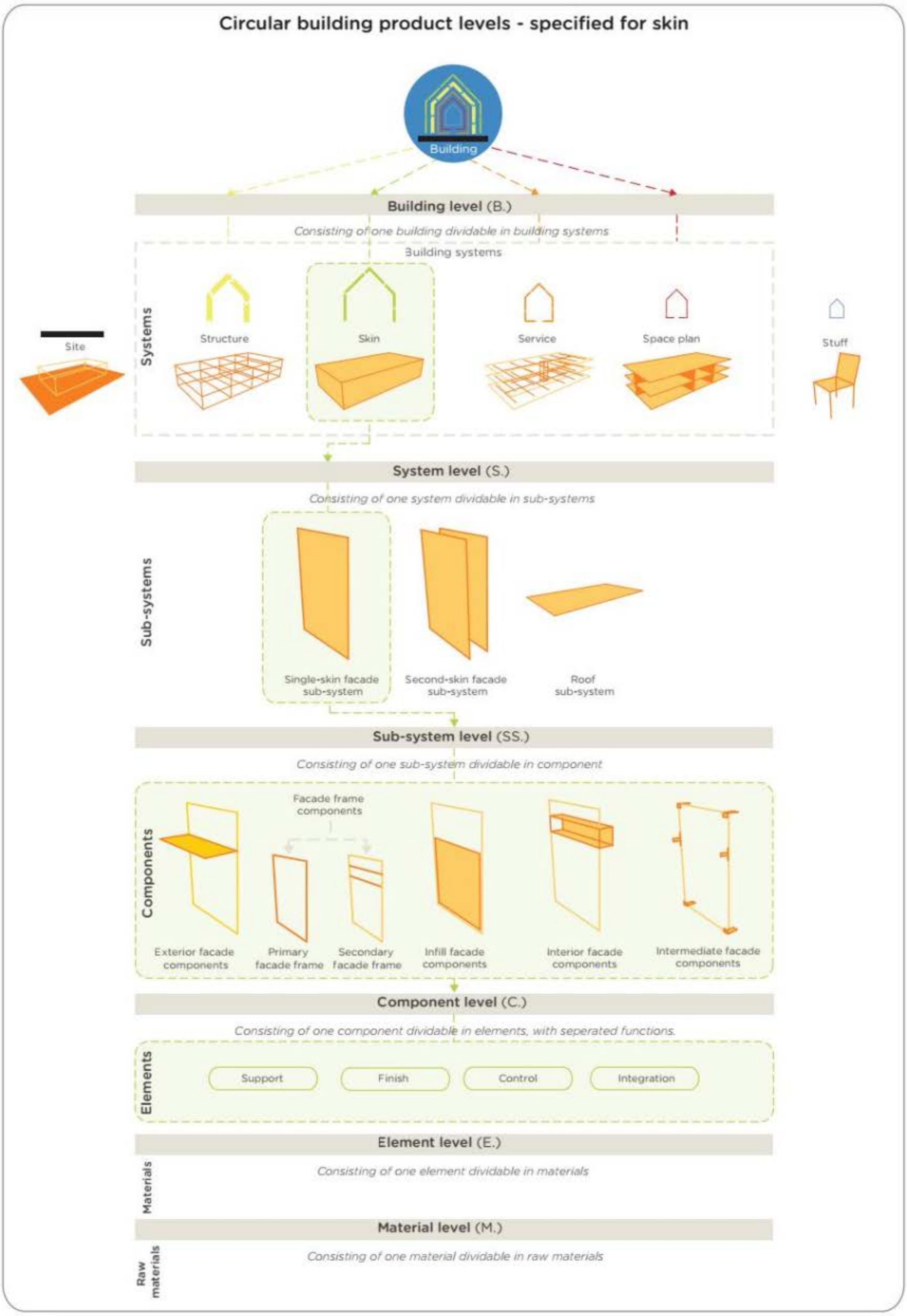
Composition levels object data according to the NEN2660:1996 with NL/SfB codes.



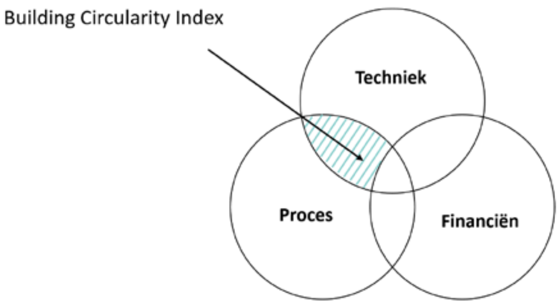
Circular building product levels (Bakx et al., 2016)

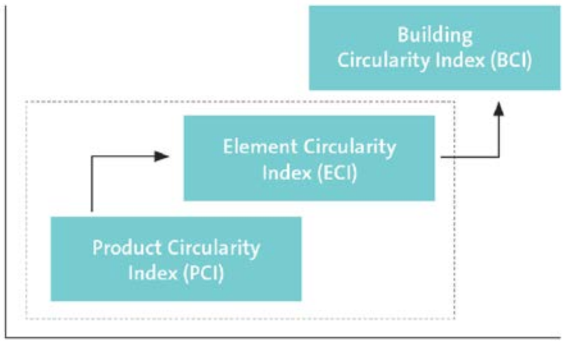


Circular building product levels – Specified for skin (Bakx et al., 2016)

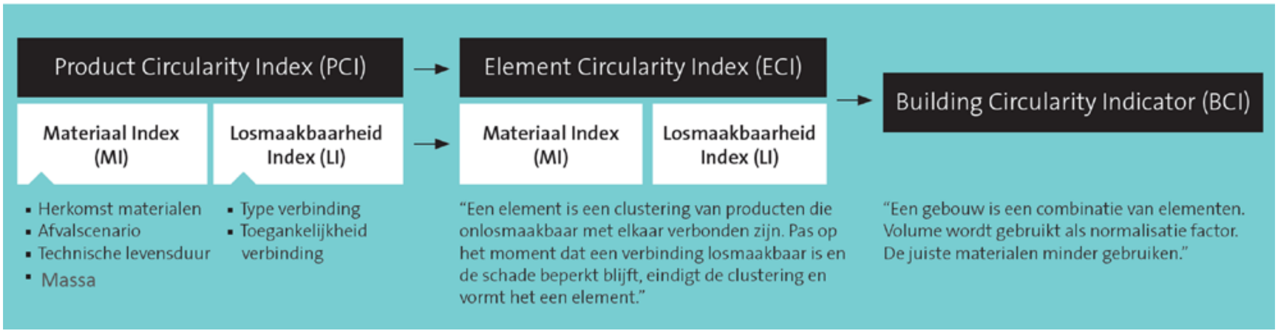


Appendix II Documents from Alba Concepts





DRIVERS	RANDVOORWAARDEN
Materiaalschaarste Financieel/restwaarde Imago	Toxiciteit Uitstoot van schadelijke stoffen Uitputting van fossiele energiedragers

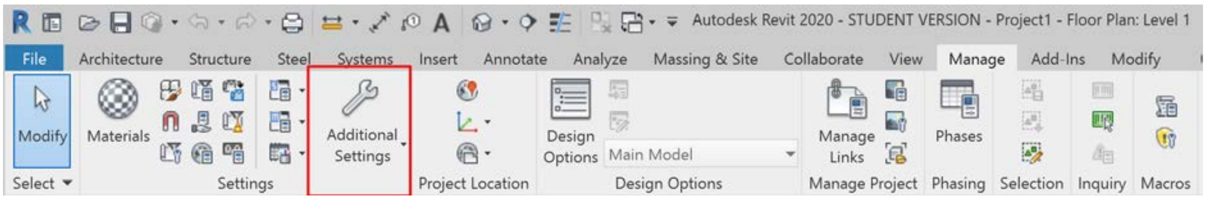


Appendix III The Process of Loading Classification System into AutoDesk Revit

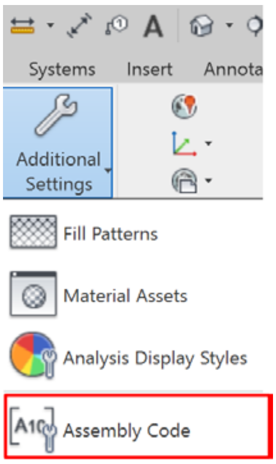
Loading NL-SfB classification into Autodesk Revit

The loading process of NL-SfB classification code is performed by going to the Manage tab within Revit in the Ribbon and selecting Additional Settings. Select the "Assembly Code" function at the bottom of the drop-down menu. In the menu that appears, the NL-SfB file with the format of tab-delimited text can be loaded using the "Browse ..." function. When the NL-SfB list is loaded, these can be hung on objects by clicking on the "block" in the properties. This opens a list of all available codes with descriptions when a code is selected automatically entered the description at the parameter Assembly Description.

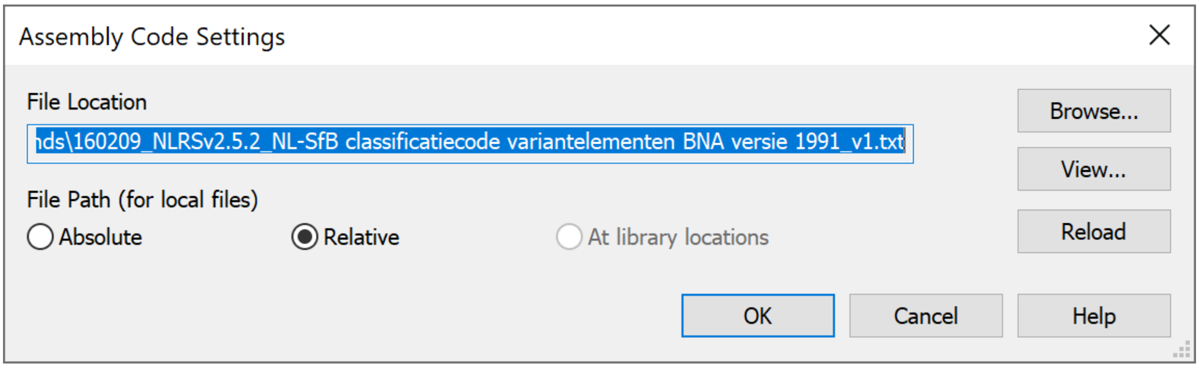
Step 1: Autodesk Revit >Manage tab >Additional Settings



Step 2: Additional Settings>Assembly Code



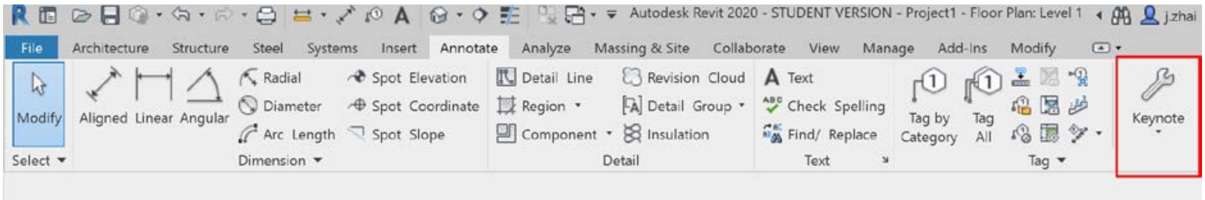
Step 3: Loading NL-SfB file



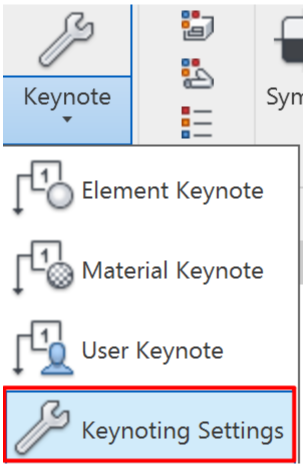
Loading disassembly classification into Autodesk Revit

Similar to assembly code, a tab-delimited text file that defines the categories and keynote value is edited and imported into Revit. Lading disassembly potential by following the instruction below.

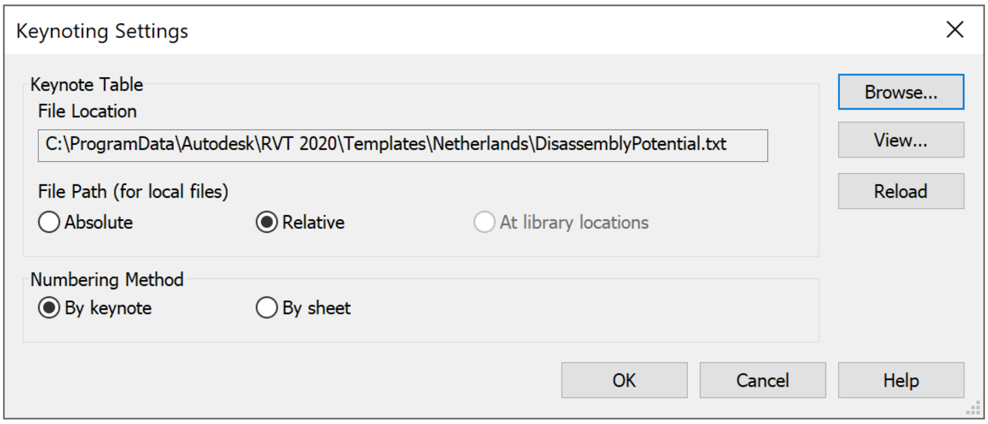
Step 1: Autodesk Revit >Annotate tab >Keynote



Step 1: Keynote>Keynoting Setting



Step 3: Loading disassembly classification file



Appendix IV The customized Python notes in Dynamo Script

Python Script 1: Obtain all model categories in Revit

```
import clr

clr.AddReference('RevitServices')
clr.AddReference('RevitAPI')

import Autodesk
import RevitServices

from Autodesk.Revit.DB import *
from RevitServices.Persistence import DocumentManager

doc = DocumentManager.Instance.CurrentDBDocument

modelCats = []
for cat in doc.Settings.Categories:
    if cat.CategoryType == CategoryType.Model and cat.CanAddSubcategory:
        modelCats.append(cat.Name)

OUT = sorted(modelCats)
```

Python Script 2: True for any

```
# Load the Python Standard and DesignScript Libraries
import sys
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# The inputs to this node will be stored as a list in the IN variables.
list = IN[0]
# Place your code below this line
out = []
for sublist in list:
    if True in sublist:
        out.append(True)
    else:
        out.append(False)
OUT = out
```

Python Script 3: List all disassembly types

```
# Enable Python support and load DesignScript library
import clr
MyList = [
"TOC1.ATC1","TOC1.ATC2","TOC1.ATC3","TOC1.ATC4","TOC1.ATC5",
"TOC2.ATC1","TOC2.ATC2","TOC2.ATC3","TOC2.ATC4","TOC2.ATC5",
"TOC3.ATC1","TOC3.ATC2","TOC3.ATC3","TOC3.ATC4","TOC3.ATC5",
"TOC4.ATC1","TOC4.ATC2","TOC4.ATC3","TOC4.ATC4","TOC4.ATC5",
"TOC5.ATC1","TOC5.ATC2","TOC5.ATC3","TOC5.ATC4","TOC5.ATC5",
"TOC6.ATC1","TOC6.ATC2","TOC6.ATC3","TOC6.ATC4","TOC6.ATC5",
]

OUT = MyList
```

Python Script 4: List all disassembly scores

```
# Enable Python support and load DesignScript library
import clr
MyList = [
1,0.9,0.8,0.7,0.55,
0.9,0.8,0.7,0.6,0.45,
0.8,0.7,0.6,0.5,0.35,
0.6,0.5,0.4,0.3,0.15,
0.55,0.45,0.35,0.25,0.1,
0.55,0.45,0.35,0.25,0.1,
]
# Place your code below this line
```

Python Script 5: GUI of pop-up window

```
import clr
import math

clr.AddReference('UnmanagedCode')
clr.AddReference("System.Windows.Forms")
clr.AddReference("System.Drawing")

from System.Windows.Forms import Application, Form, Timer, Label, Button, TextBox
from System.Drawing import Size, Color, SolidBrush, Pen, RectangleF, Rectangle, Point, Font, Bitmap, Graphics
from System.Drawing.Drawing2D import SmoothingMode, LineCap
from System.ComponentModel import Container
from System.Drawing.Imaging import ImageFormat
from System.Drawing import Bitmap, Image
from UnmanagedCode import User32, GDI32

# add title to each subplot
def addTitle(g, x1, y1, w, h, title):
    font = Font("Arial", 15)
    brushNum = SolidBrush(Color.Black)
    g.DrawString(title, font, brushNum, x1+w/2-len(title)*5, y1+10)

# plot bar, like subplot 2,3,6
def myBar(g, x1, y1, w, h, data, title):
    # input g: current graphics
    # input x1,y1: the position of top left corner of subplot
    # input w,h : the size of subplot
    # input data :include values and labels
    # input title : the title of this subplot
    values,labels = data
    # determinate the y-axis information: like dx and nDiv( # of vertical line )
    maxL = max([ len(_) for _ in labels ])
    n = len(values)
    maxV = max(values)
    dx = 0.01
    while maxV/dx>=10:
        dx*=10
    if dx>1:
        dx = int(dx)

    nDiv = int(maxV/dx)+1
    addTitle(g,x1,y1,w,h,title)

    # x-axis y-axis for axes
    xl = x1+w/4
    yl = y1+7*h/8
    # set font and brush for each bar
```

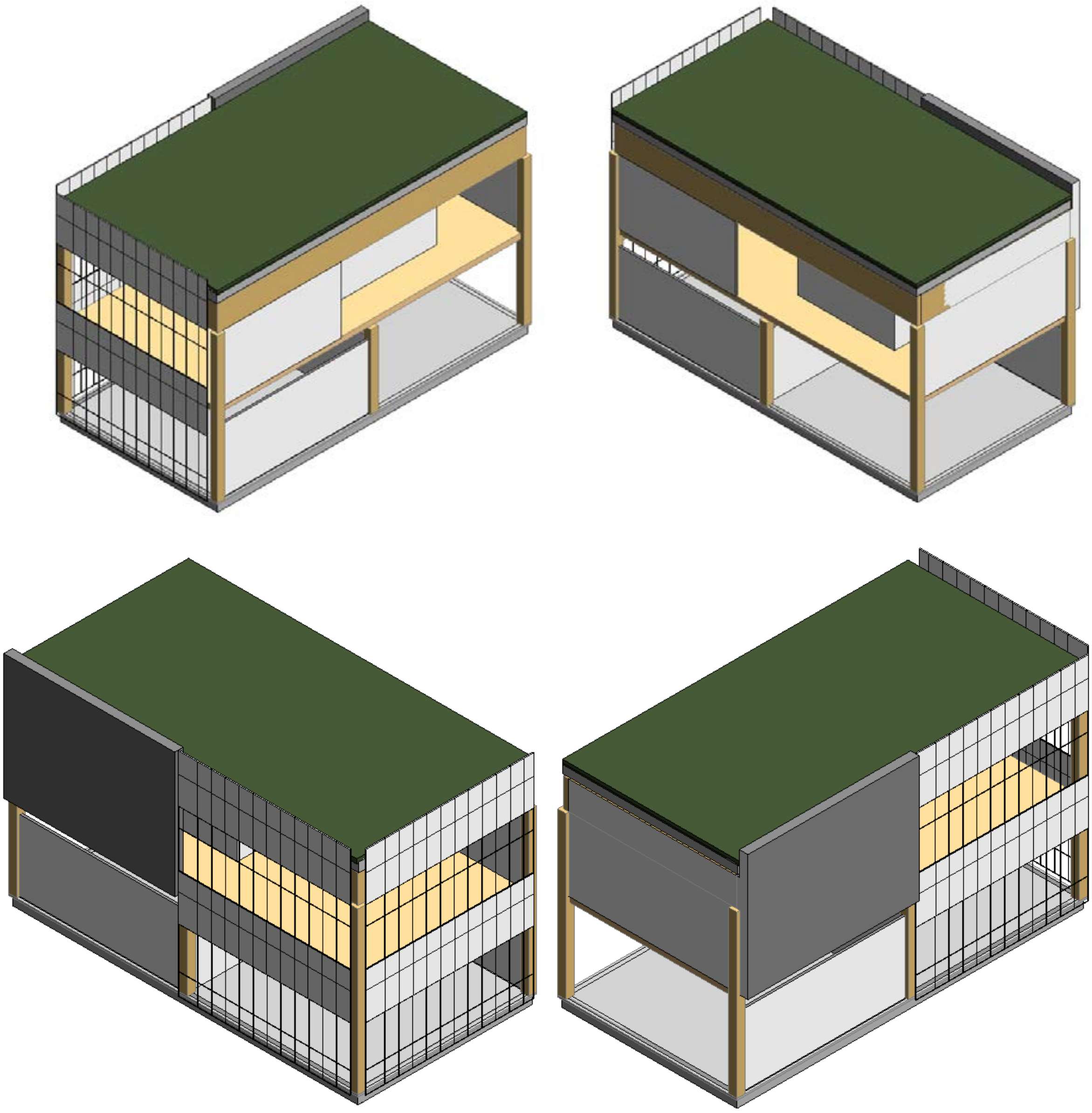
```
    font = Font("Arial", 8)
    brush = SolidBrush(Color.DarkBlue)
    # plot x-axis
    pen = Pen(Color.Black, 2)
    padx = -10
    pady = 10
    g.DrawLine(pen, xl, yl, xl, yl-5*h/8)
    g.DrawString(str(0),font, brush, xl+padx, yl+pady)
    # plot grid parallel to x-axis
    pen = Pen(Color.Gray, 1)
    dw = 3*w/(4*nDiv)
    for i in range(nDiv-1):
        xx = xl + i*dw+dw
        g.DrawLine(pen, xx, yl, xx, yl-5*h/8)
        g.DrawString(str(i*dx+dx),font, brush, xx+padx, yl+pady)
    # plot bar
    dh = h/(4*n)
    dh2 = 9*h/(n*16)
    for i in range(n):
        g.FillRectangle(brush,xl,yl-dh2*i-dh2,1.0*values[i]/maxV*5*w/8,dh)
        g.DrawString(labels[i],font, brush,xl-w/4+15+(maxL-len(labels[i]))*6, yl-dh2*i-dh2)

# plot pie, like subplot 4,5,
def myPie(g, x1, y1, w, h, data, title):
    # input g: current graphics
    # input x1,y1: the position of top left corner of subplot
    # input w,h : the size of subplot
    # input data :include values and labels and colors for each part of pie
    # input title : the title of this subplot
    values,labels,colors = data
    # center coordinate of pie
    centx = x1+w/2
    centy = y1+h/2
    n = len(values)
    # radius of pie
    r = min(w,h)/4
    rect = Rectangle(centx-r, centy-r, r*2.5, 2.5*r) # 2r width and height
    startAngle = -90
    total = 0.0
    addTitle(g,x1,y1,w,h,title)
    font = Font("Arial", 10)
    # function of labeling for each part of pie
    def pos(r, deg):
        alpha = -deg/180*3.141592653
        return centx+r*math.cos(alpha)-10, centy+r*math.sin(alpha)-10

    # add legend
    for i in range(n):
        brush = SolidBrush(colors[i])
        g.FillEllipse(brush,x1+10,y1+i*35+50,15,15)
        g.DrawString(labels[i],font, brush,x1+35, y1+i*35+50)

    for v in values:
        total += v
    # plot pie
    for i in range(n):
        brush = SolidBrush(colors[i])
        deltaA = values[i]/total*360
        g.FillPie(brush, rect , startAngle, deltaA)
        startAngle += deltaA

    # add label for each part of pie
    startAngle = -90
```

```
    for i in range(n):
        deltaA = values[i]/total*360
        percentString = '{:.2f}%'.format(values[i]/total*100)
        brushNum = SolidBrush([Color.Gold,Color.DarkBlue][i%2])
        x, y = pos(0.6*r,startAngle+0.5*deltaA)
        g.DrawString(percentString,font, brushNum, x, y)
        startAngle += deltaA

# plot loop, like subplot 7,8,9
def myLoop(g, x1, y1, w, h, data, title):
    # input g: current graphics
    # input x1,y1: the position of top left corner of subplot
    # input w,h : the size of subplot
    # input data :include values and labels and colors for each part of loop
    # input title : the title of this subplot
    values,labels,colors = data
    # center of lopp
    centx = x1+w/2
    centy = y1+h/2
    n = len(values)
    r = min(w,h)/4
    rect = Rectangle(centx-r, centy-r, r*2, 2*r) # 200 width and height
    startAngle = -90
    total = 0.0
    addTitle(g,x1,y1,w,h,title)
    font = Font("Arial", 10)
    # function of labeling for each part of loop
    def pos(r, deg):
        alpha = -deg/180*3.141592653
        return centx+r*math.cos(alpha)-10, centy+r*math.sin(alpha)-10
    # add legend
    for i in range(n):
        brush = SolidBrush(colors[i])
        g.FillEllipse(brush,x1+10,y1+i*35+50,15,15)
        g.DrawString(labels[i],font, brush,x1+35, y1+i*35+50)

    for v in values:
        total += v

    for i in range(n):
        brush = SolidBrush(colors[i])
        deltaA = values[i]/total*360
        g.FillPie(brush, rect , startAngle, deltaA)
        startAngle += deltaA

    brush = SolidBrush(Color.White)
    r_in = min(w,h)/6
    g.FillEllipse(brush,centx-r_in,centy-r_in,2*r_in,2*r_in)

    startAngle = -90
    # add label for each part of loop
    for i in range(n):
        brushNum = SolidBrush([Color.Gold,Color.DarkBlue][i%2])
        deltaA = values[i]/total*360
        percentString = '{:.2f}%'.format(values[i]/total*100)
        x, y = pos(0.6*r,startAngle+0.5*deltaA)
        g.DrawString(percentString,font, brushNum, x, y)
        startAngle += deltaA

# width and height of final saved image
imgW = 1200-16
imgH = 800-40
class IForm(Form):
```

```
    def __init__(self):
        self.Text = 'Assessment Report'
        self.Width = 1200
        self.Height = 800
        self.w = 400
        self.h = 260
        # fig 1
        # add button control
        button = Button(Text='Save')
        button.Click += self.click
        button.Height = 50
        button.Width = 120
        self.version = TextBox()
        self.version.Location = Point(180,89)
        self.changes = TextBox()
        self.changes.Location = Point(180,121)
        self.Controls.Add(self.version)
        self.Controls.Add(self.changes)
        button.Location = Point(self.w/2-button.Width/2, self.h*3/4-25)
        button.BackColor = Color.LightBlue
        button.ForeColor = Color.White
        self.Controls.Add(button)
        self.Paint += self.OnPaint
        self.CenterToScreen()
        #self.g.Save('a.png')
        self.image = Bitmap(imgW, imgH)

    def click(self, sender, event):
        #save image callback function
        #self.image.Save('Version{}.png'.format(self.version.Text))
        # fill in the absolute path of picture, like D:/a.png
        self.image.Save('{}'.format(self.version.Text))

    def OnPaint(self, event):
        values2 = IN[0]
        values3 = IN[1]
        values4 = IN[2]
        values5 = IN[3]
        values6 = IN[4]
        values7 = IN[5]
        values8 = IN[6]
        values9 = IN[7]
        values10 = IN[8]
        values11 = IN[9]
        g = event.Graphics
        self.g = g
        # set label before textbox
        font = Font("Arial", 14)
        brushNum = SolidBrush(Color.Black)
        g.DrawString('Version:',font, brushNum, 88, 88)
        g.DrawString('Changes:',font, brushNum, 88, 120)
        pen = Pen(Color.Gray, 1)
        w = self.w
        h = self.h
        addTitle(g, 0, 0, w, h, 'Assessment Report Information')
        for x in [w,2*w]:
            g.DrawLine(pen, x,  0, x, 3*h)
        for y in [h,2*h]:
            g.DrawLine(pen, 0, y, 4*w,  y)
        # plot each subplot
        # fig 2
        myBar(g, w, 0, w, h, [
values2,
```

```
values11,
], 'Material Mass(kg)')

    # fig 3
    myBar(g, 2*w, 0, w, h, [
values3,
values10,
], 'SCI')

    # fig 4
    colors = (Color.Gray, Color.DarkCyan, Color.DarkRed, Color.DarkOrange, Color.DarkSlateBlue, Color.DarkBlue)
    myPie(g, 0, h, w, h, [
values4,
( 'Input-Virgin', 'Input-Reused', 'Input-Recycled', 'Input-Biologisch'),
colors ] , 'Overrall Origin of Material')
    # fig 5
    myPie(g, w, h, w, h, [
values5,
( 'Output-Landfill', 'Output-Incineration', 'Output-Recycle', 'Output-Reuse'),
colors ] ,'Overrall Future Scenario of Materials'
)
    # fig 6
    myBar(g, 2*w, h, w, h, [
values6,
( 'Technical', 'Functional')
], 'Overall Lifetime(years)')
    colors = (Color.DarkCyan,Color.Gray,  Color.DarkRed, Color.DarkOrange, Color.DarkSlateBlue, Color.DarkBlue)
    # fig 7
    myLoop(g, 0, 2*h, w, h, [
values7,
('MCI', 'Other'),
colors ], 'Overrall MCI' )
    # fig 8
    myLoop(g, w, 2*h, w, h, [
values8,
('Disassmbly potential', 'Other'),
colors ], 'Overrall Disassembly potential' )
    # fig 9
    myLoop(g, 2*w, 2*h, w, h, [
values9,
('BCI', 'Other'),
colors ],'BCI')

    # save to image
    hdcSrc = g.GetHdc();
    hdcDest = GDI32.CreateCompatibleDC(hdcSrc)
    hBitmap = GDI32.CreateCompatibleBitmap(hdcSrc, imgW, imgH)
    GDI32.SelectObject(hdcDest, hBitmap)

    # 0x00CC0020 is the magic number for a copy raster operation
    GDI32.BitBlt(hdcDest, 0, 0, imgW, imgH, hdcSrc, 0, 0, 0x00CC0020)
    self.image = Bitmap(Image.FromHbitmap(hBitmap))
    User32.ReleaseDC(User32.GetDesktopWindow(), hdcSrc)
    GDI32.DeleteDC(hdcDest)
    GDI32.DeleteObject(hBitmap)
    g.ReleaseHdc(hdcSrc)
    g.Dispose()

Application.Run(IForm())
```

Appendix V Axial view of the Chosen Module in the New Weener XL



Appendix VI Building Product Circularity Database (Excel)

NL-SfB	Description	Product Code	Product Name	Product Descriptoin	Layers of Brand	Material	Weight(kg/m2)	Weight(kg/m3)	New (%)	Reused (%)	Recycled (%)	Biologisch (%)	Deposit (%)	Burn (%)	Recycly (%)	Reuse (%)	Techical lifetime(yr)	Funcational lifetime(yr)	MCIp
21.10	buitenwanden; niet constructief, algemeen (verzamelniveau)																		
		21.10.1	HoutSkeletBouw(HSB)basis 3	Timber 378mm	Skin	wood	0	470	0%	0%	0%	100%	0%	34%	66%	0%	75	75	0.85
21.14	buitenwanden; niet constructief, vlieswanden																		
		21.14.1	Kizijnen_vliesgeve aluminium	Kizijnen_vliesgeve alu	Skin	glass+alum	26.8	0	44%	0%	56%	0%	0%	0%	87%	13%	75	75	0.80
		21.14.2	Gelam. lariks (60x175); alumir	Gelam. larch (60x175);	Skin	wood+glas	27.8	0	12%	0%	3%	85%	5%	82%	13%	2%	50	50	0.55
22.10	binnenwanden; niet constructief, algemeen (verzamelniveau)																		
		22.10.1	Kantplank 175mm	Isulation toe board	Space plan	Insulation	0	30	91%	0%	9%	0%	6%	25%	65%	3%	75	75	0.45
22.23	binnenwanden; constructief, systeemwanden; vast																		
		22.23.1	Hsb 100mm	hsb 100mm	Structure	wood	0	510	0%	0%	0%	100%	0%	34%	66%	0%	75	75	0.85
		22.23.2	Hsb 150mm	hsb 150mm	Structure	wood	0	510	0%	0%	0%	100%	0%	34%	66%	0%	75	75	0.85
23.20	vloeren; constructief, algemeen (verzamelniveau)																		
		23.20.1	Druklaag 80mm	druklaag 80mm	Structure	concrete	0	2400	80%	0%	20%	0%	1%	0%	99%	0%	75	75	0.64
		23.20.2	Wooden floor 200mm	wooden floor 200mm	Structure	wood	0	450	2%	0%	0%	98%	0%	97%	3%	9%	100	100	0.55
		23.20.3	Concrete floor 200mm	concrete floor 200mm	Structure	concrete	0	2400	75%	0%	25%	0%	75%	0%	25%	0%	25	25	0.33
		23.20.4	Loose floor	loose floor	Structure	wood	0	1500	100%	0%	0%	0%	0%	0%	0%	100%	50	50	0.55
27.11	daken; niet constructief, vlakke daken																		
		27.11.1	Plantaardige membraan	Vetetable membrane	Skin	Plant	0	1500	74%	0%	26%	0%	65%	4%	11%	21%	75	75	0.36
		27.11.2	Beton	Concrete	Skin	concrete	0	2400	75%	0%	25%	0%	75%	0%	25%	0%	25	25	0.33
27.21	daken; constructief, vlakke daken																		
		27.21.1	Concrete roof (30% recycled) ir	Concrete roof (30% rec	Structure	concrete	0	2400	63%	0%	37%	0%	5%	8%	87%	0%	30	30	0.66
		27.21.2	Concrete roof (10% recycled) ir	Concrete roof (10% rec	Structure	concrete	0	2400	89%	0%	11%	0%	5%	8%	87%	0%	30	30	0.54
		27.21.3	Daken; niet constructief, vlakl	daken; niet constructie	Structure	Steel	70	0	30%	0%	70%	0%	23%	50%	22%	6%	30	30	0.54
28.11	hoofddraagconstructies; kolommen en liggers, kolom-/liggerconstructies																		
		28.11.1	Loofhout liggerconstructies	loofhout liggerconstru	Structure	wood	0	450	5%	0%	0%	95%	0%	100%	0%	0%	100	100	0.53
		28.11.2	Loofhout liggerconstructies_r	loofhout liggerconstru	Structure	wood	0	450	5%	0%	0%	95%	0%	0%	0%	100%	100	100	0.98
		28.11.3	Loofhout kolom	loofhout kolom	Structure	wood	0	450	5%	0%	0%	95%	0%	100%	0%	0%	100	100	0.53
		28.11.4	Loofhout kolom_reusable in t	loofhout kolom_reusa	Structure	wood	0	450	5%	0%	0%	95%	0%	0%	0%	100%	100	100	0.98
		28.11.5	Steel beams + columns	Steel beams + column	Structure	Steel	0	7800	70%	0%	30%	0%	0%	0%	49%	51%	75	75	0.69
28.31	hoofddraagconstructies; ruimte-eenheden, doosconstructies																		
		28.31.1	Timber structure frame hoog	Timber structure fram	Structure	wood	0	450	5%	0%	0%	95%	0%	100%	0%	0%	100	100	0.53
31.40	buitenwandopeningen; gevuld met puien, algemeen (verzamelniveau)																		
		31.40.1	Glas_buiten_25mm	glas_buiten_25mm	Skin	glass	22.5	0	100%	0%	0%	0%	100%	0%	0%	0%	75	75	0.10
		31.40.2	Paneel_vliesgevel_50mm	paneel_vliesgevel_50r	Skin	wood	30	0	100%	0%	0%	0%	85%	5%	10%	0%	45	45	0.15