Data-Driven Decision-Making for Circular Building Design

Development of an automated decision-support framework for an improved circular design workflow

M. van der Zwaag
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Development of an automated decision-support framework for an improved circular design workflow

By

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Preface

Before you lies the master thesis “Data-Driven Decision-Making for Circular Building Design: The development of an automated decision-support framework for an improved circular design workflow”. This graduation thesis finalises my double master’s degree for the Master of Science in Building Engineering and the Master of Science in Construction Management and Engineering, both at the faculty of Civil Engineering and Geosciences of the Delft University of Technology. This research was conducted from February 2022 to October 2022, in collaboration with the Royal BAM Group and the Delft University of Technology.

My interest for this subject started when I came in touch with data analytics during my master and at my part-time job as a data analyst. I was fascinated by how a data-driven mindset could help to improve the efficiency and efficacy of current practices in the construction industry. Next to this, I have always been interested in sustainable design. As a professional in a not so environmental friendly industry, the construction industry, you have to do your utmost best to contribute to a more sustainable industry. Therefore, the combination of Data-Driven Decision-Making and sustainability was the perfect research direction for me. In addition, I noticed during my study that I had the urge to implement the theoretical knowledge taught at the university into practice. I am pleased with this research, I did not only contribute to the academic world, but also developed a tool that assists professionals in real life with the design of circular buildings.

Looking back on this journey of writing my master thesis, I would like to express my gratitude to everyone who supported me along the way. First, I would thank Douwe for the guidance at Royal BAM Group and the inspiring discussions about data-driven working. Next, I would like to thank my graduate committee for their guidance, advice, and insight throughout the graduation process. My first supervisor Tong, thanks for the advice and feedback regarding the academic underpinning of my research. Her critical mindset and reflection helped me to improve the quality and added value of my research. Sander and Marco, thanks for the guidance on the development process of the tool and the interesting discussions about the practical views of the topic. And Hans, thanks for guiding this research into a manageable scope and for the feedback that led to a higher academic level of this research. Furthermore, I would like to thank my colleagues at Royal BAM Group for the warm welcome in the team. I had a great time at the office, meeting new people, and with interesting chats and discussions with everybody.

Next, many thanks to my fellow Building Engineering and Construction Management students for their continuous support during the study and for helping each other through the graduation process. A special thanks to my family for their support during my career, my girlfriend for always being by my side and keeping me motivated, and my friends for an amazing time in Delft!

For now, I hope you enjoy reading my thesis!

Marco van der Zwaag
Den Haag, October 2022

Executive summary

Introduction

It is well known that the construction industry belongs to one of the sectors with the highest waste generation and environmental impact (Nuñez-Cacho, Górecki, Molina-Moreno, & Corpas-Iglesias, 2018). Therefore, as one of the main contributors to environmental deterioration and climate change, the construction industry should step up and minimise its environmental impact by putting a halt to the linear economy and shifting to a more circular economy. This transition aims to eliminate waste, reduce harmful environmental emissions, and create a closed-loop system for resources. The emerging trend of Building Information Management (BIM) and Data-Driven Decision-Making could play an important role in this transition by facilitating the technological potential for circular building design.

Previous research has shown that there is a demand for tools that quantitatively support circular design in the early design phase. Currently, the assessment of building circularity is a time-consuming process which leads to circularity assessments only being used to evaluate the design afterwards. This research positively contributes to the transition to a circular economy by the development of a decision-support framework to support circular building design in the early design phase. Thereby, automation is an important aspect to speed up the circularity assessment process, so decision-support tools can be deployed as a steering instrument instead of only for evaluation. An improved workflow is generated to deal with the limited information available early in the design, while still performing a sound estimation of the circularity performance to steer the design process. To fulfil the development objective of this research, the following main research question was formulated:

"How can Data-Driven Decision-Making support circular building design during the early design phase?"

Methodology

To answer the research questions and to develop the decision-support framework, this research adopted a development cycle that consists of four phases: analysis, synthesis, simulation, and evaluation. The first phase consisted of a literature and exploratory study with semi-structured interviews. At the end of this phase, a circularity assessment method was determined and a system requirements specification was set up. In the synthesis phase, the program of requirements was translated into a practical solution with the development of a decision-support framework for circular building design in the early phases. After that, the framework was demonstrated, verified, and validated with the use of a case study in the simulation phase. In this phase, it was established whether the decision-support framework had met the functional and technical requirements of the analysis phase. Lastly, the results were interpreted, the conclusion was drawn, and future recommendations were given in the evaluation phase.

Results

This research aimed at developing a framework to support circular building design in the early design phase. To assess and steer circular building design quantitatively, the Building Circularity Index (BCI) measurement method was used. This method builds on the guidelines of Platform CB'23 for circular design and is an acknowledged method by the construction industry. The method was slightly adapted per design phase, so the framework can deal with the information scarcity in the schematic and detailed design. In the schematic design phase, circularity was assessed with an indicative BCI, which determines the material usage based on the BIM model and with potential disassembly scenarios based on the literature. A provisional BCI was used for the detailed design phase, which applies the complete BCI measurement method of Alba Concepts.

To develop a decision-support framework to integrate BIM and circular building design, a data platform with an automated connection was constructed between BIM models and an external material database. The data platform consists of three layers: a data, analytical, and application layer. The data layer collects all the necessary information in the form of project data in BIM and material data in external material databases. Essential is to capture the data input procedures in a BIM protocol to safeguard the data quality. Storage of the data and data analytic operations, like data cleaning, merging, and calculations, are performed in the analytical layer. In the application layer, a circular design dashboard was developed for the end-user where the results of the circularity assessment are presented dynamically and interactively suitable to support decision-making.

The framework was verified and validated by practitioners. This research showed that the decision-support framework can assist practitioners to steer on circular building design in the early design phase in the following way:

1. Motivate design choices between variants in a transparent way: the dashboard allows the end-user to substantiate design choices with objective circularity performance indicators. Besides that, the evaluation of the data quality contributes to the transparency and reliability of decision-making.
2. Support the design team with feedback on circular building design in early design phases: the decision-support framework gives the end-user a method, with indicative and provisional BCI, to assess the circularity in the schematic and detailed design phase. Furthermore, the circularity of a building can be assessed as a whole, or for individual building components.
3. Provide sustainability specialists with insight into the degree of circularity of the design: the tool allows sustainability specialists to investigate the circularity of design alternatives. Especially, the insight into the individual circularity indicators is a great addition because it decomposes the final score and therefore more effective circularity measures can be proposed targeting specific aspects.
4. A suitable interface of the tool for the intended audience: the interface of the tool is adjusted to the technical skills of the end-user. This makes the dashboard user-friendly and simple to use. Furthermore, the interactive and dynamic features of the dashboard contribute to a better user experience because more detailed analyses can be performed.

Conclusion

In the end, this research satisfied the main objective to develop a decision-support framework to support circular building design in the early phases. A suitable and quantitative circularity assessment is applied with an emphasis on the model maturity and level of information in the early design stages. Furthermore, the decision-support framework integrated the necessary information systems and automates the data analytical procedures to reduce manual procedures for circularity assessments. Like this, the circular design dashboard can be adopted as a steering instrument throughout the design phase instead of just an evaluation tool when decisions already have been made. The dashboard supports the design team by assessing the circularity of alternatives, it supports and substantiates design decisions, and sustainability specialists can gain insight into the degree of circularity of the design. All in all, the decision-support framework and circular design dashboard are useful and effective instruments for the design team to enhance circular building design.

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List of abbreviations

Abbreviation	Explanation
BAMB	Building as Material Banks
BCI	Building Circularity Index
BIM	Building Information Management
C2C	Cradle-to-cradle
CDE	Common Data Environment
CE	Circular Economy
DAX	Data Analysis Expression
DDDM	Data-Driven Decision-Making
DI	Disassembly Index
ECI	Element Circularity Index
EPD	Environmental Product Declaration
EMF	Ellen MacArthur Foundation
ETL	Extract, Transform, and Load
IDS	Information Delivery Specification
LCA	Life Cycle Assessment
LOD	Level of Development
MCI	Material Circularity Index
NIBE	Nederlands Instituut voor Bouwbiologie en Ecologie
NMD	Nationale Milieudatabase
PCI	Product Circularity Index
SRS	System Requirements Specification

1. Introduction

This chapter starts with an introduction of the research context by describing the transition to a Circular Economy (CE) and the upcoming trends of Data-Driven Decision-Making (DDDM). Next, a brief literature review is conducted to investigate the current problems and the knowledge gap. Based on this, a development objective and research questions are determined. Furthermore, the research scope and the methodology, or development cycle, are explained and the different ways of data gathering and analysing are elaborated. Lastly, a reading guide for this research is presented.

1.1. Research context

1.1.1. Transition to a Circular Economy

Nowadays, the construction sector is categorised as one of the least sustainable industries in the economy worldwide. It belongs to the sectors with the highest waste generation and environmental impact (Nuñez-Cacho, Górecki, Molina-Moreno, & Corpas-Iglesias, 2018). Currently, the consumption of natural resources is twice as much as the production, while in 2050 it could be tripled (Akhimien, Latif, & Hou, 2021). Next to the grow in resources, the exponential growth of CO_2-concentration and energy and water consumption is observed as well. The environmental deterioration and causes of climate change are leading to new agreements and sustainable approaches to the economy. As one of the main contributors, the built environment is under pressure to minimise its impact. To mitigate the pressure, the construction industry should halt the linear economy and enhance the transition to the CE.

The linear economy follows the principles of 'take-make-dispose', whereby raw materials are collected at the start, converted into useable products, and disposed of as waste at the end of life. The issue with the linear system is that a lot of materials need to be extracted from nature, while potentially valuable materials are being discarded. On top of that, the waste could harm the environment. The sustainable focus in the linear economy is on eco-efficiency (Di Maio, Rem, Baldé, & Polder, 2017). This means that the goal is to minimise the environmental impact while getting the same output. The opposed model to linear economy is the CE model which is proposed by the Ellen MacArthur Foundation (EMF). The circular system embraces the 'reduce-reuse-recover' principles. The focus is to eliminate waste and pollution, circulate products and materials, and regenerate nature. To achieve this, building elements and resources are held in a continuous loop of construct, use, reuse, repair, recycle, and back as material for new construction (Ingemarsdotter, Jamsin, Kortuem, & Balkenende, 2019). Furthermore, the aim is to maintain the highest intrinsic value for building components, if possible, which allows materials to be kept in repetitive loops. The transition from linear economy to CE is visualised in figure 1.

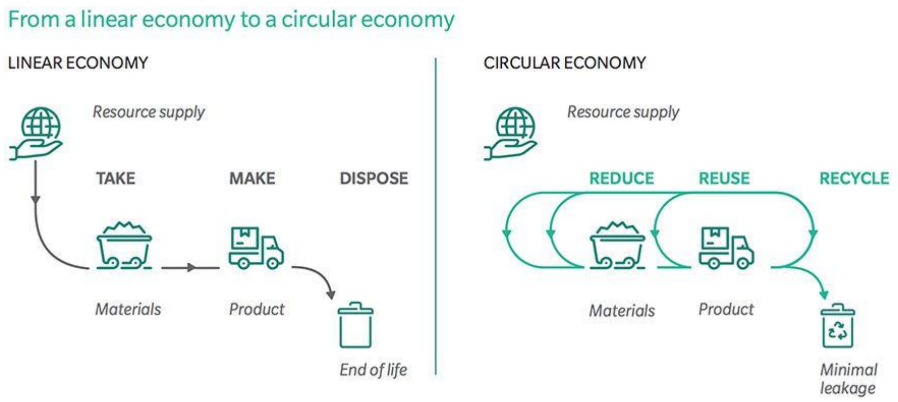


Figure 1: From linear to circular economy (Wyman, 2017)

In the built environment, the implementation of CE is relatively new so there is no standardised approach to measure circularity yet (Rahla, Bragança, & Mateus, 2019). In the future, circular building design could play a role in the decision-making of the development of concepts. If circular building design becomes more popular, circular building assessment methods can be deployed as benchmarks or to compare variants on circularity performance. In the past, different assessment methods have been developed focusing on circularity in general or on a single aspect of circularity. EMF and Granta Design (2019) developed a 'Circular Indicators Project' which consists of several tools that allow companies to append a circularity value to their products. One of the tools is the Material Circularity Indicator which provides an indication of the 'degree of circularity' focusing on minimising the linear flow and maximising the restorative flow. Following up on this method, Verberne (2016) has developed the Building Circularity Indicator (BCI) to assess circularity performance on material, product, system, and building levels. Furthermore, there is Platform CB'23 which is an organisation that develops working agreements, frameworks, guidelines, and material passports to achieve the circularity goals for the Dutch construction industry. They are currently working on a core method with guidelines to measure circularity for the construction sector.

1.1.2. Data-driven decision-making and Building Information Management

Nowadays, construction companies are not only constructing new buildings or bridges, but they are also generating tons of data during design, construction, and operation. All this data is collected, with Building Information Management (BIM), and can be used to better substantiate complex decision-making regarding scheduling, sustainability, or consulting the most viable design alternatives. BIM contributes to sustainable and circular building design through effective material selection, waste minimisation, energy-saving alternatives, and interoperability (Xue, et al., 2020). DDDDM and BIM could provide a huge opportunity for the adoption of CE. Especially because 96% of all data captured in the built environment is not effectively used by firms due to a lack of interoperability, information exchange procedures, and supporting technology (Thomas & Bowman, 2020).

The emerging trends of BIM and DDDM become more important as the construction industry embraces digital transformation. Project management can benefit from the rapidly growing amount of data in engineering and construction projects. The access to high-quality and timely available information allows project managers to make smart and informed decisions. DDDM is not just about having the right information systems and appropriate data analytics technology. It is about having facts, metrics, and data to guide managerial and actionable business decisions that align with a higher goal or objective, which is visualised in figure 2. It supports understanding the foundation of decisions by leveraging objective and accurate data instead of assumptions and gut decisions (Provost & Fawcett, 2013). DDDM comes with a couple of benefits for the construction industry (Emmanuel, 2021; Brynjolfsson, Hitt, & Kim, 2011; Stobierski, 2019). It creates more confidence in making decisions because a better understanding of the impact could be gathered. Also, decision-making becomes more proactive instead of reactive. Data-driven insight helps proactively steer projects in the right direction before they can grow in real problems. Furthermore, by effectively leveraging big data and operational information systems, patterns in processes can be detected, and project managers can be prepared for uncertainties along the process. Nevertheless, there are some pitfalls to data-driven processes (Thomson, 2017). First, the reliability and completeness of the data must be ensured to prevent unexpected outcomes. Second, too much data could also be counterproductive as it makes it more difficult to connect the dots. Lastly, it is important to be critical of data-driven analytics. Data analysis can be positively or negatively manipulated to achieve the desired results.

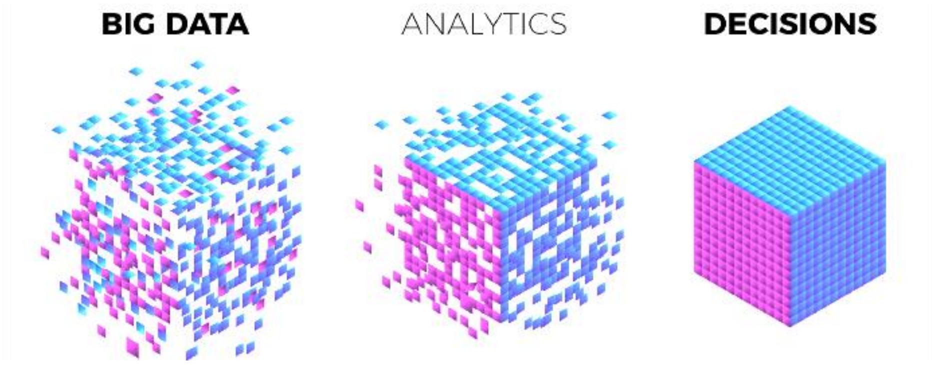


Figure 2: From data to decision-making (Wadan, 2020)

1.2. The Problem

This section dives deeper into the current problems regarding CE and DDDM. First, the problem statement is defined based on a literature review and internal meetings with the company. Afterwards, the knowledge or development gap of current circular assessment tools is identified and presented.

1.2.1. Problem statement

In recent years, the construction industry becomes aware of the upcoming transition from a linear to a CE. The interest in CE arises because of the growing environmental concern, material scarcity, and increasing demand for construction materials. The result of the linear system is that the construction industry is responsible for 33% of greenhouse gas emissions, 40% of raw material consumption, and 40% of waste generation (Askar, Bragança, & Gervásio, 2022). With the transition to CE, the new paradigm aims to eliminate waste, reduce harmful environmental emissions, and create a closed-loop system for resources. However, the construction industry struggles with the transition to a circular economy due to many challenges and the complex landscape. For example, at the company level, there are few common CE practices to measure circularity and evaluate performances (Sassanelli, Rosa, Rocca, & Terzi, 2019). Furthermore, there is a lack of motivation, awareness, and knowledge in the building industry for CE, especially for the end-of-life value of components in the design.

At the same time, the technology of building information modelling has been established with the implementation of national standards and guidelines. There is a growing interest in the use of BIM for sustainability purposes. BIM has great potential for achieving circularity goals through waste minimisation, material selection, green building design, and as a support tool for complex decision-making. Design support tools could benefit from the integration of BIM because of the accurate and adequate non-graphical information in the design process. It could assist in the design process by making better-informed decisions. Nevertheless, the problem with current design tools is that they do not fulfil the intended need and users' expectation, or that they are too complex, time-consuming, expensive, and not user-friendly (Cambier, Galle, & de Temmerman, 2020).

Following the interviews with professionals in the construction industry, it becomes clear that awareness of circularity increases, whereby more often circularity aspects are included in the design process. Organisations are still looking for suitable tools to support circular building design. Currently, the support tools are mostly qualitative in the form of guidelines and design principles, while there is a need for quantitative tools. Quantitative tools will support design decisions based on data and objective measurements instead of experience or personal preferences.

Besides that, professionals point out that the current assessment tools mainly focus on determining the circularity of buildings at the end of the design, while it is preferred to determine the circularity earlier on when most impact can be made. It would benefit the industry when decision-support tools are used as a steering tool when developing design alternatives, instead of an assessment tool to determine the final score of the design. In other words, become proactive instead of reactive. However, the issue is with the information management in the current workflow of the design. In the early design phase, information is uncertain and incomplete in the BIM environment. The maturity of a design develops throughout the design process, so also the non-graphical information increases. The usefulness and reliability of circular assessment methods to steer circular building design depend on the information availability per design phase. For example, in the schematic design phase is the BIM model too generic with limited non-graphical information. The building sequence is not yet known which makes it hard to estimate the disassembly potential of elements. Therefore, it should be considered that the circular assessment method fits with the available information per design phase. Currently, the available information at certain moments in time does not match with what is necessary to assess building circularity in the early design. It would help to revise the current design workflow to assess building circularity by integrating present technological potentials to improve the process.

Lastly, designing a building is an iterative and continuously developing process, which means that decisions have to be made for certain design choices. Therefore, time is a critical aspect when evaluating different design choices. Nowadays, the process of assessing circular building design involves mostly manual procedures which is time-consuming. The data from the building model with corresponding quantities are provided by the BIM specialists, which are used as input for tools that perform sustainability and circularity assessments. Thereby, the current procedure is that the element data is entered manually in circular assessment tools and connected with the right material data. The technological evolution of BIM makes it possible to streamline this process and connect different information systems to automate the process as much as possible.

1.2.2. Development gap

According to the literature, only a few tools address the end-of-life stage and material recovery assessment (Charef, 2022). Charef suggests linking the key principles of CE to the design phase, particularly the 'design for deconstruction', 'design for disassembly', and 'design for adaptability'. A lot of research is focussing on the integration of BIM and Life Cycle Assessment (LCA), while research on BIM and circular design strategies and circularity indicators are still under development. Where the theoretical implementation of circularity is quite well established, the building industry needs practical tools that assess circularity performances of design options and that stimulate the added value of circularity along the full lifecycle (Askar, Bragança, & Gervásio, 2022). Also, it is recognised by Xue et al. (2020) that the integration of CE into a BIM-based LCA for design is hardly considered in the literature. He points out that there is a need for simpler strategies where the interaction between CE, LCA, and design should be assessed. Especially, the adoption of CE in BIM-based studies lacks focus on the whole building assessment, where it is mostly on the element level (Xue, et al., 2020).

One of the shortcomings in current circularity assessment tools is that circularity is only assessed as an added value to sustainability while integrating the environmental impact and end-of-life options could result in a more elaborated assessment. There is a lack of approaches that assess and advise on the circularity of design options. Thereby, it is essential to evaluate design options based on automated circularity indicators (Askar, Bragança, & Gervásio, 2022). Furthermore, there is a need for complementarity of assessment tools instead of creating new ones from scratch. In literature, there are a few approaches for assessing circularity with BIM-based models in the design phase. The Building as Material Banks (BAMB) has developed a circular building assessment prototype to assess material resource flow during the lifetime of buildings. Also, Madaster has an assessment tool that allows the import of BIM models and assesses the building's circularity. However, these tools require inefficient and time-consuming manual procedures, while designing a building is an iterative process where for every step these procedures need to be redone (Zhang, Han, de Vries, & Zhai, 2021). Therefore, there is a need for more automated BIM-based circularity assessment tools that directly evaluate the building circularity during the design.

Previously, Akanbi et al. (2019) developed a BIM-based assessment tool to evaluate the disassembly and deconstruction performances on the whole building level. However, this research focuses only on two circularity aspects, reuse and recycling at the end-of-life phase. Also, Di Biccari et al. (2019) have managed to enrich a BIM model with visualisations of a circularity assessment for the whole building. Nevertheless, both these tools only focus on the whole building level, while in the early design phase it is needed for decision-makers to have insight into circularity performance on different levels and for multiple variants. Zhang et al. (2021) have partly tackled this problem by creating an assessment tool with Dynamo in Revit which evaluates the circularity on different building levels. The limitations of this model are the technical knowledge of Revit that is required and that it calculates the building circularity index without considering the environmental cost indicator of materials. It is investigated that increasing the circularity of buildings, can negatively influence the environmental impact (Saadé, et al., 2022). Therefore, there is a need to ensure both benefits in terms of circularity and the environmental impact of materials. This is also highlighted in a study by Kayaçetin et al. (2022) which stated that the circular assessment should be extended with tools that combine circularity and environmental impact methods. Another limitation of current circularity tools is the static presentation of the results which makes it difficult for decision-makers to investigate why certain building elements negatively influence the circularity score of a variant. To take circular assessment tools to the next level, interactive and dynamic dashboards could enhance user involvement and provide them with more elaborate analyses for circular building design (Nadj, Maedche, & Schieder, 2020). Hence, a dynamic and interactive assessment model is needed for a more comprehensive and convenient decision-making tool that automatically evaluates the building circularity and environmental impact on different levels during the early design phase of buildings.

After reviewing the knowledge gap from existing literature and exploratory interviews, the following concrete aspects can be summarised:

- There is a demand for circular decision-support tools to steer alternatives in the early phase of the design instead of an assessment at the end of the design phase.
- An improved workflow is necessary to match the level of information with a suitable assessment method in the early design phase.
- There is a need for automated decision-making tools that instantly evaluate and provide insight into the circularity of building design variants on different building composition levels.
- BIM-based circularity assessment tools that consider the integration of circular design principles and the environmental impact of building materials are missing.
- Not necessarily new circularity tools have to be created, but there is a need to complement and improve current quantitative assessment tools which do fulfil users' expectations.

1.3. Development objective

As mentioned before, the CE is a possible solution to minimise waste, environmental emissions, and raw material consumption. The higher goal of this research is to positively contribute to the transition from a linear to a circular economy for the building industry. Thereby, the main objective is to develop a decision-support framework for circular building design in the early design phase. The framework emphasises the level of information necessary for a suitable circularity assessment per design phase. The target is to create an automated and interactive circular design dashboard, as part of the framework, to provide the design team and sustainability specialists insight into the circularity performances of different components in design variants. This means that they are directly in control of the decisions made in the design process, and they can substantiate the design choices in a transparent and objective way. In this way, the design team can steer toward circular design early in the process. To instantly evaluate and assess the circularity performance of design variants, the framework will be developed with software that has great interoperability with BIM and high automation potential. More specifically, the decision-support framework will combine data from different information sources, like Revit and external material databases, and process the data with analytic tools to support the DDDM process by presenting the results in the form of a circular design dashboard.

The development gap of current circularity assessment tools is presented in the previous section. The decision-support framework developed during this master thesis used the current literature as a starting point. It expands the current assessment tools by developing a BIM-based decision-support framework that integrates the building circularity assessment with the environmental impact of building materials, which gives design managers the possibility for a more comprehensive sustainability evaluation of the design variants in the early design phase. In the early design, the framework distinguishes the level of development (LOD) of models in the schematic and detailed design. It deals with the fact that the reliability of circularity assessments depends on the data availability. The framework proposes a solution to steer on circular design with the available information per design phase. Besides that, an interactive and dynamic circular design dashboard will be created with a focus on design managers and sustainability specialists, while current research presented the assessment in a static way mainly suitable for BIM specialists and less user-friendly. An interactive and dynamic circular design dashboard allows the end-user to further investigate the circularity assessment with up-to-date data and interactive features rather than just viewing the results at a certain moment in time. It gives a better understanding of which building components or circularity aspects contribute to a certain circularity score, which helps them find solutions that can target a specific aspect or component.

1.4. Research Questions

To fulfil the development objective, the main research question is formulated. This main question is as follows:

"How can Data-Driven Decision-Making support circular building design during the early design phase?"

To guide the research in a structured way, the main research question is divided into three sub-questions which are presented figure 3.

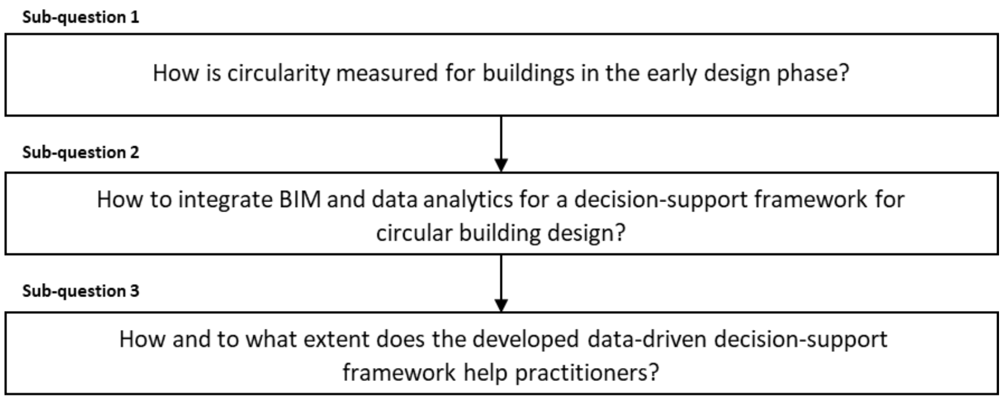


Figure 3: Sub-research question

1.5. Scope

Implementing DDDM to steer circularity performance is an extensive and multifaced topic. Therefore, the scope is narrowed down to make this research more manageable within the available time for a master thesis. Also, it is crucial to determine a fixed scope to obtain more specific knowledge in certain domains. In the table below, the choices that are made on the topics are elaborated.

Table 1: Research scope

Subject	Elaboration
Construction type	The construction industry in general is broad. It compromises three markets: building construction (residential and commercial), infrastructure construction (heavy civil industry), and industrial construction (off-shore, power-, and manufacturing plants, etc.). Each market has its characteristics and performance indicators. This research is limited to **commercial building construction** only. The reason for this is that according to the World Resources Institute, buildings are responsible for roughly 40% of waste production and consume approximately 40 % of the energy (Bergen & Driever, 2019).
Case study	The case study is a **fictive project, a retail store** because this fits perfectly as a construction type for commercial buildings. Besides that, the awareness of circularity increases among retail franchises. For example, Albert Heijn has the ambition to be CO_2-neutral by 2025. To fulfil this ambition, they opened the first circular supermarket in Gouda in 2018 as a pilot project and are planning to open more circular stores in the future (Dutch Green Building Council, 2018). For this research, the project is available as a Revit tutorial project in Autodesk. The LOD of the Revit data is adjusted per design phase according to the BIM protocol used at Royal BAM Group.
Building element	The purpose of the model is to assess the building as a whole and to assess components of the building as well. However, to have a manageable scope, only the **building structure, skin, and space plan** will be included. This excludes the electrical and mechanical systems, installations, and inventory. The system is set up generically so that afterwards it is easy to extend the model to other building components as well if necessary.
Lifecycle phase	A decision-support framework for circular building design is most beneficial when the impact is substantial, and the effort limited (Morkunaite, Naber, Petrova, & Svidt, 2021). Thereby, assessing the circularity of design variants in the **early design phase** gives the design team the possibility to successfully implement circular design principles in the design of different alternatives. At a later stage, implementation of circular design principles would be more costly, because the design is more or less fixed. In this research, the early design distinguishes the **schematic** and the **detailed design** phases.
Design criteria	The building design is an integrated process whereby all kinds of design criteria and performances are considered to evaluate different variants, like structural feasibility, construction cost, or aesthetics. However, this research will only focus on decision-making based on **circularity and environmental performance** of building variants.
Circular building principles and assessment method	The literature defines all types of building circularity strategies and assessment models. For example, the well-known 10R-model prioritises strategies based on their impact. However, not all strategies are suitable for building projects. In this research, circularity is assessed with the **Building Circularity Index**. This model is developed throughout the years, where different performance indicators are included, like Material Circularity Flow,

	disassembly possibilities, and environmental impact of materials. Thereby, the following design for circularity principles are included: **Design Out Waste, Design for Disassembly, and Design for Recover Output.**
Project Delivery Model	The complexity of building projects is increasing. Project teams need to integrate different types of stakeholder interests, like costs, scheduling constraints, circularity principles, or climate adaption. Therefore, to integrate circular building design, the design process should shift from a traditional to a more integrated process. Multi-disciplinary design teams have a broad spectrum of knowledge and experience which could be beneficial for decision-making in the design process. The implementation of the decision-support framework is most suitable for **integrated contracts, like Design & Construct**. However, this does not mean that it is not possible to use the framework in other types of contracts.
End-user of the circular design dashboard	The circular design dashboard is established for **the design team and sustainability specialists** to assess and compare the circularity performances of design variants. In this way, the design manager is in control of the decisions that are made, and the sustainability specialists have great insight into the circularity aspects of the variants and how to optimise this. Besides that, the dashboard could be used to show the client the decision-making process in a transparent way.

1.6. Development cycle (methodology)

This chapter describes the process of the master thesis and how the decision-support framework is developed. The objective is to develop a BIM-based system that can assess and compare the circularity of several design variants on different levels of building components. The development cycle for this master thesis consists of the analysis, synthesis, simulation, and evaluation phase. The development cycle is summarised in figure 4. In the end of this section, a roadmap for this research is presented in figure 5. The main activities are visualised together with the related sub-questions. This gives a clear overview of which steps need to be taken to achieve the main objective of this research.

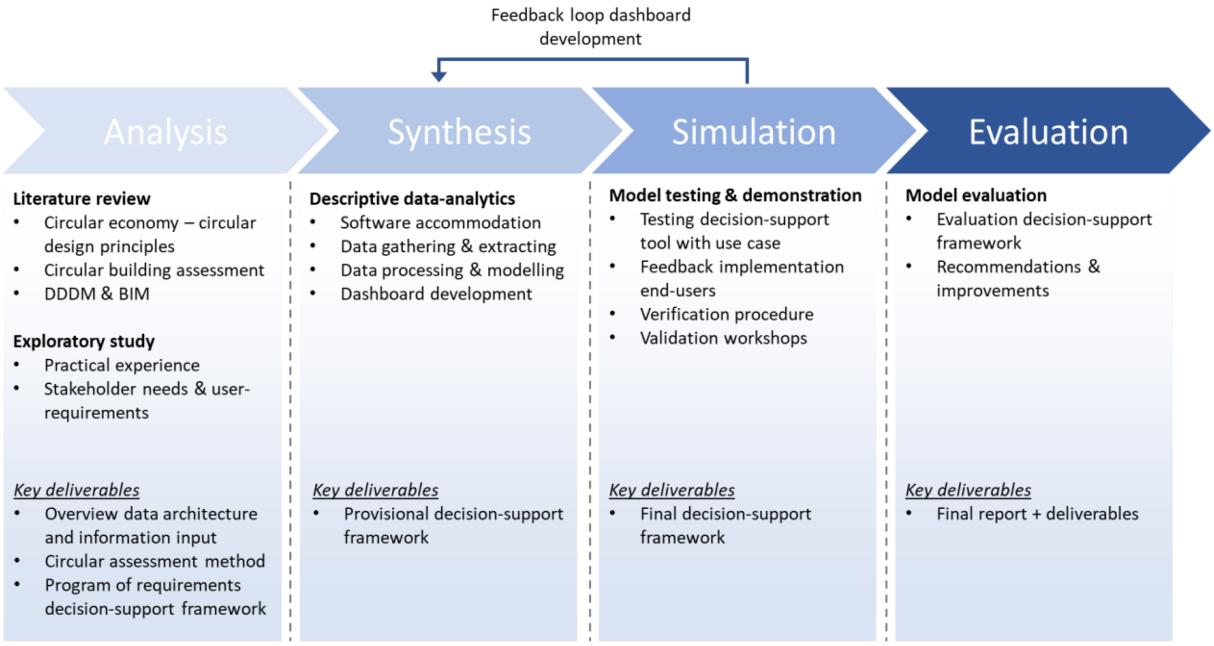


Figure 4: Research methodology

1. Analysis phase

The analysis phase is divided into two parts: the literature review and exploratory study. Both parts run parallel to each other because relevant information gathered from the literature can be used as input for exploratory interviews, and the other way around.

A literature review is conducted to get familiar with existing research and to gain theoretical- and background knowledge regarding circular building design and BIM-based decision-support tools. This literature review includes the following main topics: CE and circular design principles, circular building assessment methods, DDDM and BIM. In the meantime, an exploratory study is performed to strengthen the theoretical knowledge with practical information from the industry. This part consists of exploratory interviews with stakeholders and end-users to get insight into the current role of circularity in the design process, and the information management systems or BIM-landscape. Besides that, semi-structured interviews are held with possible end-users of the decision-support framework to determine their needs and wishes, and to establish a System Requirements Specification (SRS).

At the end of this phase, the research focus in terms of circularity and circularity assessment methods is mapped out and a SRS for the decision-support framework has been drawn up. With the information from the analysis phase, sub-question 1 can be answered.

2. Synthesis phase

In the synthesis phase, the results from the literature study and the SRS will be translated into a practical solution, a provisional decision-support framework for circular building design. It starts with gathering and extracting the necessary data and practicing how information sources and data analytic tools can be integrated. Thereby, attention is paid to ensuring the data quality principles to gather usable and high-quality data. Next, data modelling is needed to clean and process information to deal with the different information sources, the connection between the BIM model and corresponding material data, and to obtain the circularity indicators. Once the data is gathered, extracted, and processed, it is analysed and visualised with business intelligence tools. An interactive and dynamic dashboard is developed which acts as a decision-support tool to assist data-driven decisions based on high-quality information about the design variants. The dashboard development is an iterative process with end-user to gain feedback on how the circularity performance indicators are defined and how the data is presented to get effective insights on the design variants and to improve the quality of managerial decisions. The key deliverable is a provisional circular design dashboard ready for demonstration on a pilot project. Also, the second research sub-question can be answered.

3. Simulation phase

In the third phase, the simulation phase, the decision-support framework is verified with a pilot project and validated by potential end-users. A simulation takes place to test and demonstrate the solution and see if the actual behaviour of the system met the desired behaviour. Thereby, an internal test in an artificial environment is performed to verify the operations in the decision-support framework step-by-step and to see if the system runs as intended without technical defects. Also, workshops are conducted with practitioners to validate whether the needs and expectations of the circular design dashboard are fulfilled. If the system is not running perfectly, requirements are not met, or the dashboard does not satisfy the end-user's needs, the model will be adjusted. Iterations are made until the decision-support framework satisfies the verification and validation procedure. In this phase, the last research sub-question can be answered.

4. *Evaluation phase*

In the last phase, the evaluation phase, the decision-support framework is evaluated based on the results of the validation and verification. The theoretical and practical findings are discussed, the shortcomings of the decision-support framework are mentioned, and the conclusion is presented. In the end, recommendations are given for further improvement and implementation of this research.

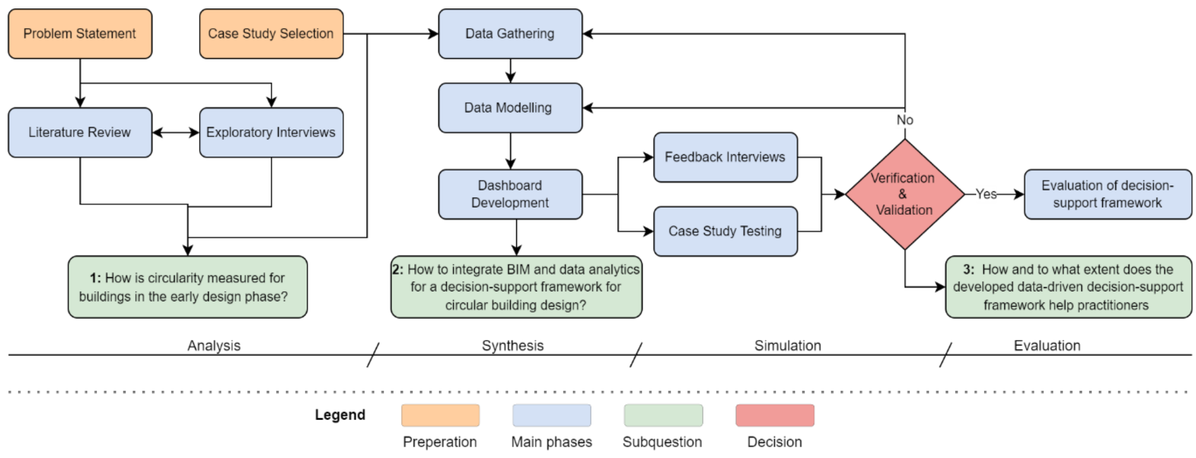


Figure 5: Research Roadmap

1.7. Data gathering and analysis

In this section, the different categories of data gathering are explained: qualitative and quantitative data. Furthermore, it is elaborated on what method is used to analyse the data. After that, it is explained which software is used during the process of gathering, analysing, and presenting the data.

1.7.1. Qualitative Data Gathering: Interviews

First, the qualitative data gathering consists of an exploratory study of circular building design, DDDM, and input for the program of requirements. This is based on interviews with key stakeholders who serve information about circular building design, supporting software, and building information modelling, and interviews with end-users to determine their needs and wishes for the decision-support framework. The interviews will be conducted in a semi-structured way. This means that it consists of some predetermined questions to lead the direction of the interview and sketch the context but will leave space for the exploratory nature of the interviews. The participants for the interviews are selected using a purposive sampling method. This method is mostly used for exploratory studies where specific groups will be targeted to deliver desired information which leads to better insight and results. Table 2 presents an overview of the interviewed participants.

Table 2: List of interviewees

	Organisation	Role	Subject
Stakeholders: decision-support framework			
Participant 1	Royal BAM Group	Head of Department: Digital Construction Program	Digitalisation & decision-support tools
Participant 2	Royal BAM Group	Project leader BIM	Building Information Management
Participant 3	Royal BAM Group	Specialist Digital Construction	Information Management & data analysis
Participant 4	Royal BAM Group	Project leader Sustainable Buildings	Sustainability and Circular design
Participant 5	Alba Concepts	Consultant Circularity	BCI measurement method

End-user: circular design dashboard			
Participant 6	Royal BAM Group	Manager Sustainability and Environment	Circularity in the design process & Program of Requirements
Participant 7	Royal BAM Group	Manager Sustainability IP	
Participant 8	Royal BAM Group	Design leader – Civil	
Participant 9	Benthem Crouwel NACO	Design team / architects	

1.7.2. Quantitative data gathering: Information Systems of case study

Next, quantitative data is gathered from the case study. For this study, quantitative data refers to the model geometry, data stored in the BIM models, and factual data from external information sources. To develop the decision-support framework properly, the following data is gathered:

- BIM model of case study: Revit tutorial
- NL-SfB classification scheme
- Environmental Product Declaration database: Nationale Milieudatabase (NMD), Nederlands Instituut voor Bouwbiologie en Ecologie (NIBE)
- Building circularity database of BCI Gebouw & Alba Concepts

The Revit tutorial, NL-SfB classification, and NMD or NIBE material databases are all open-source and available online. The circularity database of Alba Concepts is not open-source and a license is necessary. However, this database is based on the information from the NMD and NIBE which is available, so it companies can gather the product information needed for this research.

1.7.3. Data analysing: descriptive data analysis

In a construction project, a lot of data is generated with different information systems in an unstructured way. Therefore, data analytics can play an important role. Data analytics can be divided into five categories: diagnostic, descriptive, predictive, prescriptive, and cyber analytics (Morris, 2021). This research will be limited to descriptive data analytics. Descriptive data analysis tries to identify problems and opportunities by studying current processes. It is used to provide KPIs and metrics to track project performances and assists with the conversion of raw data into an easily understandable and interpretable form. Data analytics can help detect patterns, trends, or insightful information by describing, relating, showing, and summarizing data from information sources. It can analyse real-time and historical data which gives insight into how to steer the design process or manage projects (Provost & Fawcett, 2013). The advantage of descriptive data analysis is that it has a high degree of objectivity and neutrality which initiates decision-making based on objective data instead of intuition or experience. The downside is that the focus is on past performances without looking beyond the data. In-depth analysis requires diagnostic, prescriptive or predictive analytics.

The structure of this research is made in such a way that it suits the procedures for descriptive data analytics (Morris, 2021). This stepwise procedure for descriptive data analysis is as follows:

1. State business metrics: identify the metrics for circularity performances in the design phase of building projects based on literature review and exploratory interviews
2. Identify data required: exploratory interviews to locate necessary data from different information systems and to involve the end-user at an early stage
3. Extract and prepare data: data modelling by gathering and processing data from information systems to usable and high-quality state

4. Analyse data: aggregation and mathematical operations to analyse data with business intelligence tools
5. Present data: presenting data in visual forms which makes it easy to understand and interpret for making decisions

1.7.4. Software

Different software tools are needed in phase 2 for the development of the decision-support framework. Essential actions for data science are extracting, processing, analysing, and visualising the data. A brief market analysis is performed to evaluate multiple applications and data workflows. A summary is presented in Appendix A: Market analysis software.

For this research, Revit Autodesk is used as the core program for the design models because it is one of the most common design tools in the construction industry. Furthermore, Dynamo in combination with Python is used for data extraction to have high flexibility and potential for data extraction. Dynamo is a visual programming framework which can automate the manual procedures for data extraction and enables freedom in the desired exporting file types. Python is used as the programming language to extend the data mining possibilities and smoothen the process. Python is used to clean, process, and perform the calculations for the assessment. Python offers many data-oriented feature packages that save time to process and clean the data, and which are valuable for analytics.

In the next step, Power BI is used to analyse, visualise, and report the data. Power BI is a cloud-based analysis service used to extract and visualise data from multiple information sources. Thereby, it creates an analytical environment with interactive and dynamic dashboards to monitor and control the projects. The benefit of Power BI is that it provides the right data to the right user at the right time with applications on different devices. This could be helpful to have quick access to high-quality data to make certain decisions. Also, the use of publicised Power BI dashboards does not require a high level of expertise, which makes it suitable for design managers and sustainability specialists to use the design tool.

1.8. Thesis guide

This section contains the outline of this research project. It consists of eleven chapters in four phases:

1. Introduction:
   The first chapter contains the research framework of this thesis. This includes the research context, problem statement, research objective, scope, methodology, and data gathering and analysing procedures.

PART 1 – ANALYSIS PHASE

2. Theoretical framework:
   Chapter 2 describes the theoretical framework and the results of the literature study. Thereby, the focus is on the CE, circular building design and assessment methods, and digitally informed decision-making with BIM.

3. System Requirements Specification:
   This chapter compromises the SRS for the decision-support framework. The requirements are drawn up based on the exploratory study and interviews.

PART 2 – SYNTHESIS PHASE

4. Framework introduction:
   Chapter 4 introduces the decision-support framework. The concept of the system is explained, the workflow of circular design, and the applied design phases.

5. Circular assessment method:
   The next chapter explains the BCI measurement method that is used for this research. The important aspects of the method are highlighted and summarised. Also, a slightly adapted assessment method is proposed.

6. Framework design:
   Chapter 6 presents the design steps for the decision-support framework. It goes through all the essential steps and choices that are made to construct the framework.

PART 3 – SIMULATION PHASE

7. Circular design dashboard:
   Chapter 7 presents the end product of the decision-support framework, the dashboard for circular building design. Furthermore, the case study for the simulation phase is presented.

8. Verification and validation:
   The verification and validation procedures are performed in chapter 8. The verification is done to check if the framework is constructed correctly, while the validation process determines if the framework fulfils the end-user's needs.

PART 4 – EVALUATION PHASE

9. Discussion and limitations:
   The following chapter discusses the practical and theoretical findings of this research. Furthermore, the shortcomings of the project are highlighted.

10. Conclusion:
    Chapter 10 presents the conclusion of this research. This chapter answers the sub-research questions and eventually the main research question.

11. Recommendation:
    The final chapter contains recommendations for future research and further development of the decision-support framework.

PART 1 | ANALYSIS PHASE

The starting point for this research is the analysis phase. This phase consists of a literature review and an exploratory study. The literature review comprehends a theoretical framework that provides insight into the current situation regarding the CE and digitally informed decision-making. The exploratory study broadens the theoretical knowledge with practical information and results in the program of requirements of the framework according to the needs and wishes of the end-user.

2. Theoretical framework

To understand the importance of the objective of this research, it is meaningful to know the reason why the industry moves toward a CE. Therefore, this chapter starts with an elaboration on the CE as a concept. Afterwards, it explains how the concept and principles of the CE can be translated to circular building design strategies. Furthermore, it describes how these circular building design strategies could be evaluated with building circularity assessment methods. Several methods are explained with their advantages and disadvantages. In the end, this chapter answers the first sub-research question:

"How is circularity measured for buildings in the early design phase?"

Additionally, digitally informed decision-making is introduced to utilise the current technology of DDDM and BIM with circular building design. This part sets the theoretical basis for the second sub-research question:

"How to integrate BIM and data analytics for a decision-support framework for circular building design?"

2.1. The transition from a linear to a circular economy

The United Nations Brundtland Commission has defined sustainability as follows: "meeting the needs of the present without compromising the ability of future generations to meet their own needs. (Brundtland, 1987)". Sustainable development is based on three important pillars: the social, economic, and environmental pillars. These pillars are important for circular development, whereby technical solutions are needed to solve the economic and environmental problems regarding finite resources (Munaro, Tavares, & Bragança, 2020). For example, in the built environment, constructions are designed as permanent structures with an average technical and functional lifespan of 50 – 75 years. However, buildings are demolished way earlier because they do not fulfil the users' needs or have a low return on investments due to the reduced service life (Debacker & Manshoven, 2016). If it is not possible to effectively remove and reuse building components during the demolition of buildings, the result is an increase in waste production and material consumption. Therefore, circular building design could enhance the transition to a more sustainable sector. In other words, sustainability can be seen as the end goal, where CE is a roadmap towards a sustainable economy (Munaro, Tavares, & Bragança, 2020).

The evolution of circularity principles exists in several major schools of thought. First, the concept of CE emerged back in the 1980s, when Frosch and Gallopoulos (1989) introduced a new paradigm of a more integrated industrial ecosystem. They recommend substituting raw input materials with the outflow of other industrial processes. Circularity became more prominent in the late 1990s, with the concept of William McDonough and Michael Braungart (2002), who developed the cradle-to-cradle (C2C) framework. They identified two circular loops: the technical and biological cycles of nutrients. The biological cycle focuses on the products of consumption, whereby the consumed products will be safely returned to the earth as biological nutrients. In the technical cycle, existing products are re-utilized as technical nutrients, with no contamination, for new products. Furthermore, CE gained attention when the underlying principle of C2C was adopted by the EMF. Ellen MacArthur came up with a system that has the intention for design to be restorative and regenerative. Thereby, the use of renewable energy is promoted, the use of toxic chemicals is eliminated, and waste is minimised through the superior design of materials, products, and systems (Ellen MacArthur Foundation, 2013a). More recent platforms that adopt circularity are the BAMB and Platform CB'23. BAMB is a European project which investigates circular ways to increase the value of building materials and systems. With new methods and tools, such as reversible building design and material passports, they aim to prevent waste and minimise virgin resources. CB’23 is a national platform with the ambition of a CE by 2050. They are connecting all initiatives and pilots sector-wide and developing a uniform approach with guidelines for circular construction.

2.1.1. The concept of CE

Throughout the years, the different schools of thought all have slightly different definitions of the concept of CE. Although the definitions differ, they share the same principle: transforming from a linear to a circular economy by reducing waste. In line with the current academic, policy, and industry consensus, and based on previous literature, the following definition of circularity is used in this research (Nobre & Tavares, 2021):

> *“Circular Economy is an economic system that targets zero waste and pollution throughout materials lifecycles, from environment extraction to industrial transformation, and final consumers, applying to all involved ecosystems. Upon its lifetime end, materials return to either an industrial process or, in the case of a treated organic residual, safely back to the environment as in a natural regenerating cycle. It operates by creating value at the macro-, mezzo- and micro levels and exploits to the fullest the sustainability nested concept. Used energy sources are clean and renewable. Resources use and consumption is efficient. Government agencies and responsible consumers play an active role ensuring correct system long-term operation.”*

This concept comprehends previous circularity principles and concepts, makes use of tools and techniques that apply CE to all three system perspectives: macro, mezzo, and micro, and is meant to achieve the balance among the environmental, economic, and social pillars. The main circularity principles in this concept are reducing waste and pollution, shifting to renewable sources, and increasing the effectiveness of the material lifecycle.

In conjunction with this concept, one of the most popular and common CE frameworks which provide a comprehensive visual understanding of the concept of CE, is the Butterfly framework, presented in figure 6 (Ellen MacArthur Foundation, 2013a). In the butterfly model, the principles of C2C of McDonough and Braungart are adopted by implementing the biological cycle (left) and technical cycle (right). The top of the model illustrates the preservation of natural capital. It separates renewable feedstock and finite materials. As input material, clean and renewable energy is fed into the process and can decompose, while minimising finite materials and toxic components. The second part enhances the usefulness of products, materials, and components and keeps them in the loop at their highest utility and values. In the centre, the economic model, the manufactured parts, products, and services are separated to facilitate a continuous reintroduction of components in the system. The technical cycle aims to keep materials, products and components circulated in the economy for as long as possible. The most effective cycles are the maintenance and reuse of products which preserve the product value and increase the lifespan. When a product becomes obsolete, parts can be refurbished for other products. Lastly, the materials can be recycled and used as raw material for new production. The strategy of the biological cycle is to restore nutrients and rebuild natural capital. Materials are renewable in nature and additional value can be created by cascading for other applications. Furthermore, the conversion of biological nutrients can produce high-value chemicals or fuels. Other organic materials, like food waste or sewage sludge, can be composted or anaerobically digested to extract valuable nutrients. In the end, the systematic leakages and negative externalities are minimised. In this research, the newly developed concept by Nobre and Taveres and the Butterfly framework of EMF are adopted as concepts for circularity.

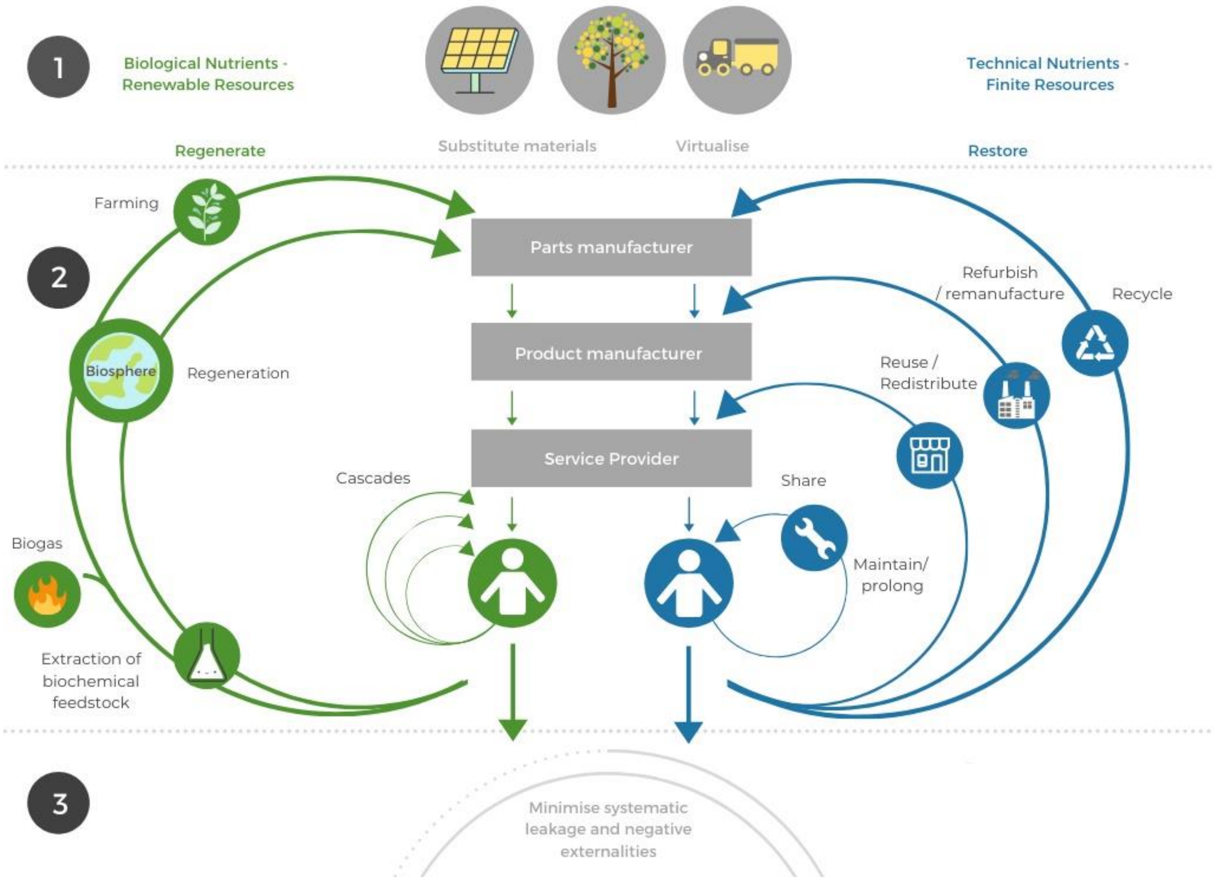


Figure 6: Circular economy system: Butterfly diagram (Ellen MacArthur Foundation, 2013a)

2.1.2. Circular economy principles

As mentioned previously, the CE concepts and schools of thought are gaining momentum, with many new circularity definitions in the past years. The circular approach could have a different meaning for different people. Nevertheless, a consensus is developed on core principles among practitioners. The most employed and accepted definition of CE is the one of EMF (Kirchherr, Reike, & Hekkert, 2017). The EMF embraces the following core principles: regenerate nature, circulate products and materials, and regenerate waste (Rahla, Mateus, & Bragança, 2021; Ellen MacArthur Foundation, 2013a).

1. ***Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows***

The first principle aims to regenerate nature or in other words, build natural capital instead of degrading the environment. The shift from a linear to a circular economy comes together with the shift to regenerate sources instead of extract. The starting point for this principle is dematerialisation. Thereby, critical thinking about the need for production is necessary. In case the product is necessary, the focus must lay on the selection of renewable or better-performing resources as input material instead of finite material. The complete system, including processes and technology, should run on renewable energy sources instead of fossil fuels. Thereby, the resource-consuming society is the true bottleneck (Ellen MacArthur Foundation, 2013b). Integrated systems are needed to capture the energy value of by-products efficiently. This solution will increase the demand for human labour which is beneficial because there is no shortage of labour, so human labour should be utilised more in the long term.

2. ***Optimise resource yields by circulating products, components, and materials at the highest utility at all times in both technical and biological cycles***

The second principle aims at retaining the intrinsic value of materials and products by circulating them as long as possible in the economy. The circulation of products and materials can be achieved through the technical or biological cycle, explained in the butterfly model. In these cycles, value can be best retained in smaller cycles, such as maintaining, reusing, and cascading. Currently, the economy consists of products that are not suitable for circulation in one of the cycles. These products cannot be separated and reused which results in waste. Therefore, for successful circulation of products, the future circulation processes must be already kept in mind during the design.

Circularity is a complex, non-linear and feedback-rich system, whereby a flexible approach is needed to adapt easily to dynamic circumstances (Ellen MacArthur Foundation, 2013b). Therefore, system thinking is an essential ability to optimise resources. The understanding of the system as a whole is crucial. Different parts within a system influence each other, the relationship between parts and the system, and the connection between elements and environmental and social context need to be considered as well. Also, resilience needs to be built to deal with the continuous development of systems. Resilience can be created through diversity. The resilience of diverse systems with multiple nodes, connections and scales prove to be higher when facing external shocks (Ellen MacArthur Foundation, 2013b).

3. ***Promote system effectiveness by revealing and designing out negative externalities.***

The last principle is preventing negative externalities by eliminating waste and pollution. This is in line with the transition from a take-make-dispose system to a reduce-reuse-recover system. In the current linear system, finite resources are extracted while the waste gets lost or ends up in landfills. To shift to a CE starts by treating the current design flaws of the linear production process and making sure that, at the end of life, material could re-enter the economy. In other words, it is needed to design out waste. Non-toxic biological materials can re-enter earth through composting and anaerobic digestion, while technical materials need to be designed in such a way that they can be reused or recovered with maximum retained quality.

2.2. Circular building design strategies

CE principles are often generic and can be used as starting point for circular design strategies. Scaling the circularity principles to circular design strategies for the built environment holds the commitment to minimise the environmental impact of building materials and keeping resources and products in the economy at the end of life. Essential circular building design concepts are the building layers 6S-model and the circular product design with the 9R-framework. Based on these frameworks, design practices, like the design for adaptability, flexibility, and disassembly, are introduced to design for a CE.

2.2.1. Building layers 6S-model

The optimum use of resources and preserving the value of building components is in correlation with the lifespan of building components. Brand has investigated circular design strategies, incorporated system thinking, and came up with the widely known six, or shear, layers framework (Brand, 1995). According to this framework, six different but interlinked layers are distinguished in buildings, each with an associated technical and functional lifespan which can be seen in figure 7. The following layers are distinguished in the 6S-model:

1. Site: the geographical setting and location of the building.
2. Structure: the structure consists of the foundation and main load-bearing elements.
3. Skin: the skin is the exterior surface of the building such as the façade and roof.
4. Services: electrical and mechanical systems like HVAC, wiring, piping, plumbing and elevators.

5. Space plan: non-load bearing elements which define the interior layout.
6. Stuff: furniture and lighting

The idea behind this concept comes from processes in nature, where different processes operate on different timescales, while there is no information or energy exchange between them (Salthe, 1993; O'Neill, DeAngelis, Waide, & Allen, 1986). Brand translates this concept to adaptability for buildings: in an adaptive building, slippage between the six differently-paced layers must be allowed. If not, the slow-paced layers will obstruct the flow of quicker layers while the quick ones demolish slower layers with their constant change (Brand, 1995). This principle of 'pace-layering' allows a circular design with maximum adaptability. The adaptability capacity can be increased if the layers are separable and demountable (Platform CB'23, 2020a). This ensures the retained value if adjacent layers need to be adapted.

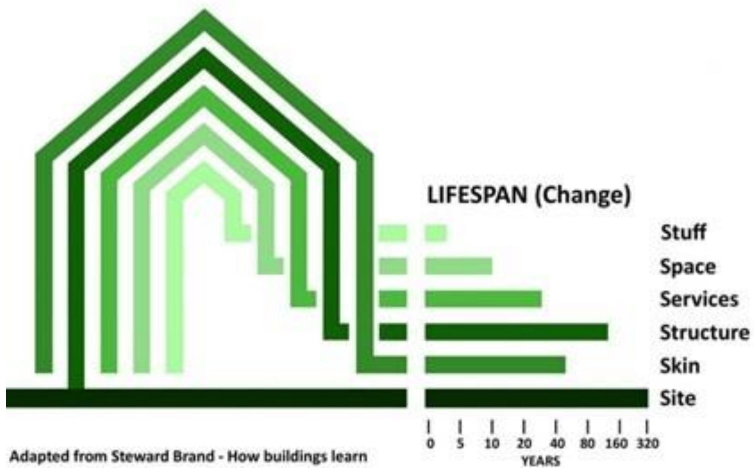


Figure 7: Stewart Brand's 6S-model (NxtGen Houses, 2021)

2.2.2. 9R-framework

The next circular building design concept is the 9R-framework by Potting et al. (2017). This framework orders the effectiveness and power of circularity strategies. Various academia and practitioners implemented the 9R-framework as starting point and rules of thumb for circular design. It started with the 3R-framework, with reduce, reuse, and recycle, but this is expanded to a proposed 9R-framework as the latest version (Kirchherr, Reike, & Hekkert, 2017; Platform CB'23, 2020a). As presented in figure 8, the circularity strategies are prioritised according to the level of circularity. Generally, the strategies for smarter product use and manufacture are preferred over extending the lifetime or useful application for materials. The higher the level of circularity, the fewer the depletion of natural resources and environmental pressure. This is in line with the second circularity principle of retaining the highest intrinsic value of products and materials. In the 9R-framework, the lowest group of strategies (recycle and recovery) is related to the waste hierarchy where materials are obtained from recycling and energy is conversed from recovery processes. However, the energy and material conversion yield rates are low, with expensive treatment procedures, and destruction of products' integrity (Morseletto, 2020). The second group, to extend the lifetime of products and components, consist of five strategies: repurpose, remanufacture, refurbish, repair, and reuse. These strategies focus on retaining the intrinsic value of materials and products while keeping the goods as long as possible in the economy. Repurposing products means that discarded products are used as products with a different function, also called open-loop reuse (Willskytt, Böckin, André, Tillman, & Ljunggren, 2016). Remanufacture, refurbish, or repair aims to postpone or reverse the extinction of products.

Typically, a product can be subjected to one of these three strategies but cannot be treated simultaneously. The reuse strategy refers to products that are in good condition that can be reused by a second owner while retaining the same function. Furthermore, the highest circularity group encompasses reduce, rethink, and refuse. This group focuses on circularity before production takes place and therefore favourable for the implementation of design strategies (Morseletto, 2020). Reducing requires fewer natural resources in terms of energy, raw material, and waste. Rethink aims at increasing the usage intensity for products, including dematerialisation. Lastly, the refuse strategy refers to making a product over-abundant by fulfilling the function with different products.

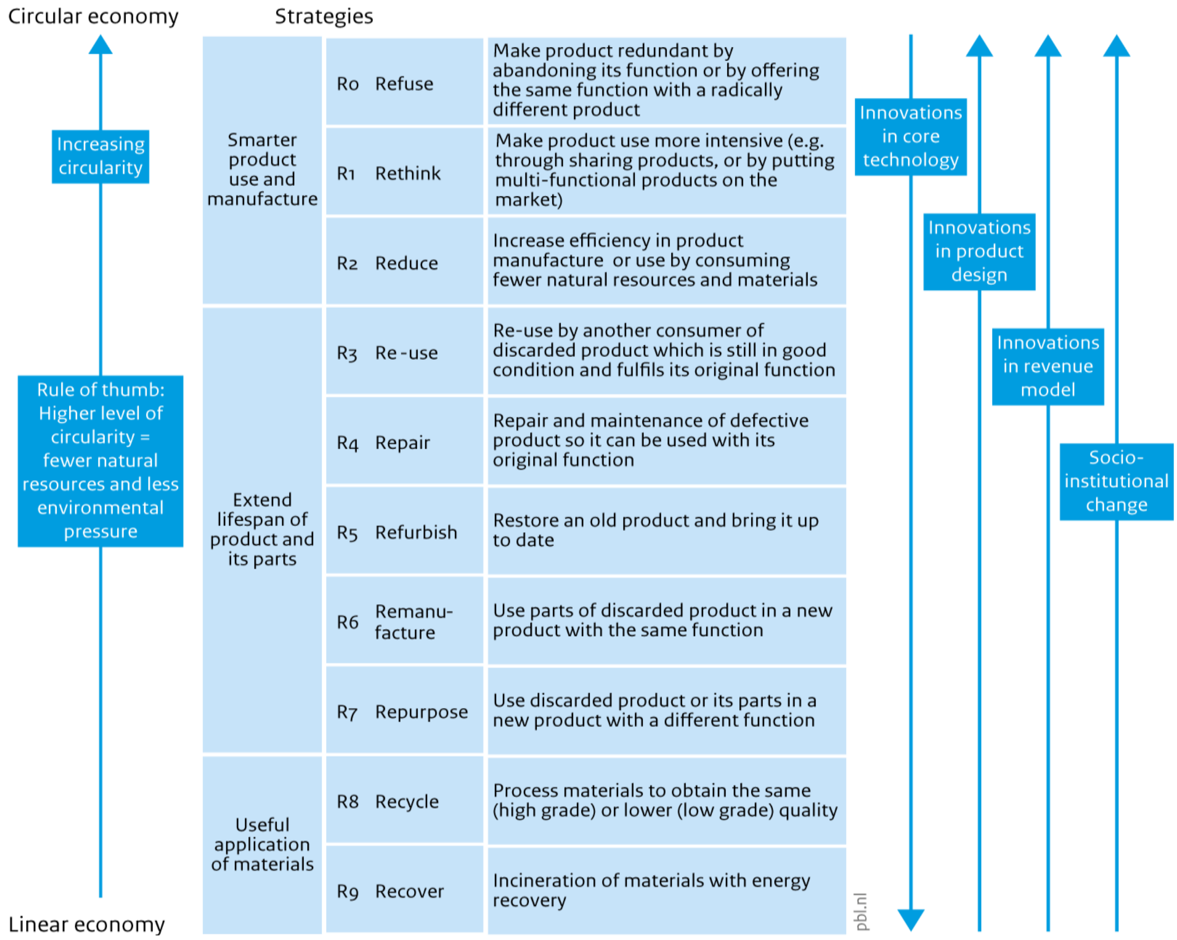


Figure 8: 9R-framework (Potting, Hekkert, Worrell, & Hanemaaijer, 2017)

2.2.3. Design for 'X'

The butterfly diagram of EMF, the six shear layers framework of Brand, and the 9R-framework of Potting present all various circularity strategies that can be considered when designing a building. All the design strategies fall under the umbrella of Design for Circularity to create value retention or value recovery by clever thinking in the design phase (Amory, 2019). The paradigms of Design for X are developed to gather the strategies all focussing on a different aspect of circularity. In current literature, there are no strict defined definitions for the strategies, and all strategies are complementary to each other. This study refers to the following three Design for X approaches: Design out Waste, Design for Disassembly, and Design for Recover Output.

Design out Waste

Design out Waste is a strategy for the development phase of buildings that focuses on the refuse and reduce strategies of the 9R-framework. The goal is to minimise the use of primary materials and to introduce secondary 'waste' material in the design process (Amory, 2019). Therefore, control of the type of material, quantity, and quality is needed. Virgin materials are directly extracted from natural resources and have not been used in other processes in the economy. The reduction of virgin materials can be achieved by designing with regenerated inputs and non-virgin products or materials. Thereby, the regenerated inputs are in the form of renewable energy and sustainably produced raw materials (Platform CB'23, 2020a). Non-virgin or secondary materials are reused, refurbished, remanufactured, or recycled from previous life cycles. The advantage of non-virgin materials is that it benefits the environmental impact of the structure because they have a lower CO_2 footprint (Verberne, 2016). Ideally, a circular building is designed with 100% non-virgin materials, which means that it closes the material cycle and prevents material waste.

Design for Disassembly
For the utility phase of products and materials, Design for Disassembly is a suitable strategy which focuses on extending the lifespan of building components, especially on reusing and repurposing components. Design for Disassembly is closely related to Design out Waste because it extends the lifecycle of products and prevents products to end up as waste. Products are turned into food for new products instead of ending up as waste. By Design for Disassembly, the building components are prepared to be easily deconstructed for reuse in a later lifecycle with the same or different purpose. Thereby, minimal maintenance or cosmetic cleaning is required to retain their functionality. The environmental benefits of this strategy are that it extends the life of raw materials, lowers the cost of materials, and reduces the embodied energy and carbon footprint (Rios, Chong, & Grau, 2015).

One of the main factors that influences the demountability of products is the type and accessibility of connections (Guy & Ciarimboli, 2008). Guy and Ciarimboli mentioned that the efficiency of deconstruction depends on the type of connection and better accessibility can avoid expensive equipment or environmental health and safety protection measures that need to be taken. In general, bolted, screwed, and nailed connections are preferred, while chemical connections should be prevented. Besides accessibility and type of connection, interchangeability is also important. The deconstruction of components not only plays a role at the end of the life of a building but also during the use phase. As mentioned in the 6S-model of Brand, different layers have various lifespans, which results in different replacement cycles. Therefore, interchangeability can be stimulated by making use of modular, interdependent, and standardised materials and systems (Guy & Ciarimboli, 2008).

Design for Recover Output
Design for Recover Output contributes to the circularity of buildings in the end-of-life phase. It is a strategy that focuses on the future impact of the output of products and materials once the intended lifecycle is finished. It aims at retaining material value while limiting material loss. Thereby, the strategy anticipates the recovery of materials through cascading of hierarchical levels, reuse and redistribution of products, and the recyclability and incineration of materials. According to Hopkinson et al. (2019), to create a fully CE, it is essential to employ recovery, upcycling, and reuse of building components at the end of life because currently a large part of construction waste is downcycled. An aspect which needs to be considered for the Design of Recover Output is material health, also known as toxicity. Toxic substances in materials and products can limit future use because of new regulations that come in place regarding material health (Verberne, 2016).

2.2.4. The relation of circularity strategies with Environmental impact

Circular design strategies seek to minimise the environmental impact by reducing the total extraction of resources and by reducing the generation of waste over the building life cycle. Design for Disassembly aims at elongating the product material lifespan, which slows down the resource flow and results in a reduction of the environmental impact. On the other hand, Design out Waste and Design for Recover Output contributes to the reduction of the environmental impact by considering the inherent circularity of materials and products. Thereby, the inherent circularity of a product is distinguished from the environmental impact. Inherent circularity is defined as the composition of the product in terms of recirculated and virgin material, while environmental impact relates to global environmental sustainability in the form of harmful emissions (Saidani, Yannou, Leroy, Cluzel, & Kendall, 2019). According to the study of Linder et al. (2020), the more recirculated components in a material, the lower the environmental impact. However, circular building design leads not always to a reduction of the environmental impact. Saadé et al. (2022) investigated examples where recirculating materials and products could worsen the environmental footprint. For example, recycled material could be less environmentally friendly than virgin material due to a more intensive and polluting production process. Saadé et al. (2022) argued that a circular design strategy should be used as a means to reach sustainability and not as an end in itself. Therefore, it is necessary to ensure that circular design strategies also are beneficial to global environmental sustainability.

2.3. Building Circularity Assessment

To support sustainability and circularity, or to evaluate circular design strategies, it is necessary to measure the overall circularity. In this way, circularity can be objectively integrated into the procurement procedure. For sustainability in terms of environmental performance, LCA methods are well developed, standardized according to norms, and established in the Dutch Building codes. However, this is not the case for circularity assessment methods. Several authors and institutions have investigated assessment models and criteria, but there are no standardized and well-established methods yet (Kayaçetin, Versele, & Verdoodt, 2022). Current research is conducted to assess environmental performances by applying LCA in circular building design and how to effectively assess building circularity (Xue, et al., 2020; van Stijn, Eberhardt, Jansen, & Meijer, 2021).

2.3.1. Life Cycle Assessment

In the Netherlands, the environmental performance of buildings and other civil structures is determined with the method 'MilieuPrestatie Bouwwerken', also called 'The Determination Method'. This is a uniform measurement method based on the European norms EN 15804 (Sustainability of construction works - Environmental product declarations), EN 15978 (Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method), and ISO 14025 (Environmental labels and declarations) (Jonkers, 2021). These European norms set methodical requirements to determine the Environmental Product Declaration (EPD) of building products. In an EPD, the environmental impact of products is calculated based on an LCA. The Dutch government uses the Determination Method and LCA as important instruments to shape environmental policies. Furthermore, clients and contractors can use the Determination Method as a tool to set project requirements in terms of quality and sustainability.

The LCA is a method to quantify the environmental impact of products and consists of two main steps: a life cycle inventory and a life cycle impact assessment. For the life cycle inventory, information is gathered about environmental relevant input and harmful output that is emitted during the full lifecycle of a product. In the construction industry, the following life cycle stages are considered: the production stage of (half) products (A1 – A3), the construction stage (A4 – A5), the use stage (module B), the end-of-life stage (module C), and benefits or loads beyond the system boundary (module D) (Jonkers, 2021). All the life cycle stages of an LCA are visualised in the figure below.

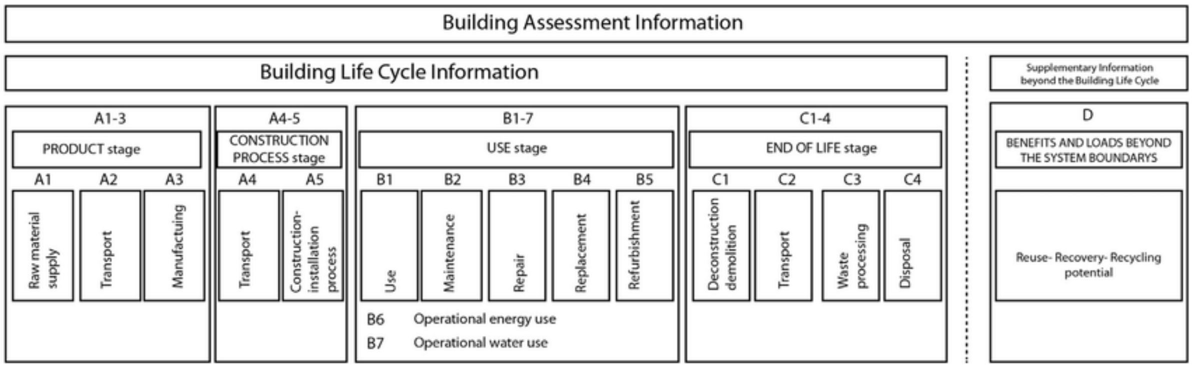


Figure 9: Life Cycle stages of an LCA (Jonkers, 2021)

After the life cycle inventory, a life cycle impact assessment is done to assess the environmental impact. This results in an environmental profile for the full lifecycle of products. Until 2020, this environmental profile consisted of eleven environmental impact categories which are shown in table 3. In 2021, this is extended to nineteen categories according to EN 15804+A2 (NMD, 2022). For each category is an equivalent unit defined. All compounds belonging to that category are weighted against the unit equivalent. In the end, one value is calculated for every impact category. The collection of all the environmental impact categories results in the environmental profile which is presented in an EPD. The next step is to monetize the environmental impact to obtain the environmental cost indicator. According to ISO 14040, shadow costs can be assigned to each environmental impact category. The shadow cost is the theoretical value of the costs required to undo or prevent damage to the environment. This is also called the 'polluter-pays-principle', whereby the environmental cost will be internalised in the product (Jonkers, 2021). To determine the total ECI, the amount of unit equivalent multiplied by the assigned shadow cost should be aggregated for all impact categories.

Table 3: Environmental impact categories (Jonkers, 2021)

Impact category:	Abbreviation:	Unit equivalent (UE):	Shadow costs per UE in Euro:
Abiotic depletion non-fuel	ADP-non fuel	kg Antimone	0,16
Abiotic depletion fuel	ADP-fuel	kg Antimone (4,81E-4 kg antimone/MJ)	0,16
Global warming	GWP100	kg CO_2	0,05
Ozone layer depletion	ODP	kg CFC-11	30
Photochemical oxidation	POCP	kg Ethene	2
Acidification	AP	kg SO_2	4
Eutrophication	EP	kg PO_4^{3-}	9
Human toxicity	HTP	kg 1,4-dichloro benzene	0,09
Fresh water aquatic ecotoxicity	FAETP	kg 1,4-dichloro benzene	0,03
Marine aquatic ecotoxicity	MAETP	kg 1,4-dichloro benzene	0,0001
Terrestrial ecotoxicity	TAETP	kg 1,4-dichloro benzene	0,06

The LCA is a great method to quantify the environmental impact of products and thereby aligned with the environmental aspects of CE. However, the LCA alone would not be suitable to assess circularity in a broader spectrum whereby it neglects other circular metrics (Walzberg, et al., 2021). Whereas conventional LCA methods focus on the environmental impact of products for a single lifecycle, the CE assumes potentially multiple lifecycles. Nevertheless, LCA can strengthen the transition to circular economy as a complementing tool.

2.3.2. Material Circularity Indicator

The Material Circularity Indicator is developed by the EMF and is part of the 'Circular Indicators Project'. A dynamic assessment tool is developed in collaboration with Granta that automatically evaluates the Material Circularity Indicator. Where the LCA focuses on the environmental impact of products throughout the lifecycle, concentrates the Material Circularity Indicator on the flow of materials during the use phase of a product and could be used as a complementary indicator to provide a more accurate circularity credential of products (EMF & ANSYS Granta, 2019). The Material Circularity Indicator recognised the product's utility in terms of durability and usage intensity while promoting reusability and recyclability of materials. Thereby, it encourages the transition from a linear to a circular process by thinking beyond the single lifecycle of products and as a result, it minimises the linear material flow. Furthermore, the Material Circularity Indicator focuses on the maintenance of material flow in the technical cycle where the restorative flow is maximised. An informative representation of the material flow is presented in figure 10.

The Material Circularity Indicator measures the linear and restorative flow based on three characteristics (EMF & ANSYS Granta, 2019):

- the use of raw virgin material;
- the amount of unrecoverable waste;
- the utility factor of products.

To calculate the Material Circularity Indicator, input is needed about the production process, the utility phase of products, the end-of-life destination, and the efficiency of recycling processes. The Material Circularity Indicator measures circularity in a range of 0 to 1, where 0 represents a full linear process with only virgin materials as input and landfills as output, and a score of 1 represents a fully CE. To conclude, the Material Circularity Indicator is an essential method to strive for a CE on the product level. It supports the preservation of materials in circular building design. However, the Material Circularity Indicator is only limited to microscale, addresses only partially the environmental view of circular design principles, and often gives contrasting results with the LCA (Rigamonti & Mancini, 2021).

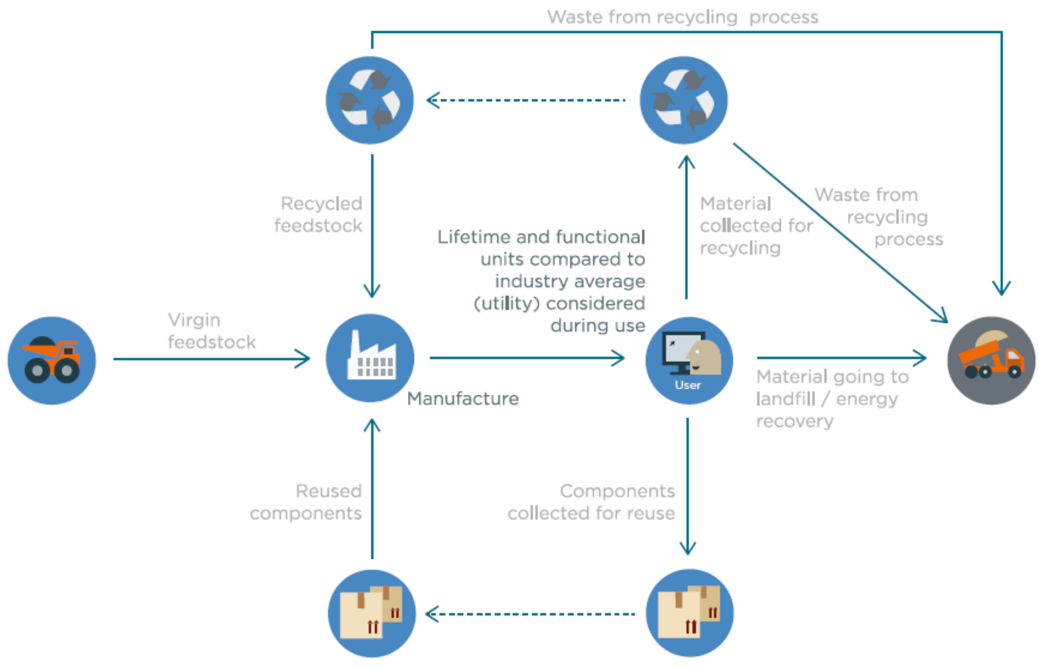


Figure 10: Diagrammatic representation of material flows (EMF & ANSYS Granta, 2019)

2.3.3. Platform CB'23

Platform CB'23 stands for 'Circulair Bouwen in 2023' and is an organisation that connects involved parties (clients, contractors, architects, suppliers, policymakers and academics) in the Dutch construction industry to smoothen the transition to CE. Their ambition is to come up with concrete results and national, sector-wide agreements for circular building design before 2023. As a result, the agreements are not formal standards but more in the form of working agreements and guiding principles which can be used as input for national or European standards.

Platform CB'23 produced guidelines to measure circularity as further development of, and in addition to, the existing methods of LCA, Material Circularity Indicator, and the Determination Method for Environmental performances of buildings. This method is called the core measurement method and can be applied to the whole construction sector, building and civil engineering, at any level of scale in a structure, and for all lifecycle phases (Platform CB'23, 2020a). This method consists of an adaptive capacity report and individual circularity indicators (core indicators), which are not weighted and aggregated in an overall score. Developing a method to determine the degree of circularity of the individual results and aggregate them to an overall score is on the research agenda. The core indicators focusing on the three main circularity principles of Platform CB'23 are protecting the existing stock of materials, environment protection, and value retention. The core indicators and explanations are presented in table 4.

Part of the core measurement method is an instrument that assesses adaptive capacity. This instrument can assist the decision-making process of design for adaptability for future change in a qualitative way. It helps to compare design alternatives, include design optimisation, or as impact assessment for adaptive interventions based on their circular design principles. The focus of this report is on three types of adaptive capacity:

1. Structural transformation with design for demountability;
2. Spatial transformation with design for adaptability;
3. Element and materials transformation with design for reuse or recycle.

Table 4: Core indicators of the core measurement method (Platform CB'23, 2020a)

Core principle	Core indicator	Explanation
Protection of the existing stock of materials	1: The quantity of materials used (input)	Dimension 1: Degree of primary (renewable and non-renewable) and secondary (reused and recycled) material
		Dimension 2: Degree of raw materials usage that is physically scarce and socio-economically scarce or abundant
	2: The quantity of materials available for the next cycle (output)	The degree of reuse and recycle possibility at end-of-life
	3: The quantity of materials lost (output)	The degree of material used for incineration for energy production or landfills at end-of-life

Environmental protection	4: Impact on the environment	Weighted environmental cost of the 19 impact categories from the Determination Method of Environmental performances of buildings, according to the Stichting Bouwkwalitiet method
Value retention	5: The quantity of initial value (input)	The degree of techno-functional and economic value of an objects current state
	6: The quantity of value available for the next cycle (output)	The degree of techno-functional and economic value of an objects subsequent use or function
(still in development)	7: The quantity of existing value lost (output)	The degree of decrease in techno-functional and economic value during the lifecycle

The guidelines of Platform CB'23 to measure circularity are a good method to assess elements of circularity, but it is not yet suitable as a full circular assessment method. It provides a deeper understanding of the circularity performances of a building and is sufficient to use as an assessment tool to determine a certain degree of circularity for elements. However, it comes with some limitations, mainly because it is still in development. Especially, the value indicators to measure value retention are not fully defined and validated. Besides that, the core measurement provides a list of individual circularity indicators rather than an instrument to assess circular building design. It does not provide a tool for circularity calculations, but the indicators can be integrated with existing assessment instruments.

2.3.4. Building Circularity Index

The BCI is a method to assess and steer the circularity potential of buildings. The BCI steers the development of circular building design by assessing the circularity of products, elements, and the building itself. The method arose from the need to focus on circular building design in the early design phase. The BCI is not a new circularity assessment method but unites existing methods such as the LCA, Material Circularity Indicator and the core measurement method of Platform CB'23. The first concept is developed by Verberne (2016), in collaboration with Alba Concepts and Eindhoven University of Technology. Later, van Vliet (2018) addressed the limitations and redeveloped the BCI model, mainly focussing on the disassembly potential. The latest version is developed by Alba Concepts and BCI Gebouw (2022). This version also considered the environmental impact of products. This research uses the latest version of the BCI model. Furthermore, the BCI method ties well with the uniform and effective core measurement method of circularity of Platform CB'23. The same circularity principles are used as starting point and there is a similarity in the measurement of circularity indicators. The BCI is ahead of the core measurement method of Platform CB'23 because it has integrated the circularity indicators into a single building assessment score.

The BCI gives meaning to the concept of circularity through two main aspects: material usage and disassembly potential. Thereby, the method distinguishes itself from other assessment methods such as Material Circularity Indicator and LCA. The BCI score is built up by the Material Circularity Index (MCI), Disassembly Index (DI), the Product Circularity Index (PCI), the Element Circularity Index (ECI), and the Environmental Cost Indicator, as can be seen in figure 11. The exact calculation for this method will be further elaborated in the synthesis phase.

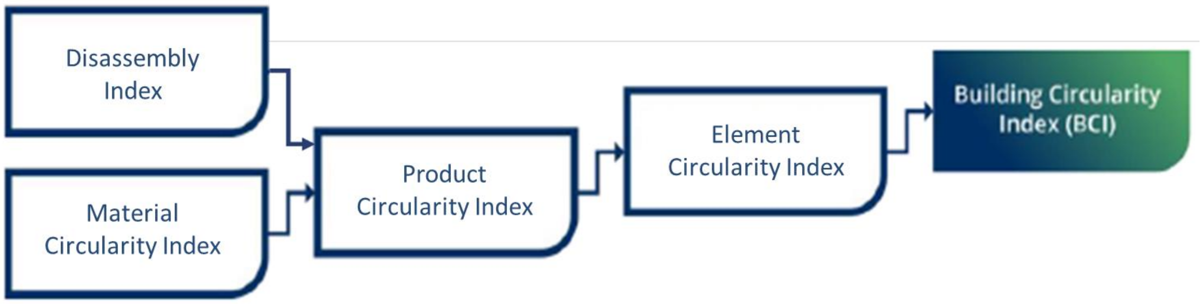


Figure 11: BCI Measurement method (Alba Concepts; BCI gebouw, 2022)

The definitions that are used in the BCI measurement method are explained as follows:

- **Material Circularity Index:** The MCI of Alba Concepts is comparable to the MCI method of EMF but slightly adapted (EMF & ANSYS Granta, 2019). The MCI is determined by the origin of materials (virgin, recycled, reused, and biobased), future scenario (landfill, incineration, reuse, and recycle), and the product lifecycle (technical and functional). The definition for material usage is based confirm the guide of Platform CB'23. The score range is between 0.10 and 1.00, where a higher score means a more circular material usage of the product.

- **Disassembly Index:** The disassembly potential of products is essential for circular buildings because otherwise the elements cannot be reused for a high-quality purpose (Alba Concepts; BCI gebouw, 2022). The DI is to what extent a product can be disassembled from the building without compromising the current function. The score is determined based on the type of connection, accessibility of the connection, form confinement, and cross-throughs. It only focuses on products and elements, while sealing- and mounting material is neglected. Thereby, the theory of the 6S-layers of Brand is applied to constrain the assessment of demountability. The range for the DI is also between 0.10 and 1.00. However, it is not always desirable or possible to develop a product with DI of 1.00 to design a demountable building (Alba Concepts; BCI gebouw, 2022).

- **Product Circularity Index:** The PCI score is the score for MCI and DI combined based on a one-point score. Both aspects have similar weight in the assessment. This means that circular building design has to fulfil the needs of the origin of circular materials, circular future scenarios, and is easily detachable. However, a limitation of this is that a detachable product is not per definition reusable. Other aspects do also play a role such as quality, technical conditions, and residual value.

- **Element Circularity Index:** The BCI method does not interpret a building as a collection of individual materials but as a system that consists of multiple products and connections. Thereby, an element is defined as a collection of several products which function as a whole and are not separable. The ECI is determined by the weighted average MCI of the products and the DI of the element. To calculate the weighted average MCI, the environmental impact and the lifespan of products are important. The environmental cost indicator of products is used as a weight factor in the calculations. The lifespan of an element is equated to the shortest lifespan of the individual products.

- **Building Circularity Index:** The final BCI score of a building is a weighted average of the ECI and PCI scores, with the environmental cost indicator as a weight factor. The BCI score can range between 0.10 and 1.00 where 1.00 represents a completely circular building. A full circular building is not yet feasible in practice because there is no 100% circular product available for every product (Alba Concepts; BCI gebouw, 2022).

2.3.5. Materials Passport

The materials passport is not a circularity assessment method but more a complementary tool to support other assessment methods. The materials passport is a document that describes all the characteristics of materials used in a product which is useful for recovery and reuse. It enables stakeholders to effectively fulfil the circular potential of products. Besides that, the materials passport creates a transparent market about harmful substances in products and creates an incentive for stakeholders to choose more circular and sustainable products (BAMB, 2019). There are already initiatives that have set up a materials passport platform which contains extensive databases for circularity passports, such as BAMB and Madaster. Also, there is a national database called NIBE. This database provides data on building components regarding lifetime and future scenarios.

The efficiency of circular building assessment methods depends on the availability of material data and the consistency of a uniform framework. Many indicators need to be calculated in a systematic way to get a quantitative circularity score. Although several institutions have defined a materials passport, there is no generally accepted framework (Kedir, Bucher, & Hall, 2021). From the literature, it appears that the most common characteristics that are needed in materials passports are: product type/description, location, resource composition, future scenario potential, production data, separability, quality, and disassembly potential and instructions (Miu, 2020). An example of a material database is presented in figure 12.

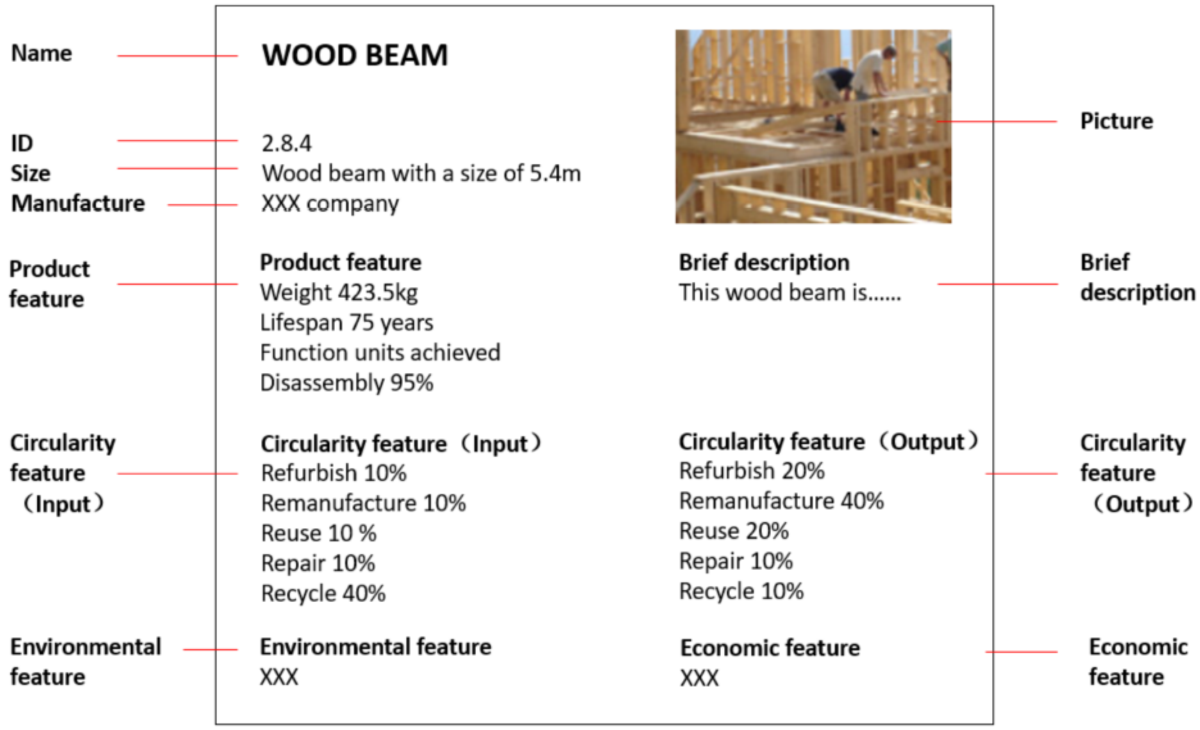


Figure 12: Example of circularity materials passport (Zhang, Han , & de Vries, 2021)

2.4. Digitally informed decisions in circular building design

Sustainability and circularity become of utmost importance for the liveable future of the planet. To control the environmental impact, mindful and efficient use of energy and material resources are the key (Santiago, 2022). Thereby, the emerging digital innovations in the Industry 4.0 can help in achieving sustainable development. Digital innovations can be supplementary to building circularity assessment where it can ensure digital informed design decisions regarding material use and environmental impact. For example, BIM can assist in increasing the efficiency of material use and reducing waste in the construction industry. Therefore, this section focuses on the digital transformation of the construction industry and how the CE can benefit from BIM and data-driven decision-support tools.

2.4.1. Industry 4.0

The Fourth Industrial Revolution or Industry 4.0 represents an era where innovation and technology form the connection between organisations and processes. Industry 4.0 can be described as a collection of technologies and concepts that aims at enhancing the whole value chain, where the physical and digital environments are collaborating and communicating which facilitates decentralised decision-making (Bolpagni, Gavina, Ribeiro, & Arnal, 2022). The main idea is to see the physical and digital environments as one with a continuous flow of information (Deloitte, 2021). Firstly, information is captured from the physical world to establish a digital record. Secondly, information is shared between multiple sources in the digital world to support data analytics with real-time data. Lastly, analytics in the digital world are applied to generate decisions and actions in the physical world.

In analogy with Industry 4.0, the digital innovation within the architecture, engineering, and construction industry is called Construction 4.0. Construction 4.0 is driven by the development of BIM in combination with technologies like the internet of things, cloud computing, big data, and artificial intelligence. One of the main trends in Construction 4.0 is digital technologies, which encompass the concept of BIM and cloud-based information sharing (Bolpagni, Gavina, Ribeiro, & Arnal, 2022). This includes the creation of digital information, data interoperability, data analytics, simulation and analysis, and information visualisation. Thereby, BIM creates the foundation for all digital information management and design and collaboration processes, while the role of data is crucial.

2.4.2. Building Information Management

A Building Information Model is a digital representation of a building throughout the entire lifecycle in which multi-disciplinary data is stored. Typically, the digital model includes the geometry of the building and semantic information such as object characteristics, building plans, relationships between objects, or other meaningful information (Borrmann, König, Koch, & Beetz, 2018). According to the international standard ISO 19650:2019, Building Information Modelling can be defined as:

> *"Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions."*

However, because of the development of technology, BIM acquired a slightly different meaning over time. In the earlier definition of BIM, Building Information Modelling, the emphasis is more on the process of collaborating on a digital model. Later, in Building Information Management, the main focus is on the information itself instead of the mere "modelling". The emphasis is on the management and re(use) of digital information throughout the entire building lifecycle (BIM Loket, 2021). This research adopts the latter meaning of BIM, so Building Information Management.

Essential in BIM is information management. BIM supports various types of tools and processes for divergent goals. However, it is important that for all those tools and processes the information remains consistent. A single source of truth is required. Fundamental to a single source of truth is a Common

Data Environment (CDE). As defined in ISO 19650:1, a CDE is an agreed source of information for any project or asset, for collecting, managing, and disseminating each information container through a managed process. A CDE is an ecosystem of applications and includes a workflow describing the processes and the supporting technology.

For successful implementation of BIM, it is required to make agreements with all the involved parties about responsibilities, collaboration and modelling requirements (Barnes & Davies, 2019). Therefore, a BIM protocol is set up to register all agreements and to increase the efficiency of the design process. The BIM protocol consists of agreements of administrative nature, such as communication, ownership, liabilities, or process requirements. On top of a BIM protocol, there is a BIM execution plan in which technical and practical agreements are documented. This plan is essential to that the information models are structured correctly, which is beneficial for efficient data sharing between models and systems.

BIM dimensions

BIM is a building construction environment that is rapidly growing with different sorts of input and information. Therefore, BIM dimensions are created to structure and specify the overflow of information. There is no consensus on the exact definitions of BIM dimensions because of the continuously expanding applications. Currently, the following seven dimensions are adapted and accepted in the construction industry (Habib & Kadhim, 2020):

- 3D modelling: the process of creating a three-dimensional digital model of the building with semantic information shared in a CDE.
- 4D planning: linking the project schedule with the 3D model to visualise the entire process and prevent scheduling conflict.
- 5D cost analysis: connecting quantity data and cost plan to the BIM model.
- 6D sustainability: integrating sustainability aspects in BIM which assist in decision-making regarding sustainability performances in terms of energy efficiency and material resources.
- 7D facility management: provide BIM model with facility management data for operation and maintenance processes throughout the entire building lifecycle.

This research focuses on the sustainability dimension of BIM (6D), especially in the area of sustainable materials and the end-of-lifecycle of designs. Thereby, BIM can provide valuable information in assisting with important decisions to optimise the design, as well as developing an integrated project delivery model. BIM can support the identification of the best alternatives with the minimal environmental impact of sustainable material use or minimal construction and demolition waste at the end-of-lifecycle. Also, lifecycle analysis and assessments can be performed for comparative design options which include complex databases that can be linked to the BIM model. One of the greatest benefits of BIM lies in the combination of performance simulations and assessments of the design and the visualisation opportunities available for informed and rapid decision-making (Habib & Kadhim, 2020). It provides the design team with valuable information on design variants to develop a more efficient and cost-effective sustainable design.

Level of Development

The design of a building is a continuous development process which starts with a schematic concept design with a low level of detail and gradually evolves to a detailed design or an accurate as-built model. The BIM model has a different purpose for every phase of the design, so each model has a certain LOD which specifies the degree of maturity, geometric resolution, and reliability of information (Borrmann, König, Koch, & Beetz, 2018). It is a framework to specify the amount of building information. The LOD distinguishes between the level of detail and the level of information. The level of detail refers to the graphical representation which specifies only the geometry of the model. The level of information refers to the degree of information that is linked to objects and families.

BIM Forum has defined six LODs that enable practitioners in the construction industry to specify BIM deliverables and that provide the needed information and details in design phases (BIM Forum, 2021). The standardised LODs are LOD100, LOD200, LOD300, LOD350, LOD400, and LOD500. An elaborated summary of all LODs and specific uses of BIM is presented in Appendix B: Information documents. The different LODs can be described as follows:

- LOD100:
  At the conceptual design level, LOD100, the elements are modelled as a generic representation or a symbol, while no non-graphical information is added. Only general analysis or cost estimations based on areas or volumes can be performed.

- LOD200:
  The schematic design model has LOD200, where elements are graphically modelled as systems, objects, or general placeholders with approximate size, quantities, and locations. Also, non-graphical information could be added to the model. Quantitative data could be used for performance analysis and other estimating techniques.

- LOD300:
  For the detailed design phase, LOD300 is used with precise geometry. Elements are modelled as specific systems and objects with accurate measurements of size, shape, quantity, and location, including specific non-graphical information. Specific data is provided to analyse specific performance criteria or develop suitable cost estimates and plans.

- LOD350:
  This is an intermediate step which is required for modelling and coordination. This includes components necessary for coordination and interfaces with other building systems.

- LOD400:
  Once the design is finished and ready for construction, contractors require a detailed model with LOD400 which is suitable for manufacturing and assembling. Thereby, the detailed design model is extended with information regarding detailing, fabrication, assembly, and installation.

- LOD500:
  Lastly, an as-built model is generated with LOD500. This is a field-verified representation model which can be used during the maintenance and operational phase. As can be seen in figure 13, the graphical appearance of the model does not necessarily change in the latter stages of design (LOD300 – LOD500). However, the non-graphical information does change over time for these design phases depending on the needs of stakeholders.

It is of high importance to understand the LOD of a model because this determines the completeness and accuracy of the information provided which will be used as input parameters for further analysis. The applicability of circular building assessments to support and guide design decisions are most useful in the early design phases, while final circularity assessments are better to be conducted after the detailed design. For a circularity assessment in the final phase, LOD300 would suffice where detailed material quantities and specific information about building components are readily available to perform an accurate analysis. However, to utilise circularity assessment methods in the early design phase, an approximation of the material quantity, circularity parameters and environmental impact is needed because probably only a LOD200 is provided. A possible solution to deal with this problem is to aggregate the detailed environmental database and circularity database at the building element level which can be used as approximations (Röck, Hollberg, Habert, & Passer, 2018).

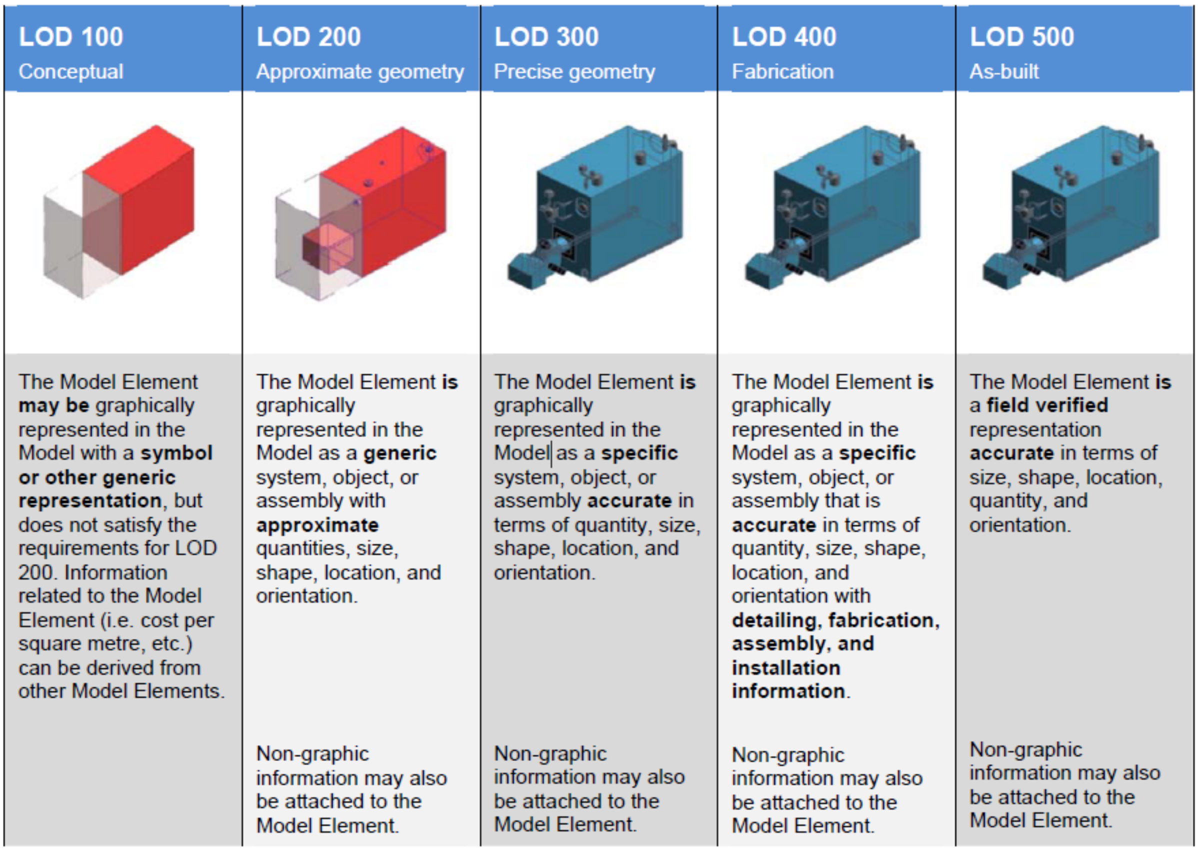


Figure 13: Summary of LOD (NATSPEC, 2013)

2.4.3. BIM-based circularity assessments

That BIM has huge potential to achieve a higher degree of circularity and support complex decision-making is discussed in the previous subsection with BIM 6D. BIM-based design supports a more sustainable design based on environmental performance. The integration of BIM and circularity assessments is important because it increases the efficiency of information flow and reduces the complexity of data collection (Xue, et al., 2020). Several studies researched a systematic integration of BIM-LCA tools, but an effective systematic integration of BIM and circularity principles is still on the research agenda (Xue, et al., 2020). Nevertheless, according to previous state-of-the-art BIM and CE integration approaches, three main streams can be concluded (Zhang, Han, de Vries, & Zhai, 2021; Xue, et al., 2020):

1. External circularity assessments with standardised exchange files

The first option is to integrate BIM and circular assessments by extracting BIM-based information as input for building circularity assessments in external software. Thereby, BIM-based information is captured in standardised exchange files, such as Industry Foundation Classes (IFC). IFC is established in ISO 16739-1 and provides a neutral open file format to exchange BIM-specific information between software applications and facilitates interoperability in the industry. The exchange files consist of information like the bill of quantities of the model, material properties, and other element-related properties. The exchange files function as input for external software or platforms that assess the building circularity. In this way, the IFC file reduces the manual actions required to enter the input needed for the circularity assessment. However, still manual procedures are required for exporting the file, while the assessment cannot be performed in real-time during the design process. Examples of studies that integrated the assessment of circular design and BIM in this way are the Circular Building Assessment Prototype of BAMB and the Madaster-platform.

2. Circularity assessments within the BIM environment

The next alternative is to internalise the building circularity information in the BIM environment. This can be realised by creating built-in parameters for building elements in BIM software, like Autodesk Revit. Custom circularity parameters could be created to capture various element attributes such as the origin of materials, end-of-life scenario, and lifespan. Once the necessary circularity attributes are captured in the model, the calculation for the assessment can be performed with custom plug-ins or Dynamo. Dynamo is a Revit Plug-in for visual programming that supports customising and assessing the building information workflow. In this integration method, designers can assess and visualise the circularity performance at any moment of the design phase. Dynamo automates the procedure which makes it suitable to conduct multiple assessments of design variants. However, this method is still time-consuming as the user needs to manually specify the custom parameters for all building elements and material-specific information needs to be added to the Revit model by the sustainability specialists. Furthermore, the assessment performance drastically reduces once the file becomes too large because of all the additional information in the BIM model.

3. An automated link between BIM and external building material databases

The third way of BIM-CE integration is to establish an automated process between the BIM environment and external environmental and circularity databases, also called semantic enrichment. This method generally consists of a data platform with two layers: a data layer and an application layer. The concept of the data platform is presented in figure 14. The data layer accommodates the connection between the information from the BIM environment and the external databases, supports data analytic operations, and provides data to the application layer. The external databases are mainly materially oriented to be on the same level of features in the conceptual design phase (Xue, et al., 2020). A common and shared vocabulary is important for linking BIM models and various databases to define and retrieve information in a CDE (Morkunaite, Naber, Petrova, & Svidt, 2021). Various studies have proposed an ontology with necessary classes and properties for circular building assessments in the early design phase. The application layer is where the results are analysed by the end-user. Business intelligence tools, like Power BI, can be used to analyse the data and present insightful reports. The benefit of this integration method is that it creates an automated and efficient process to assess building circularity. However, this approach relies on structured and reliable data input, so a well-defined common vocabulary and ontology need to be provided.

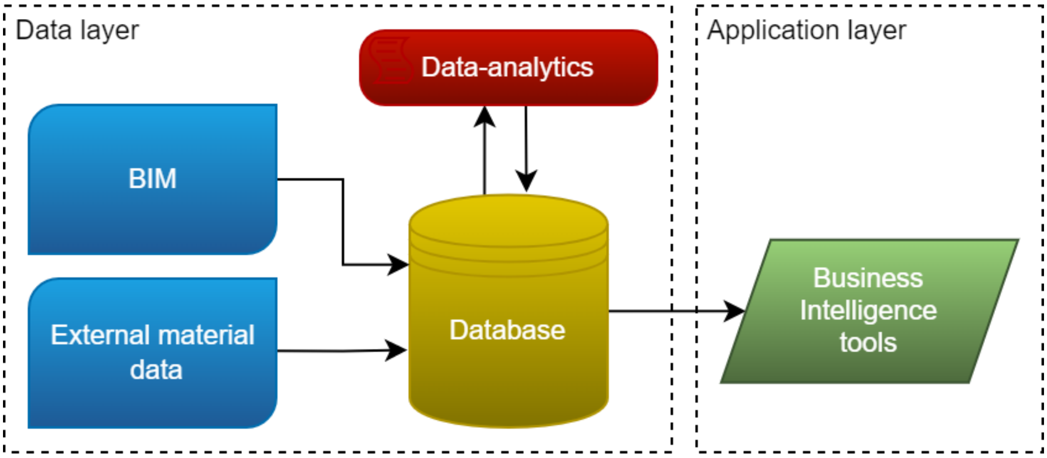


Figure 14: Data platform

2.4.4. Decision support systems

Building design is a complex process that deals with multiple decisions where choices need to be made between different design aspects. For sustainability and circularity, the design objectives are conflicting due to their dependencies and mostly, the decision-maker's preference determines the solution for a large part (Jalaei, Jrade, & Nassiri, 2015). Therefore, Decision Support Systems can facilitate the problem-solving process by offering qualitative and quantitative information to assess, compare or rank design alternatives to determine the most suitable option that meets the objectives best. Decision Support Systems increase the efficiency, productivity, and effectiveness of the decision-making process, while it also promotes communication and quick problem solving (Jalaei, Jrade, & Nassiri, 2015). This research makes use of the Multiple Attribute Decision-Making method as a multi-criteria analysis. This method deals with a predetermined set of alternatives, each with its model characteristics. The method uses attribute values and relative significance of attributes with the use of weight factors or normalisation. Attribute values describe the characteristics and criteria to assess the circular performance of alternatives, and the weight factors measure the dependencies between individual circularity aspects. In the end, the goal is to come up with a design solution that has the most desirable set of circularity attributes.

Visualisations and dashboards to support decision making

The importance of visualisations to support decision-making is widely acknowledged in the literature, especially for the interpretation of the results. Usually, visualisation techniques are implemented to better communicate and analyse information and data. It reduces complex cognitive work and enables the processing of big data to make informed decisions (Hollberg, et al., 2021). Visual features determine the effectiveness and efficiency of information that is presented to the stakeholders. To take full advantage of visualisations, dynamic visualisations can be introduced to further enhance information seeking. Dynamic adjustments could be in the form of sub-selection and data filtering to dive deeper into certain elements, expanding hierarchy selections to provide on-demand details that cannot be displayed at the same time, or to order data based on specific requirements.

Usually, the integration of many criteria is needed in the decision-making process. Therefore, dashboards are used as a decision-support tool which are suitable to present multiple visualisations and evaluate different criteria at the same time. Dashboards extract and aggregate data from multiple sources and combine them into a more manageable interface to gain useful insights. Three different types of dashboards can be considered: static-, interactive, and interactive analytical dashboards (Nadj, Maedche, & Schieder, 2020). Static dashboards summarize information in graphs and visualisations to present performance metrics. The disadvantage of static representation is that it does not involve the end-user and that it has issues with presenting multidimensional data. It does no longer suffice to analyse and interpret complex data efficiently and effectively (Kohlhammer, Proff, & Wiener, 2018). To take the decision-support tool a step forward, interactive dashboards do involve the users and provide them with more elaborate analyses because of the additional features for visualisations. The interactive nature and dynamic visualisations create a better understanding of the complex data for decision-makers. In recent years, interactive analytical dashboards have made their appearance in literature (Nadj, Maedche, & Schieder, 2020). Implementing data analytics equips the end-user with the possibility to quickly calculate and assess the data for dynamic and interactive performance analysis. The end-user can interact and analyse complex analytical problems with computational models running in the background to reduce manual procedures to process the data.

2.5. Conclusion analysis phase

The literature review provides interesting findings into the different aspects of circularity and digitally informed decision-making. It offered a glimpse into the transition to a more circular economy and the circular building design principles. Also, different environmental and circular assessment methods are discussed. Moreover, the theoretical basis for the integration of BIM and circularity assessments is set. In the end, this information makes it possible to answer the first sub-research question:

"How is circularity measured for buildings in the early design phase?"

Circularity is an upcoming and evolving trend in the construction industry. There is not yet a consensus on the definition of CE, circular building design and circular assessment methods. Nevertheless, the principles of circularity are generally accepted by all the different schools of thought, which makes it possible to find a thread through the various circular building design strategies and circularity assessment methods. In terms of circularity, it is acknowledged by most assessment methods and principles that the flow of materials during the full lifecycle is a good start to measure circularity (Alba Concepts, 2018; EMF & ANSYS Granta, 2019; Platform CB'23, 2020a; McDonough & Braungart, 2002). Additionally, according to the Design for X principles, Platform CB'23 and the Building Circularity Index, the design for disassembly is also essential to include in the circularity assessment. However, Alba Concepts came up with a generally accepted method to assess the disassembly potential quantitatively while others came up with qualitative assessment methods. This Building Circularity Method is maybe not perfect since some adjustments are still necessary. Nevertheless, it gives a good indication of the degree of circularity in the design phase of a project. Besides that, the method is based on the working agreements and guiding principles from Platform CB'23, which is trustworthy and representative of the Dutch construction industry.

Furthermore, it is presented that circular design strategies should be used as a means to eventually reach sustainability. It is proven that a circular building design aims to reduce the environmental impact but that this is not per definition the truth (Saadé, et al., 2022). Therefore, it is necessary to verify a circular design by ensuring the benefits of global environmental sustainability as well. In the Netherlands, the LCA is a well-established, science-based tool to measure the environmental impact dimension of circularity and is suitable to apply in combination with other circular assessment tools.

Besides answering the first question, the literature study is used for the theoretical part of the second sub-research question:

"How to integrate BIM and data analytics for a decision-support framework for circular building design?"

BIM and DDDM are essential elements in the digital transformation of the construction industry whereby high-quality and timely available information supports smart and informed decision-making. The sustainability dimension, BIM 6D, focuses on integrating circularity performances in terms of material resources. The benefit of BIM lies in the combination of performing quick simulations and assessments with multiple design variants and the visualisation opportunities of the results to support circular design decisions.

The integration of BIM, data analytics, and circularity assessments is important because it increases the efficiency of information flow and speeds up the assessment procedure. A vital aspect of the BIM-CE integration is to consider the LOD in the early design phases. The model maturity and data availability differ per phase, so it has to be considered that the circularity assessment is aligned with the available information per phase. Furthermore, the literature study investigated three streams of BIM-CE integration: external circularity assessments with standardised exchange files, circularity assessments within the BIM environment, and an automated link between BIM and external material databases. Each stream has its potential or drawbacks. The most suitable stream is elaborated in the next subsection, the research focus. Moreover, information reporting and visualisation are important elements for decision-support systems. Visualisation techniques are implemented to better analyse the results and to communicate the story around the data. It can be concluded that interactive dashboards with dynamic features enhance information seeking, engages the end-user, and supports the decision-making process.

2.5.1. Research focus

The literature review presented a broad insight into the aspects of circular building design. Due to the broad scope, the focus of this research is narrowed down and summarised. First, the butterfly framework of EMF is adopted as the main concept of circularity with the following principles: preserve and enhance natural capital, optimise resource yields by circulating products at the highest utility, and promote system effectiveness by designing out negative externalities. Furthermore, the focus is only on the technical and environmental properties of circular building design. The technical properties refer to the building material properties in terms of intrinsic properties (material characteristics) and relational properties (use characteristics). The environmental properties refer to the environmental impact of building materials. The measurement method for circularity in this research is the BCI measurement method of Alba Concepts, which is based on the circular design guidelines of Platform CB'23. The method of Alba Concepts seems most suitable and relevant for this research because it captures all individual circularity components and merges them into a final score. This makes it possible to assess circularity in a quantitative way which is essential to steer on circularity.

Besides that, the focus of BIM-based circularity assessment is in the direction of conducting an automated connection between BIM and external building circularity databases, presented in subsection 2.4.3 as stream 3. For this research, this is the most efficient assessment method with opportunities to develop a suitable decision support framework for circular building design. A decisive factor was the high automation potential of data platforms and the possibility to develop an interactive and dynamic dashboard in an external application. Automation of the process is essential to reduce the manual procedures and speed up the circular assessment process, which makes the decision-support framework more usable as a steering tool for circular building design. The interactive and dynamic dashboard has the advantage to engage the end-user and creating a better understanding of complex data.

3. System Requirements Specification

The exploratory study is performed simultaneously with the literature study to expand the theoretical knowledge with practical experience and to determine the needs and wishes of professionals in the construction industry. This chapter comprises the SRS for the decision-support framework which describes the system features and behaviour. Thereby, the end-user's needs are first identified, whereafter the intended functionality is specified in function and system requirements. Furthermore, the external interface requirements of the embedded environment are presented. Lastly, the technical requirements in terms of performance are defined.

3.1. Functional requirements

First, the end-user's expectation of the framework and the desired functions are mapped out. The intended audience, the end-users of the tool, are the design team and sustainability specialists. Identifying their needs is essential to determine the expected and desired functional requirements for the system. The functional requirements specify the overall intended functionality that the framework provides, with as child items the system requirements to describe in a tangible way how to achieve this. Furthermore, in the simulation phase, the functional requirements can be used to validate the decision-support framework with the end-user. Information on the needs and wishes of end-user is gathered based on a user research sprint approach to gain insight effectively. Semi-structured interviews are conducted with professionals from the design and sustainability departments at Royal BAM Group, summarised in Appendix C: Semi-structured interviews. The result of the interviews is translated into a list of functional and system requirements in table 5.

Table 5: Functional and system requirements according to the interviews with end-users

Functional requirements	System requirements
1. Motivate design choices between variants in a transparent way	1.1. The tool substantiates design decisions and stimulates the discussion process
	1.2. The tool evaluates multiple design variants with circular design trade-offs
	1.3. The tool involves stakeholders through dynamic and interactive reports in a transparent way
2. Support the design team with feedback on circular building design in the early design phase	2.1. The tool facilitates steering on circular design early in the design process
	2.2. The tool assesses the building circularity score in a quantitative way
	2.3. The tool evaluates the circularity for the building as a whole, as well as for specific building components
	2.4. The tool gives insight into the reliability of the data
3. Provide sustainability specialists insight into the degree of circularity of the design	3.1. The tool analyses the individual circularity aspects of the design: the material flow, disassembly potential, environmental impact, and lifespan of materials
	3.2. The tool identifies circular hotspots, both positive and negative
	3.3. The end-user can specify certain data for comprehensive and detailed analysis
4. The interface of the tool is suitable for the intended audience	4.1. The tool is user-friendly with an intuitive interface
	4.2. The tool is applicable for non-experts without technical skills or knowledge of the software

The main functionality of the tool is that it provides insight into the degree of circularity of design alternatives in an early phase of the project. This gives the design team the possibility to steer the project based on trade-offs and make well-thought decisions early on when the impact of circularity measures is highest and the cost of changes minimal. The tool is aimed to gain insight into the current status of circularity goals that need to be achieved for the project.

However, the tool is not aimed at providing a final circularity assessment at the end of the design phase. It is not developed to calculate the circularity score to determine if the design fulfils official agreements in the tender contract, the aim is to steer the design process not to evaluate the end product. Furthermore, the framework is not meant to create a new method to determine the degree of circularity. It makes use of existing and verified measurement methods for circular building design.

3.2. External interface requirements

The second type of requirements are the external interface requirements. The decision-support framework is operating in an embedded system and these requirements are important for the interface between the system components. The input for the decision-support framework comes from design models in Revit and a material database which is set up in Excel. The data processing and circularity assessment is performed in Anaconda which supports Python 3.8. The circular design dashboard is developed in Power BI Desktop and is available for the end-user in the Power BI app. The software, specific versions, and installed packages can be found in table 6.

Table 6: External interface requirements

Software	Version	Installed packages
Autodesk	Revit 2021	Dynamo 2.0.3
Office 365	Excel 2016	
Anaconda3	Anaconda3-2022.05, Python 3.9	Numpy, Pandas, OS, fnmatch
Power BI	v2.1 – aug 2022	VCAD

The input data is subjected to certain model requirements to guarantee a successful operation of the framework. The sustainability specialist is required to update the material database according to a prescribed template, which is explained in subsection 6.1.2. Besides that, it is essential for the process that the BIM specialist assigns the essential parameters for all elements according to a prescribed method, see subsection 6.1.1. To summarise, the model requirements are:

- 3D-model compatible with Revit 2021
  - Create alternatives as a new Revit model, or as design options in Revit
- Set up Revit model according to the prescribed method for data gathering
  - Include NL/SfB classification as assembly code
  - Assign disassembly parameters as project parameters
  - Assign material classification as Keynote
- Set up material database according to the prescribed template

3.3. Technical requirements

Besides functional requirements, there are technical requirements such as performance, safety, and security requirements. In this study, the focus is limited to technical requirements that keep the system up and running, so performance-related requirements. The requirements regarding, for example, safety, security, or maintenance are not included in the scope of this research. The technical requirements consist of objective measurements and will be used for verification of the system in the simulation phase. The following categories are essential for optimal performance of the system: system operation, integration of data sources, data analytic performance, and the design workflow. The list of technical requirements is presented in table 7.

Table 7: Technical requirements

Subject	Technical requirements
System operation	1. The system runs as intended on existing Revit models
	2. The system produces no errors during the whole process
	3. The system removes manual procedures for circularity assessment
Integration of data sources	4. The system can extract the project data to a database
	5. The system can link the material data to the corresponding project data
	6. The system can process the data and perform circularity calculations
	7. The circular design dashboard can import the data and update the visualisations frequently
	8. The circular design dashboard can visualise the 3D-model
Data analytic performance	9. The system can regenerate the circularity results dynamically
	10. The system can verify the data quality for the assessment
	11. The end-user can change and play with the weight factor for calculations in the BCI measurement method
	12. The end-user can filter the data in the circular design dashboard according to their needs
Design Workflow	13. The system separates the data input and responsibilities from different disciplines
	14. The end-user has access to the data from intermediate steps to control the input data

PART 2 | SYNTHESIS PHASE

The third part of this research is the synthesis phase. The results from the literature study and the SRS will be translated into a practical solution. First, the framework is introduced by describing the concept of the framework and the design phases in which it can be applied. Also, the applied circularity measurement method is summarised. After that, information is provided about the design process of the framework. The framework consists of three parts: the data-, analytical- and application layer. The data layer section is explained how the project and material data are gathered. Next, in the analytical layer part, it is elaborated on how the data is integrated and processed, and how the process is automated where necessary. Once this is all done, the data is ready to be visualised and analysed in the application layer. The technical aspects of the dashboard are explained in the last section. This includes the Power BI data model and the data transformations.

4. Framework introduction

The decision-support framework operates in an embedded system. Therefore, it is important that not only the circular design dashboard is developed according to the specification but that the entire system is arranged correctly. A decision-support framework is constructed to establish a BIM-CE integration and to perform an automated circularity assessment. The concept of this framework is explained in the first section. Furthermore, the focus of the framework is on the early design. What is meant with the early design and which information is available is clarified in the second section.

4.1. Concept of the decision-support framework

The concept of the decision-support framework is to create an automated data-driven circularity assessment framework to support the transition to CE. The implementation of the framework focuses on the early design phase, as in this phase the design choices have the most impact on circular building design. Thereby, the goal is to steer projects on circularity by assessing design variants throughout the design process. The framework is developed for the design team and sustainability specialists. The design team can use the dashboard to determine the total, or partial, circularity score of design alternatives. Thereby, the circularity scores could be one of the trade-offs to determining sustainable design. Besides that, the interactive dashboard can help motivate design choices to the client transparently and understandably. The use of dashboards to substantiate design choices has been experienced as pleasant by clients of Royal BAM Group in previous projects. Moreover, sustainability specialists can gain a deeper level of understanding of the degree of circularity of the design. This helps them to identify circular hotspots and to come up with solutions to enhance circular building design.

The decision support framework is an interoperable system that analyses the design to inform decision-making. This system consists of three layers: a data layer to collect the necessary data, an analytical layer that accommodates the connection between different data sources, processes the data, and performs the calculations, and an application layer in which the dashboard is developed and made accessible for the end-user. A general concept of the operations that are performed is presented in figure 15. The applications used in the system are presented below in the workflow. The design data is created in Revit, a BIM tool developed by Autodesk. The data is extracted and exported using Dynamo, a visual programming language in Revit. The material data is gathered in Excel. Subsequently, the project and material data are linked and processed in Python to conduct the circularity assessment. In the end, the data is visualised and reported with an interactive and dynamic dashboard in Power BI. In the application layer, an additional plug-in is used called VCAD. This is a plug-in that produces a custom visualisation for Power BI to visualise an interactive 3D Revit model in a dashboard.

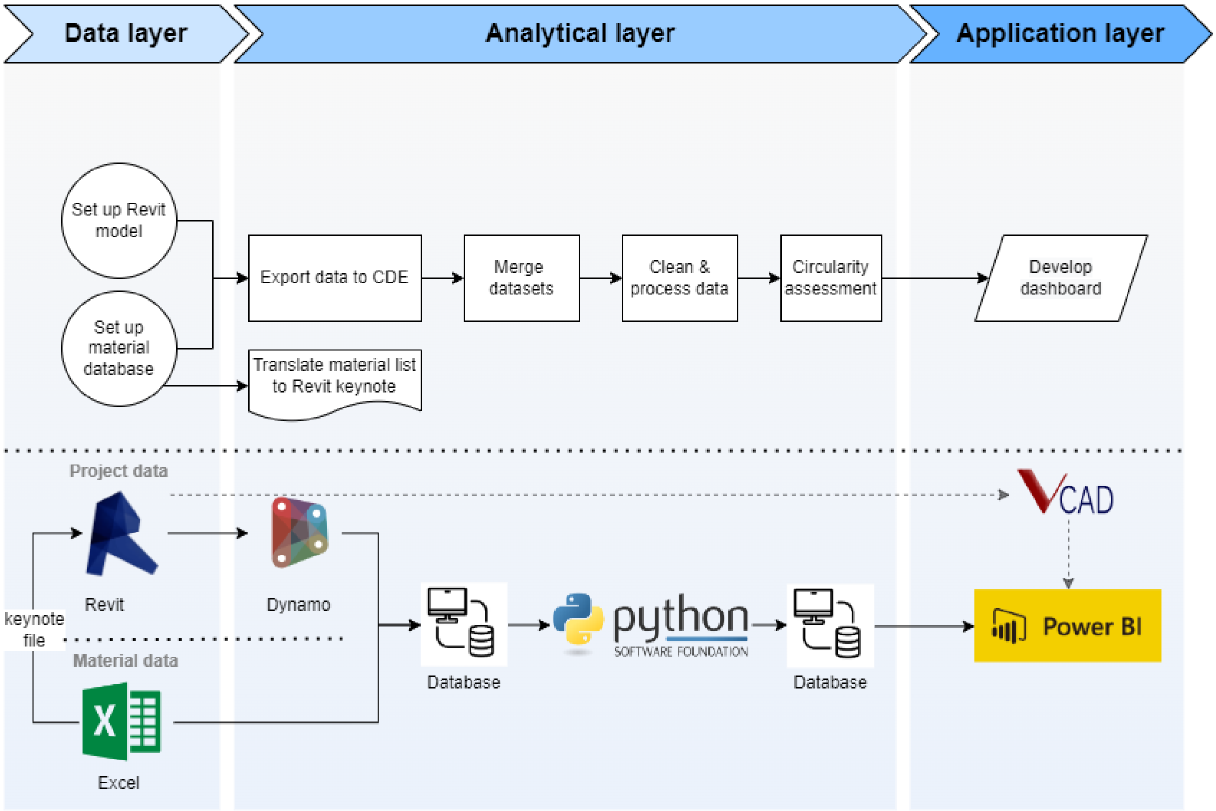


Figure 15: Development process (above), system applications (below)

4.2. Design phases of the decision-support framework

As stated before, the early design phase is highly important when striving for circular building design. It is recommended to steer on design choices as early as possible in the process to achieve a higher degree of circularity. Figure 16 shows that in the early design phase, the impact of circularity measurements is high, while the costs for circular design changes are relatively low. This comes from a well-known concept, the MacLeamy curve, which states that shifting the design effort forwards increases the flexibility of design changes while lowering the costs to implement changes (Construction Users Roundtable, 2004).

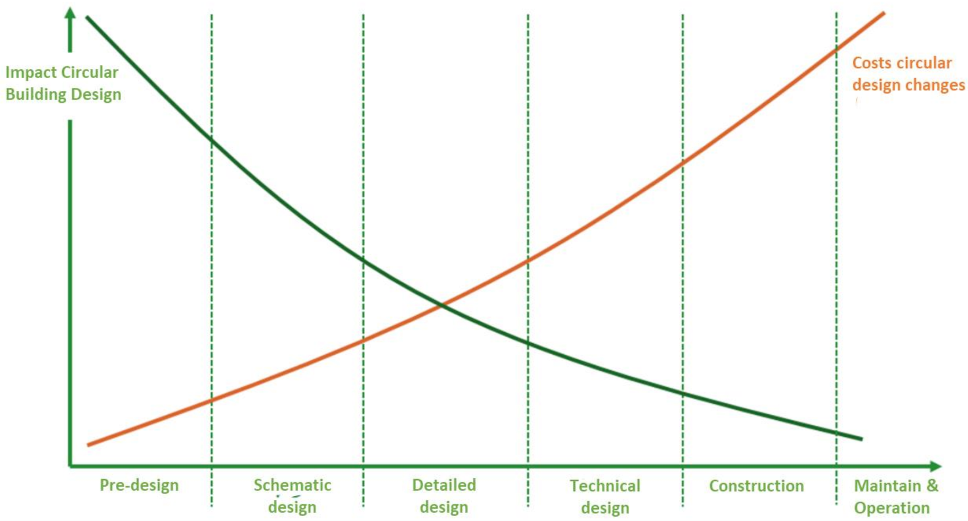


Figure 16: The MacLeamy Curve applied to Circular Building Design (Royal BAM Group, 2020)

The decision-support framework focuses on the schematic and detailed design to make an impact as early as possible. Thereby, it is not feasible to assess circularity quantitatively in the pre-design because the model is represented only in a conceptual manner. In this phase, circular building design could be included qualitatively by formulating circular ambitions and design strategies. Therefore, the focus of the framework is on the next two stages: the schematic design and the detailed design. In the schematic design, the elements are modelled with approximate sizes and materials, still with a low LOD. However, circularity analysis can be performed based on quantity estimates and material usage. A higher LOD will be achieved during the detailed design, which makes it suitable to perform a more accurate analysis based on specific material data and the disassembly potential of elements.

According to the theory stated in subsection 2.4.2, every model has a certain LOD per design phase. Nevertheless, the concept acts as a basis for a BIM protocol, but companies can deviate from this in a way that suits their own practices best. Therefore, the specific requirements per LOD are not uniform across the industry and differ per company. This framework is set up according to the BIM protocol of Royal BAM Group. In this BIM protocol, the necessary conditions for effective integral collaboration are created in terms of building the BIM model and exchanging and managing information. In this way, everyone within the project understands the maturity of the design per phase. The Royal BAM Group has moved away from the traditional classification of the LOD. They work with an Information Delivery Specification (IDS) which specifies the structure of the BIM model, the level of information of elements, and how to safeguard this information. Table 8 presents some aspects of the level of design maturity that are meaningful for this research.

Table 8: Level of maturity for design phases (Royal BAM Group, 2019)

	Schematic design	Detailed design
Level of Detail	 LOD 200	 LOD 300
Design output	- Basic alternatives generated; multiple design concepts defined	- Design options designed (basic calculations & definition of design) - Key dimensions & spatial design done
BIM Standard	- Generic dimensions are modelled - Types of structural systems set - Approximate geometry of structural elements modelled	- Overall sizes inc. external dimensions modelled - Specific sizes and orientation of main structural members
BIM parameters	- Assembly code (NL-SfB) - Assembly description - Material (NL-SfB) - Phasing	- Assembly code (NL-SfB) - Assembly description - Structural material - Material characteristics - Building sequence code
Additional information	- Development of digital goals and CDE setup - Targets / time scales set, and key programme restrictions identified that effect the design process	- CDE fully in place for main coordination of information - Schedule & build sequence checked & developed - Design Freeze dates established

5. Circular assessment method

In the previous chapter, the concept of the BIM-based circularity assessment framework is explained, and why it focuses on the schematic and detailed design phase. The maturity of the model and the level of information differ per phase. Therefore, it is not feasible to implement a fixed circularity assessment method because it should accommodate the right level of information. First, the measurement method for circularity is elaborated. After that, the adjustments of the measurement method per design phase and the proposed design workflow are explained.

5.1. BCI measurement method

The circularity measurement method for the framework comes forth from the guidelines of Platform CB’23 and the BCI Gebouw of Alba Concepts. The method follows the guidelines of Platform CB’23 as a foundation for the calculations, which is acknowledged by the Dutch construction industry. However, the guidelines of Platform CB’23 to measure circularity only consist of separate circularity indicators instead of an integrated score and do not provide a quantitative assessment of the disassembly potential of the design. Therefore, the BCI is applied as an additional method to include the design for disassembly and to determine the total circularity score of the building. The input for this method is in line with the measurement method of Platform CB’23. The calculations of the measurement methods are from a whitepaper of Alba Concepts and BCI Gebouw (2022) and are explained in this section.

The BCI measurement method is developed as a measurement instrument and as a steering tool on circularity in an early stage of the building design. It contributes to the core objectives of the transition agenda of Circulaire Bouweconomie by making circularity measurable. In the end, the BCI score is the result of the Material Circularity Index, Disassembly Index, Product Circularity Index, and Element Circularity Index, as presented in figure 11. The scope of the BCI assessment includes the following elements in the Layers of Brand: structure, skin, services, and space plan. This means that the site and stuff are not considered in a BCI assessment.

5.1.1. Material Circularity Index

One of the aspects of circularity, material usage, is defined in the MCI. This measure is a method developed earlier by the EMF as described in subsection 2.3.2 and is adapted with minor adjustments. The MCI measures the flow of material during the production and use phase of products. The higher the score, the higher the degree of circularity. It is determined by the mass fraction of the origin of materials and the future scenario. The origin of materials comes from virgin, recycled, reused, or biobased material. The possible future scenarios for products are landfill, incineration, recycle, or reuse. The mass fractions are determined according to the guidelines for Circular Design of Platform CB’23 (2020a). The MCI is calculated with the following formula:

$$MCI_p = \max\left(0, \left(1 - LFI_p * F\left(X_p\right)\right)\right) \quad (1)$$

$$LFI_p = \frac{v_p + l_p + i_p}{2} \quad (2)$$

$$F\left(X_p\right) = \frac{0.9}{\frac{l_t}{l_w}} \quad (3)$$

subindex ‘p’ = product

Where:

- LFI_p = Linear Fraction Index: addition of mass fractions that contributes to the linear economy
  - v_p = mass percentage virgin material: (origin of material)
  - l_p = mass percentage of landfill (future scenario)
  - i_p = mass percentage of incineration (future scenario)
- $F(X_p)$= Utility factor for lifespan of materials
  - l_t = technical lifetime, industrial average of materials determined by the methods for reference values (SBR, 2011)
  - l_w = functional lifetime determined by the client

5.1.2. Disassembly index

The disassembly index is the other important circularity aspect. An inseparable element cannot be reused with high quality in future projects. The disassembly potential is the extent to which an object can be dismantled at all building levels, without degradation of the product or damage to surrounding objects. The full method for measuring the disassembly index is explained in the report Circular Buildings (Alba Concepts, 2019). The disassembly index consists of four parameters: type of connection, accessibility of the connection, form confinement, and cross-through. The type of connection distinguishes into five types: dry connections, integral connections, connections with additional fixings, and hard or soft chemical compounds. The dry compounds are preferred regarding disassembly potential. Accessibility of the connection focuses on how easily an element can be reached without damage to surrounding elements. Furthermore, form confinement addresses physical containment, which determines the effort required to separate elements from each other. The last factor, the cross-through, examines the integration of multiple elements, where independent elements are easier to disassemble. More information and illustrations regarding the disassembly parameters are presented in Appendix B: Information documents. Table 9 presents the description of the parameters per category and the corresponding scores. Next, the disassembly index is calculated in the following way:

$$DI_p = \frac{2}{\frac{1}{DI_{con}} + \frac{1}{DI_{cmp}}} \quad (4)$$

$$DI_{con} = \frac{2}{\frac{1}{FC_p} + \frac{1}{CT_p}} \quad (5)$$

$$DI_{cmp} = \frac{2}{\frac{1}{TC_p} + \frac{1}{AC_p}} \quad \text{subindex 'p' = product} \quad (6)$$

Where:

- DI_p = disassembly index of products
  - DI_{con} = disassembly index of connection
    - FC_p = form confinement
    - CT_p = cross-through
  - DI_{cmp} = disassembly index of composition
    - TC_p = type of connection
    - AC_p = accessibility of connection

Table 9: Disassembly parameters (Alba Concepts; BCI gebouw, 2022)

Disassembly factor	Description	Code	Score
Type of Connection	Accessory external connection or connection system	TC1	1
	Direct connection with additional fixing devices	TC2	0,8
	Direct integral connection with inserts (pin)	TC3	0,6
	Filled soft chemical connection	TC4	0,2
	Filled hard chemical connection	TC5	0,1
Accessibility of Connection	Accessible	AC1	1
	Accessible with additional operation which causes no damage	AC2	0,8
	Accessible with additional operation which is reparable damage	AC3	0,6
	Accessible with additional operation which cases damage (20%)	AC4	0,4
	Not accessible - total damage of elements	AC5	0,1
Form Confinement	Open – no obstacle for (interim) removal of products or elements	FC1	1
	Overlap – partial obstacle to the (interim) removal of products or elements	FC2	0,4
	Closed – complete obstacle to the (interim) removal of products or elements	FC3	0,1
Cross-Through	Modular zoning of objects	CT1	1
	Intersections between one or more objects	CT2	0,4
	Full integration of objects	CT3	0,1

5.1.3. Product Circularity Index

The PCI brings together the circularity aspects, material usage and demountability. The circular product potential is determined based on the MCI and the DI of products. Thereby, in the BCI measurement method, both aspects are translated to a one-point score where they are equally important. However, the geometric mean of both indicators is used which means that if one aspect scores lower, it weighs more. The formula for the PCI has been determined experimentally by analysing existing circularity assessments.

$$PCI_p = \sqrt{MCI_p * DI_p} \tag{7}$$

5.1.4. Element Circularity Index

In the BCI measurement method, a building is not seen as just an accumulation of products, but it does distinguish elements as well. Figure 17 presents the schematical representation of a building. An element is a group of inseparable subproducts that arrives at the construction site as a composed whole. The ECI promotes modular and reusable elements instead of only circular products. The calculations of the ECI are quite similar to those of the PCI. The difference is that for the ECI the weighted average of the MCI of subproducts is used, whereby the environmental cost indicator is used as a weight factor. Besides that, the technical and functional lifespan of an element is determined by the minimum lifetime of a subproduct. The formulas are almost the same as with the MCI, except this time the LFI of an element is calculated based on a weighted average of the linear fractions of subproducts.

$$ECI_e = \sqrt{MCI_e * DI_e} \quad (8)$$

$$MCI_e = max\left(0, \left(1 - LFI_e * F(X_e)\right)\right) \quad (9)$$

$$LFI_e = \frac{1}{\sum_{i=1}^{p} MKI_p} * \frac{\left(\sum_{i=1}^{p}(MKI_p * n_p) + \sum_{i=1}^{p}(MKI_p * s_p) + \sum_{i=1}^{p}(MKI_p * v_p)\right)}{2} \quad (10)$$

$$F(X_e) = \frac{0.9}{\frac{l_{t,min}}{l_{w,min}}}$$ subindex 'e' = element (11)

Where:

- MKI_p = Environmental cost indicator of a product

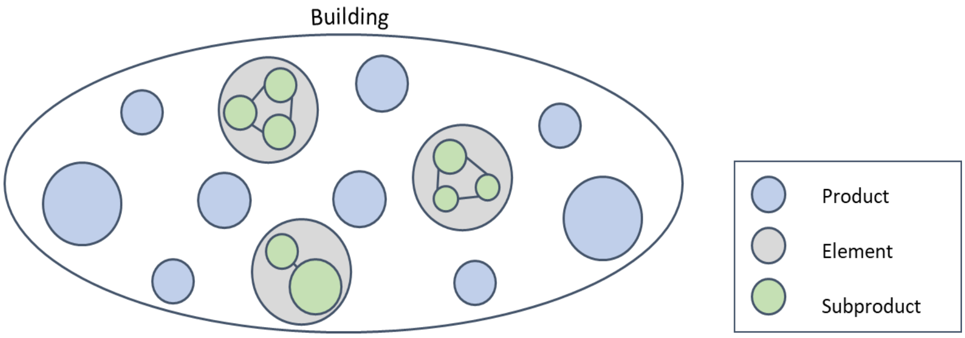


Figure 17: Schematic composition of a building

5.1.5. Building Circularity Index

In the end, all products and elements in a building are assessed based on material usage and disassembly potential. The building circularity, the final BCI score, is determined by the weighted average of all PCI and ECI scores. Again, the environmental cost indicator is used as a weight factor. The final score is calculated as follows:

$$BCI = \frac{1}{\sum_{i=1}^{n} MKI_n} * \sum_{i=1}^{n}\left((MKI_p * PCI_p) + \sum_{i=1}^{p} MKI_p * ECI_e\right) \quad (12)$$

The BCI score has a range of 0.10 to 1.00, where 10% means fully linear while 100% is completely circular. In practice, a 100% circular building cannot be achieved yet, because currently not every component in a building can be produced circularly and due to technical reasons, it is not feasible to create fully demountable products (Alba Concepts; BCI gebouw, 2022).

5.2. Circular assessment framework

The decision-support framework adopts the BCI measurement method to steer circular building design. Thereby, the BCI assessment is applied in two different ways advisable for the schematic and detailed design. This way of working is accompanied by changes in the design workflow. Therefore, a new design workflow is proposed to match the decision-support framework.

5.2.1. Adapted BCI assessment format

In this framework, the measurement methods of BCI Gebouw and Alba Concepts are adapted in such a way that the assessment fits with the level of information per phase. Therefore, in consultation with the end-users of the decision-support framework, the BCI measurement method is applied in two different formats. An indicative BCI assessment is performed for the schematic design, while the detailed design is assessed by a provisional BCI calculation. The indicative and provisional BCI assessments are defined as follows:

- **Indicative BCI assessment – schematic design**
  An indicative BCI assessment is conducted in the schematic design phase and will be used as a base estimation for the circular building performance. The goal is to identify circular hotspots and to propose circular design alternatives, strategies, and measures. In this phase, the BIM model consists of general dimensions and materials without non-graphical information like disassembly parameters. Therefore, it is most suitable to use the BIM model for the estimation of the quantities to assess the MCI. It is not feasible to make a proper estimation of the disassembly potential per product. In consultation with the end-users and the literature, a range of possible valuations have been drawn up, see table 10. In this way, the material usage of the design can be assessed with the MCI, and together with the range of disassembly potential, an expected BCI score can be estimated to gain insight in the building circularity.

Table 10: Potential disassembly scenarios (Alba Concepts, 2019)

Potential disassembly scenario	DI-score
Minimum DI	0.10
Low DI	0.40
Average DI	0.60
High DI	0.80
Maximum DI	1.00

- **Provisional BCI assessment – detailed design**
  A provisional BCI assessment is conducted during the detailed design phase and can be used to substantiate circular design decisions. The goal is to evaluate whether circularity objectives will be met and to optimise and compare circularity measures. At this point, the model includes specific element sizes and non-graphical information in the form of material characteristics. Besides that, it is possible to estimate the disassembly indicators for products and include this in the BIM model. This means that the full BCI measurement method could be applied to determine the degree of circularity.

5.2.2. Workflow circular building design

The proposal of a new framework to steer on circular building design is accompanied by changes in the design workflow. Nowadays, the circularity assessment is not integrated into the design workflow. In the current design process, the quantities are extracted from a BIM model to Excel and are manually provided with the correct coding in accordance with the material library. After that, all materials and disassembly parameters are manually entered into the BCI-calculation tool to perform the circularity assessment. This is a time-consuming process with a lot of repeating actions. Therefore, to be time-efficient, a BCI assessment is only performed at the end of the detailed design phase when design choices have already been made. This makes the current assessment tool not unsuitable to support circular design decisions because it only evaluates the choices afterwards and does not reflect on them during the process.

At this moment, the design workflow relies heavily on BIM. Thereby, a digital representation of the building is designed in BIM software consisting of the design model and non-graphical information for the entire lifecycle. To maximise the circularity potential in the design phase, the workflow must comply with the sixth BIM dimension, sustainability. This means that the sustainability and circularity characteristics of the model should be accommodated in the BIM environment. Figure 18 presents the proposed workflow for the decision-support framework. The design workflow distinguishes three streams, the departments of the design team and sustainability specialists, and the data platform of an organisation. The BIM specialists are part of the design team in which they are responsible for the design model. They are responsible for the quality of the design model, they ensure that the BIM protocol and BIM execution plan are followed and that the input data is correctly gathered. Moreover, the material database belongs to the responsibilities of the sustainability specialist. They have to update the database with products during the design process. The sustainability specialists gather the relevant material characteristics of products. Thereby, collaboration with the design team is necessary to decide which type of products are needed in the database. The third stream is the data platform, where the information is stored and data analytic operations are performed. With input from the material database and quantity take-off from the design, an indicative or provisional BCI assessment can be performed automatically. The results are reported in a dashboard that supports the decision-making of the design team throughout the design process.

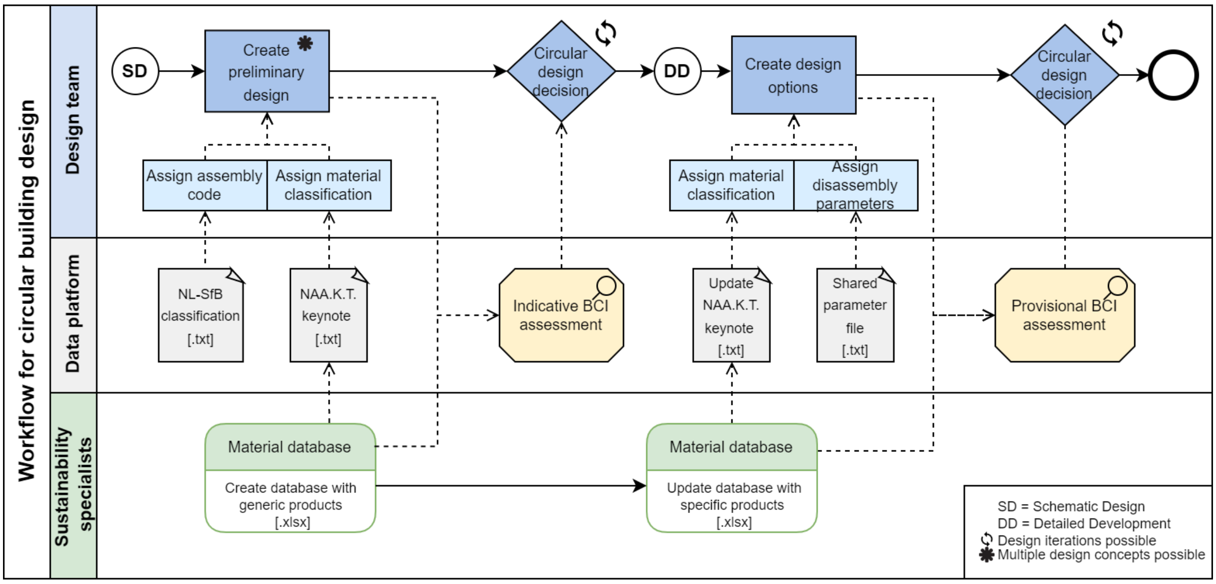


Figure 18: Proposed design workflow

The main change in the design process is that circularity assessments are performed throughout the design instead of after the detailed design. Therefore, more effort needs to be invested in the development of the design models by including circularity parameters and maintaining a material database. The extra effort pays off later when automated circularity assessments could be performed. Besides that, evaluating the circular design measures requires a more iterative approach where the sustainability specialists are involved at an early stage for their expertise regarding circular materials.

6. Framework design

This chapter describes the design of the decision-support framework step-by-step. All the information is presented that is needed for successful operation of the framework. Thereby, this chapter follows the structure of the framework, starting with the data layer, then the analytical layer, and finishing with the application layer.

6.1. Data collection – Data layer

The first step in the system is to collect the necessary data for the circularity assessment. This section describes what data is gathered and the procedure for how to do this consistently. It is important to invest up-front in the quality of the data and to capture the data consistently according to data standards and procedures to increase the reliability and automation of the assessment. The input data can be divided into two categories: project data, also called Revit data, and material data. Project data is specific data of the design which is captured in the BIM model. Material data is in the form of material passports and contains characteristics of specific materials or products. This could be information regarding the environmental impact, origin of materials, future scenarios and functional lifespan of elements. It is important to separate project and material data because the knowledge and responsibility belong to separate departments. The BIM specialist takes care the BIM model is set up in the right way with the correct project parameters, while the sustainability specialist deals with the material database and the circular design strategies. According to the interviews conducted in the analysis phase, it is preferred that each department is responsible for the input data of their expertise. So, the framework must be set up in such a way that the BIM specialist does not have to include sustainability characteristics in the model, and the sustainability specialist does not have to deal with the BIM model. In Appendix D: Framework design, the procedures for the BIM specialist are explained to assign the different project parameters in Revit.

6.1.1. Project data – Revit

The first type of data is project data which is captured in Revit. Effective cooperation in BIM can be accomplished with unambiguous agreements specified in an IDS. An IDS defines which information must be presented where and when in the process. For example, the IDS Design & Construct decomposes a construction to building elements using assembly codes (NL-SfB classification), each with its predefined element characteristics. For this research, the following aspects are important to include in the IDS: NL-SfB classification, material classification, and disassembly parameters.

NL-SfB classification

The NL-SfB is a semantic standard that captures definitions for building element classifications. The NL-SfB is the most used classification of building elements and installations in the Dutch construction industry (BIM Loket, 2020). The classification does not limit itself to the Dutch industry only. It is commonly used to encode objects in BIM- and CAD models and to provide the suppliers with information to order building elements. It gives the possibility to filter and communicate with other applications in a structured and unambiguous way. The classification is used in several NEN-norms, for example, construction drawings (NEN2574:1993) , and BIM Standards like BIM Basis ILS and IDS Design & Construct. The NL-SfB consists of five tables for spatial facilities (table 0), functional building elements (table 1), construction methods (table 2), construction materials (table 3), and activities, characteristics and properties (table 4). In practice, table 1 is commonly used in BIM models and incorporated into BIM Standards. This table classifies the elements based on a four-digit code, where the first two numbers stand for the main elements and the last two numbers for the functions or applications.

For this framework, the BIM specialist ensures that the NL-SfB classification is correctly assigned in the Revit models with the parameter called ‘assembly code’. This is a built-in parameter in Revit which can be linked to the NL-SfB classification code file and can be assigned to all elements.

Material classification

Besides the classification based on building elements, there is a material classification. Important with performance-based analysis based on materials, is to have a uniform and unique material names because all applications must recognise the same material. Identifying materials based on a standardised classification also helps when working with material passports. For the decision support framework, the element must be classified with a uniform material convention. Otherwise, it is not possible to connect the quantity data from Revit with the corresponding material data. According to the professionals at Royal BAM Group, there is no commonly used material classification within the industry yet. The material classification is mainly company-specific.

An option for material classification is to use table 3 of the NL-SfB classification which provides information mostly at a general level. The construction materials are classified at the main level, noted with a letter, and further specified with a number. For example, the letter ‘h’ stands for metal and the combination ‘h2’ for steel. In the case of a composite product, the dominant material property is governing, according to the BIM basis ILS. One of the major limitations according to colleagues at BAM and professionals at Alba Concepts is that the classification is too generic and does not match the classification required in practice. For example, heavy structural steel, light-weight steel, prestressing steel, and reinforcing steel all belong to the category steel, h2, while the characteristics in terms of environmental impact and embodied carbon differ and separation is preferred

An alternative for material classification is the NAA.K.T. unambiguous material designation which is introduced in the latest BIM basis ILS. The material classification NAA.K.T. stands for name_feature_application (Dutch: **NAA**m_**K**enmerk_**T**oepassing). The name consists of a short list of materials commonly used in the construction industry, like concrete, timber, or steel. The feature tells something about the call sign, like brick, plywood, or stainless steel. The last term refers to the application in general, for example, an element or plate. The goal of the NAA.K.T. classification is to create an unambiguous name convention that is generic enough to apply in the sector but specific enough to be of added value (BIM Loket, 2022). Currently, the construction sector investigates the possibility to improve the material classification, the connection with IFC, and the development of NAA.K.T. (Zorzi, 2019).

Although the NAA.K.T. standard is not fully adopted in the industry yet, it is used as material classification for this research because a uniform standard is necessary. Implementing the NAA.K.T. classification tackles the problem of having a uniform material convention. However, this does not mean that the material has a unique material name because multiple products can be categorised under the same NAA.K.T. classification. To solve this problem, a script is written in Python that creates a unique number after each non-unique material. The script is elaborated further in subsection 6.2.2. The input of the script is the products from the material database. The script will convert the materials from the material database into a file that is directly readable as a keynote in Revit. A keynote is a Revit parameter that is available for all model elements and materials which can be applied to assign material information. In this way, the BIM specialist can assign the material information from a list of available materials for this project and does not have to worry about determining the correct NAA.K.T. name convention. Figure 19 shows an example in Revit of the NL-SfB classification and the NAA.K.T. material classification.

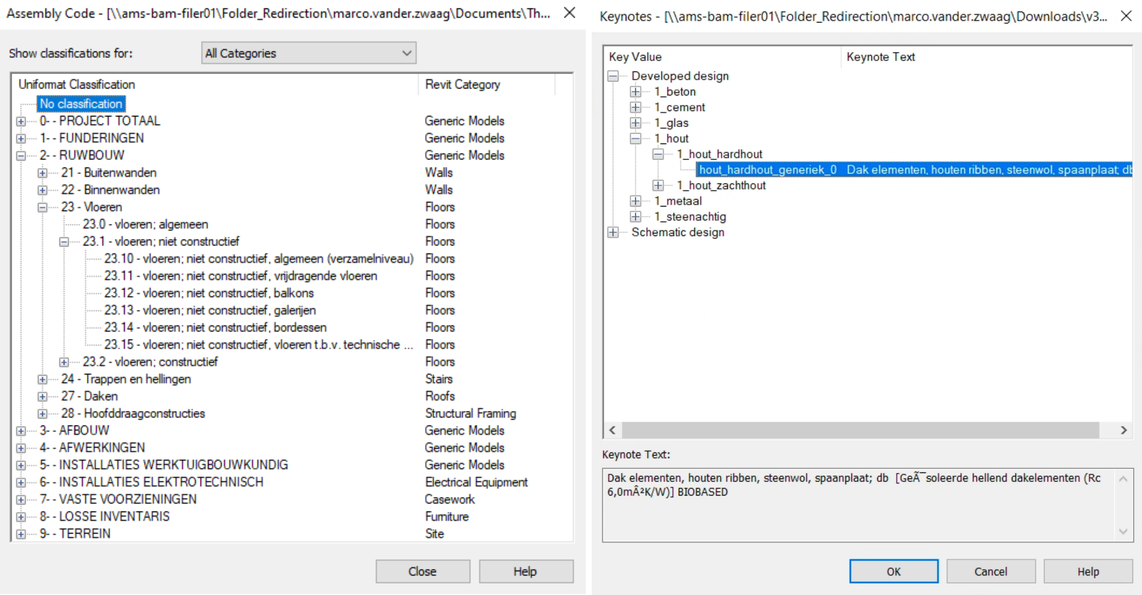


Figure 19: Left) Revit assembly code; Right) Revit material keynote

Project-specific information – disassembly parameters

The last type of information that is needed in the BIM model are project specific circularity parameters. This group consist of the four disassembly parameters which are needed to determine the disassembly index, and the functional lifetime of elements to determine the utility factor. The disassembly parameters and the corresponding codes and scores are already explained in section 5.1. It is chosen to assign the disassembly parameters in Revit because the options are design-specific and the BIM specialist has more knowledge about the design characteristics. According to the BIM Forum (2021), a BIM model of LOD350 or LOD400 contains enough detail to understand the construction and disassembly methods of the connection. Nevertheless, this framework focuses on the early design phase and estimations are necessary. In the schematic design, the level of detail is too low to make sound estimations of the disassembly potential because connections are only modelled as placeholders. In this phase, the disassembly parameters are not needed because an indicative BCI assessment is performed with general estimations of the disassembly parameters. In the detailed design phase, the disassembly factors could be estimated based on experience or the reference value determined by Alba Concepts. Therefore, the disassembly parameters must be added in the detailed design where the BIM specialist chooses the most probable disassembly indicators at that moment in time. By including the disassembly parameters in the detailed design, the provisional BCI assessment can be performed.

The project-specific circularity parameters can be included in Revit as shared parameters. Shared parameters create a uniform set of parameters for all families and elements for BIM specialists to fill in. The definitions of the shared parameters are stored in an independent text file which makes sure that the parameters are consistent for all projects.

6.1.2. Material data – Circularity database

The second type of data is material data, especially the sustainability and circularity characteristics of materials. The data can be captured in a building- or material passport. This is a database which represents a digital registration of the products used in a building model. This document consists of qualitative and quantitative information of building materials, such as the description of the product, environmental impact, origin of the material, future scenarios, and the lifespan of materials. There is no predefined format for a circularity database or material passports, but Platform CB'23 has established guidelines to construct material passports (Platform CB'23, 2020b). For this research, a template for a material database is presented in figure 20 based on the information required to perform a circularity assessment in the early design phase. The following parameters must be included in the material database:

- Assembly code: Building elements according to the NL-SfB classification
- Phase: The design phase
- Category NMD: Environmental category of products in the NMD
- Product type: Differentiation between subproducts, products, or elements
- Element code: Unique code per element
- Product: Product description
- NAA.K.T. classification: Material classification according to the NAA.K.T. method
- Unit measure: Product measured in meters, square meters, cubic meters, or per unit
- Unit weight: Weight in kg per unit
- MKI: Environmental impact in € per unit measure
- CO2: Kg CO2 per unit measure
- Origin of material: Mass percentage of input materials categorised in virgin, reused, recycled or biobased material
- Future scenario: Mass percentage of output materials categorised in landfill, incineration, recycled or reused material
- Technical lifetime: Industrial average of the material lifetime which is determined by the method for reference values (SBR, 2011)

Asssembly Code	Phase	Category NMD	Producttype	Element code	Product	NAA.K.T	Unit	Weight_kg/unit	MKI	CO2	Material.Virgin (%)	Material.Reused (%)	Material.Recycled (%)	Material.Biobased (%)	Material.Landfill (%)	Material.Incineration (%)	Material.Recyclable (%)	Material.Reusable (%)	Technical lifetime
21.22.9	Developed	3	Product		Betonsteenmetselwerk; incl. stucwerk [binnenspouwblad (dragend) incl. afwerking]	steenachtig_baksteen_gene	m2	234	4,81	49,0	100	0	0	0	28	1	71	0	100
21.22.10	Developed	3	Product		Baksteenmetselwerk; incl. stucwerk [binnenspouwblad (dragend) incl. afwerking]	steenachtig_baksteen_gene	m2	201,4	5,61	61,1	100	0	0	0	36	2	62	0	100
27.22.18	Developed	3	Product		Sandwich paneel trapeziumvormige, staal + EPS; gepoedercoat 55mu [Geïsoleerde hellend dakelementen (Rc 6,0m²K/W)]	metaal_staal_element	m2	12,8	3,13	39,9	69	0	31	0	2	34	46	18	75

Figure 20: Template material database

The input for the circularity database originates from the database of Alba Concepts. This is a database that builds upon the NMD and NIBE. The NMD is a database enriched with product cards with information regarding the environmental impact obtained from life cycle assessments according to the European norm EN 15804. NIBE is a similar database as the NMD. If possible, they use the building products from the NMD as a basis, otherwise, they perform additional calculations to construct a material profile. The database of NIBE contains, on top of the environmental impact, information on the end-of-life cycle scenario of products. Alba Concepts takes it one step further by also including the origin of materials. To perform a BCI assessment, information regarding the environmental impact, the origin of materials, and end-of-life cycle is needed, which makes the database of Alba Concepts most suitable for this research. Nevertheless, it is possible to use other sources or databases for circularity data, when the required data is available and reliable, and the measurement method is consistent and conforms to the European norms.

According to colleagues at Royal BAM group, one of the challenges with circularity assessments in the early design is the availability of reliable project and material data which fit the level of maturity per phase. Therefore, the material data is divided into data for schematic and detailed design to be consistent with the model maturity per phase. In the schematic design, generic material data is gathered with a low level of information and applicable to a wider range of materials. This suits the level of detail of the BIM model in this phase. Once the design is evolving towards a more detailed design which contains specific model elements, the level of information of circularity data could increase as well. In that case, more specific material data can be assigned as non-graphical information.

The BCI measurement method does not only consider individual products but also elements, as explained in subsection 5.1.4: Element Circularity Index. An element is a composite product of subproducts which arrives at the construction site as a whole and where the disassembly of the composition is decisive. The circularity of an element is assessed with the ECI. To integrate elements as a whole in the circularity assessment framework, columns for product types and element codes are included in the material database. The sustainability specialist can assign per material if it is a product, element, or sub-product. In the case of an element with a subproduct, a unique element code must be assigned to the element and corresponding subproducts which indicates that these belong together. In this way, it is possible to include inseparable elements in the circularity assessment to determine the ECI.

Schematic design – generic data

The generic material data is meant for the schematic design phase. The schematic design model is at LOD200, which means that the objects are modelled with approximate sizes, quantities, and materials. Therefore, the non-graphical information, like material properties, must be at the same level of information as the model. With input from the design professionals at Royal BAM Group, the Revit material library, and the available information in the database of Alba Concepts, NMD and NIBE, an initial material database is constructed with generic materials that are commonly used in the building industry.

The initial database consists of generic products with cubic meters as functional units. This suits well with the LOD of the design. In this phase, the material data is gathered based on product cards mostly in category 3 of the NMD. Category 3 means that the environmental data of products are unbranded and determined by the Stichting Nationale Milieudatabase, thus not related to manufacturers, suppliers, or branches. The other categories in the NMD are branded data from manufacturers and suppliers (Cat. 1) and unbranded data from groups of manufacturers and/or suppliers and industries (Cat. 2). The differences with category 3 are the publicity of data and that the data in category 1 and 2 are tested by an independent, qualified third party according to the verification protocol of the NMD. The information to determine the environmental impact of category 3 profiles is less complete and based on generic information, which results often in a lower score. Therefore, an additional factor is applied and managed by the NMD. The result is that category 3 product cards always have worse environmental performance than comparable verified products, which led to a conservative estimate of sustainability assessments (NMD, 2020).

Detailed design – specific data

The initial database makes it possible to determine a baseline of the circularity estimation in the schematic design phase. The next step is to update the material database with more detailed product data as the design progresses. Updating the circularity database is the responsibility of the sustainability specialists, as they have the required knowledge regarding material properties. The sustainability specialist makes sure that all the product cards of materials used in the design model are complete and up to date in the circularity database.

In this phase, the design evolves from the schematic to the detailed design, so LOD200 – LOD300. Objects are modelled as specific systems products or elements with accurate sizes and quantities. Also, the level of information of non-graphical elements, in terms of element characteristics, evolves as well. Therefore, the material database can be updated with a higher variety of products with a higher level of information accordingly. More detailed information on the elements is available, which makes it possible for sustainability specialists to assign materials with product cards belonging to category 1 and 2. Products in category 1 are manufacturer or supplier specific, which means that the use of these products comes with certain design requirements and constraints. The same holds for category 2 data which is branch-specific data. Application of categories 1 and 2 products must be in collaboration with the design team to determine if the products fulfil the design requirements. The benefit of categories 1 and 2 products is that the environmental profiles are supplied by manufacturers from the building industry, who have done more research to estimate the environmental impact more accurate. Therefore, the design team and the sustainability specialists could improve the circularity score of the design compared to the previous phase. However, the risk with category 1 and 2 data is that it is not publicly available. Therefore, the sustainability specialist cannot always know the quality of the data and under what preconditions and constraints the impact is determined. The limited transparency of category 1 and 2 data can cause a distorted image of the actual environmental impact. So, the sustainability specialists have to be aware of this issue if they still want to use manufacturer or supplier-specific data. Therefore, the material database list the category of each material, which makes it feasible to alert the end-user of the dashboard with the material data categories that are used in the assessment.

6.2. Data analytics – Analytical layer

The second part of the system is the analytical layer. Once the data is collected, it is time to extract, clean, and process the data. The data integration process is also called extract, transform, and load (ETL). First, the extraction of project data with Dynamo is described. Next, the steps involved with the cleaning and processing of the data are explained. This is done to establish consistency and improve the quality of the data. The processed data can be loaded into a database for further use in the application layer. Lastly, a key element of the framework is automation to reduce manual procedures. The automation involved in the process is elaborated on in the last part of this section.

6.2.1. Data extraction

The data extraction focuses on the project data in Revit. The Revit model can be seen as a project database where all the design information is stored. A built-in option to export the data from Revit is material take-off schedules. However, the quantity take-off shows a high level of detail about the assembly of a component, while this is not needed for the circularity assessment. For example, a steel sandwich panel filled with PIR is divided in the schedule as steel inner plate, PIR isolation, and steel outer plate. This fits not with the level of detail of products in the material databases. There the steel sandwich panel is described as one single product. Besides that, in Revit schedules, the overview is lost when there are a lot of different parameters available in big projects. This makes it difficult to choose the correct set of parameters for the schedule. To solve these problems with Revit schedules, Dynamo is used as a plug-in to extract the data from the model. The Dynamo script makes use of standard nodes and packages in the library, and of custom nodes that implement a Python script to extend the capabilities. Dynamo gives the flexibility to create and format a quantity take-off at the right level of detail which is most suitable to perform a circularity assessment later. Also, once the script is written, the BIM specialist only has to run the script with the Dynamo player to perform and export a quantity take-off. Thereby, no intervention in the Dynamo script is necessary which ensures the consistency of the data export because everything is set up in a predefined way. This is in line with one of the data quality dimensions: consistency. This dimension states that there are no differences between two or more representations of data items (Ramasamy & Chowdhury, 2020). This is essential for the different applications to communicate. The advantage of this is that there is a consistent export format of the quantity take-off which benefits the data processing procedures in a later stage.

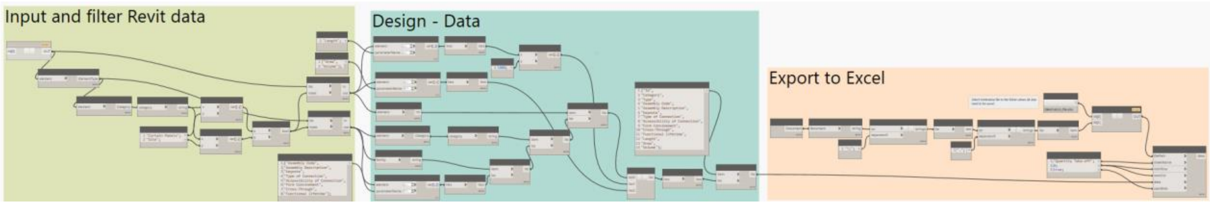


Figure 21: Full Dynamo script

Figure 21 presents the structure of the Dynamo script, whereby it can be noticed that it consists of three parts: data input, set up of data format, and data export. An enlarged figure and a more detailed explanation of the figure and the custom Python nodes can be found in Appendix D: Framework design. The three parts of the Dynamo script can be described as follow:

1. <u>Input and filtering of Revit data and elements</u>
   The first part imports the Revit data from the model. Thereby, it filters only the elements required for the circularity assessment, so only the elements that represent a 3D geometry and contain material quantities.

2. <u>Set up the data structure of the quantity take-off</u>
   In the second part are the necessary parameters stored per element and is the data structure organised. Two types of parameters are stored per element: type and instance parameters. Instance parameters are unique for every element, such as element ID, volume, area, and height. Type parameters are properties of an element which is the same for all items of the same type category. For example, an element is an exterior brick on a metal stud wall type. This means that each element of that type has the same type parameters, like NAA.K.T. classification, assembly code, and disassembly parameters. To clarify, each element is an instance that belongs to a type, as can be seen in figure 22.

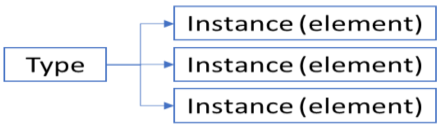


Figure 22: Revit type and instances

3. <u>Data export to excel</u>
   Exporting the data to Excel is the last part of the Dynamo script. The script exports the quantity take-off to an assigned folder. Thereby, it automatically checks if the model has an existing export and if so, it will overwrite the current file instead of creating a new one.

6.2.2. Data processing

The next step of the data analytical layer is to transform the data, which includes filtering, cleaning, formatting and merging the data. These operations are performed in Jupyter Notebook, an open-source web-based development environment supporting Python. Two scripts are written, one to convert the material database to a Keynote text file for the NAA.K.T. classification in Revit, and one to process the project and material data. The steps in the Jupyter Notebooks are explained and attached in Appendix D: Framework design.

Material database to Revit keynote

The first script ensures the consistency of the material classification and creates a keynote for Revit. This script aims to create a consistent name convention for elements in Revit and the materials in the material database. The end product of this script is a text file that lists all the materials in the correct structure and format. This text file is linked to Revit as a keynote, which gives the BIM specialist the possibility to assign material names to all elements from a drop-down menu and with the correct NAA.K.T. classification code. Figure 23 presents the transformation of a product from the material database to the element classification in Revit.

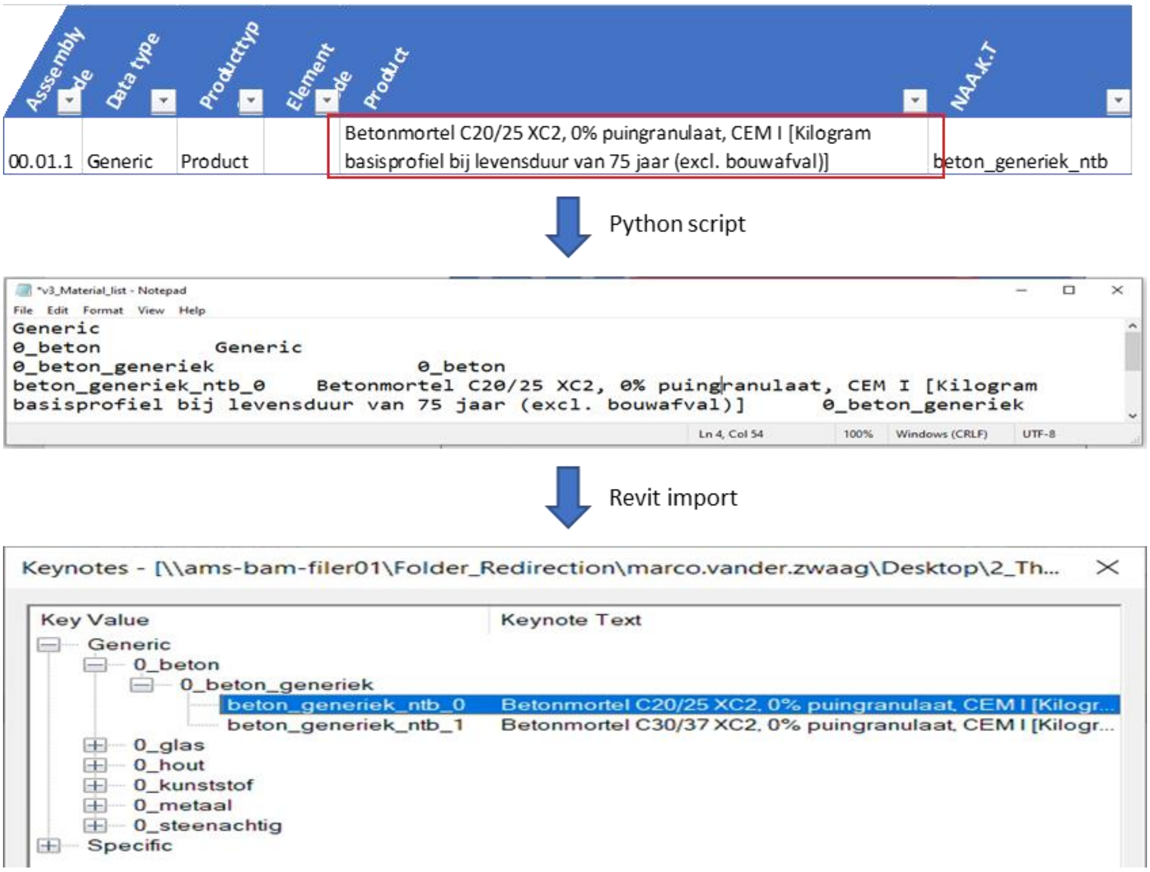


Figure 23: Process from material database to text file, to Revit keynote

Data processing

The second script performs the data processing. Therefore, a Python library, Pandas, is used to work with multiple datasets. The data processing consists of four parts: importing data, cleaning data, merging data, and performing the circularity calculations. The goal of the script is to clean the datasets, merge the data, and perform the calculations for a BCI assessment. In the end, the processed data is stored as a new file in the database, which is directly ready for visualisation and reporting purposes in the next phase. The following steps are performed to process the data:

1. <u>Import datasets</u>
   In the first part, importing the data is a relatively straightforward function in Pandas because the Revit and material data are stored in Excel. The script automatically recognised different Revit data files in the database folder, so there is no need to manually assign the different files. Next to the Revit and material data, a table is created with scores for the disassembly indicators.

2. <u>Data cleaning</u>
   The next step is to clean the data. Data cleaning is the process of removing incorrect data or dealing with missing data and is necessary to increase the data quality of the sources. In the material data, only the elements have missing data. This is expected because this data needs to be constructed based on the aggregation of underlying data of subproducts of an element. The weight, environmental cost indicator, and CO2 emission are determined with the summation of the subproducts, while the technical lifetime is determined based on the minimum lifetime of the subproducts. The data regarding the origin of materials and future scenarios are handled during the ECI calculations for BCI assessment because this depends on the environmental impact and therefore can only be determined after the data merging. Furthermore, it is observed that data is missing in the Revit data as well, for the length, area, and volume parameters. This is not a problem, because not all categories have to contain values for all three parameters. More important are the model elements that do not have a NAA.K.T. classification because then it is impossible to link them with the corresponding material data. It is chosen not to remove or handle this data in Python because the data must be added in the Revit model itself. The model elements with missing values will be kept in the data. However, in the circular design dashboard, the missing data does not contribute to the circularity assessment and the end-user will be alerted to the missing elements and values on the data quality page.

3. <u>Data merging</u>
   The third step is to merge the Revit and material datasets into one. Therefore, Pandas has a built-in function, merge, to join different datasets. There are multiple merging types in Pandas. Figure 7 presents the most common merge types. In this case, a left join is applied. This means that all the records of the Revit data are presented, while the material data is attached to it, irrespective of whether the keys in the Revit data can be found in the material data. The unique NAA.K.T. classification codes of both datasets are used as an identifier to join the data.

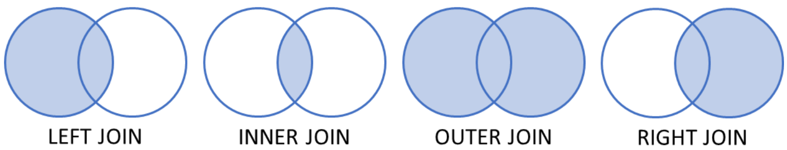


Figure 24: Types of merging with Pandas

4. <u>BCI assessment calculations</u>
   The last step consists of the calculations for the circularity assessment. The calculations are performed as explained in section 5.1. There are two things worth mentioning: the calculations of the MCI per element and the dataset for the expected BCI in the schematic design. For the MCI per element, the origin of materials and future scenarios of the elements are determined based on the values of the subproduct, in the same way as is dealt with the missing values before. Thereby, the environmental cost indicator is used as a weight factor. Also, the values of the origin of materials and future scenarios are transformed from percentages to total weight per indicator. It is preferred by the sustainability specialists and the consultants of Alba Concepts to express the result of these parameters in weight instead of percentage. The second thing is the dataset for the indicative BCI assessment in the schematic design phase. In this dataset, a range of possible PCI values is determined, which are used to establish an expected BCI score. The result is two datasets directly ready to be imported in Power BI, in the application layer.

6.2.3. Automation of workflow

One of the development objectives is to design an automated decision-support system for circular design assessment. The design is developing continuously which means that the circularity assessment needs to be performed periodically to obtain the most recent results. Therefore, it is beneficial for the process to automate steps in the ETL process to reduce manual procedures for the end-user. First, a BIM protocol is needed to capture the frequency of data updates and other BIM-related agreements. Next, the different aspects of automation in the decision-support framework are explained.

BIM protocol

According to the interviews with the end-users from the analysis phase, the preferred frequency at which the data should be updated is not fixed. The design team must have the latest data at specific moments in the design phase, these moments are called design freezes. A design freeze is a moment when they evaluate the trade-offs to make certain design decisions. At Royal BAM Group, the aim is to establish a key programme restriction with provisional dates for design freezes in the schematic design phase. Once these moments are known upfront, the execution of data processing tasks can be scheduled a few days before. Furthermore, the sustainability specialists mentioned that they also do not have to continuously monitor the degree of circularity of the design or at specific moments in time. Mostly, it depends on the type of project, and the importance of circularity within the project. The dilemma is not to find a suitable frequency to update the data but to find a way to make the current status of the data clear. They want to know when the data was last updated to prevent miscommunication and duplicated work. Therefore, it is important to capture all data-related agreements in a BIM protocol, so everybody knows what they can expect regarding the availability of data. In such a protocol, the design freeze moments can be captured, how many days before the data will be updated, or if the project should update the data at a constant interval. If the latter is the case, consider that the amount of irrelevant and outdated data could be a complication for the storage capacity in the cloud. Furthermore, the BIM protocol could include the update process, assigned responsibilities, and a contact person. In this way, if the design team or sustainability specialist suddenly wants the data updated, they know whom to contact for this.

Automation process

For the decision-support framework, attention is paid to the automation of the following tasks:

- <u>Exporting Revit data with Dynamo</u>
  The first part is to automate the process of exporting the bill of quantity from Revit to Excel. The Dynamo script explained in subsection 6.2.1, automates all the actions needed to extract the data from the Revit model and transforms this into a quantity take-off in Excel. The Dynamo script can be executed in Dynamo Player. However, running the Dynamo script still requires a manual procedure as the BIM specialist activates the Dynamo Player by clicking on play. On the other hand, this only must happen before the design freezes when updated data is required. Therefore, this procedure could be included in the BIM protocol.

- <u>Data processing in Python</u>
  The Python scripts can be automated so they will run at agreed moments as well. To do so, Python scripts can be scheduled at fixed moments in time or periodically. The frequency or moments must be captured in the BIM protocol. Next, for example, Windows Task Scheduler can be used to run Python scripts automatically at predefined moments. Therefore, a Windows executable bat file is written that can execute commands via the Windows command prompt and this command must be scheduled in Windows Task Scheduler. The result is that all the data analytic operations, generating the material list and processing the data, can be

automated so no manual procedures are required. This is one option to automate the process, but other options are also possible for automation in data platforms.

- Data importing in Power BI
  Lastly, the integration of the processed data and the reporting in Power BI is automated. Power BI has the functionality to schedule a refresh at constant intervals or when changes are made in the dataset. It creates a connection between the Excel workbooks stored in the database and the Power BI dashboard. Power BI scant the datasets at predefined intervals. It automatically updates the data at the preferred time or when changes are detected to the underlying dataset.

6.3. Circular design dashboard – Application layer

The third layer of the framework is the application layer. This is where the circular design dashboard is constructed. The dashboard is the place where all the data comes together and that tells the story through visualisations. The most important circularity metrics are presented to support the decision-making process. The circular design dashboard is the end product for the design and sustainability team. In this section are the technical aspects of the dashboard explained. It starts with explaining the underlying data model, which is a visual representation of data tables and relationships. Next, it focuses on the data transformations with the Power Query editor to determine the model health. The exact content of the tables in the data model, the measures, and data transformation operations can be found in the attached Power BI model of this research. The functionality of the dashboard is presented in the simulation phase, where it is demonstrated with the use of a pilot project.

6.3.1. Data model

One of the essential aspects behind each dashboard is the data model. This determines the way data is exposed to its end-user. A data model consists of entities, attributes, and relationships. An entity is a specific object with its unique identity, such as a Revit element. Each entity comes with multiple attributes that describe the entity, like geometry or material properties. The data model connects different entities, or tables, by creating relationships between them based on business rules. The data model is set up according to the star schema approach. This approach separates the data into dimension and fact tables. The fact table stores the actual measurements in terms of events, in this case, element data. The dimension tables are connected with the fact tables and describe the fact data with multiple attributes. The data model for the circular design dashboard is presented in figure 25.

The main takeaway of the data model is that the 'Data_processed' table is the main fact table which is the input from the analytical layer of the framework. The same goes for the table 'Data_rangeBCI', which is also from the analytical layer. To the right of this table are additional tables constructed in Power BI to assess the model health or data quality. These tables are explained in the next subsection about data transformations. Furthermore, the table 'Data_VCAD' comes from the plug-in VCAD and contains information about the 3D geometry and additional information needed for the VCAD-visual.

Another part of the data model is the measures. Measures perform real-time calculations based on active filters on a dashboard. They are necessary to recalculate circularity metrics interactively and dynamically. Measures are written in a Data Analysis Expression (DAX) formula language. DAX formulas make use of relational data in the data model. In the dashboard, measures are used to calculate the final BCI score and the weighted average MCI, DI, ECI, and PCI. The advantage of these measures is that the scores will be recalculated every time the end-user changes the filters of the dashboard. This makes it possible for the end-user to gain ad-hoc insight into different circularity aspects of the design.

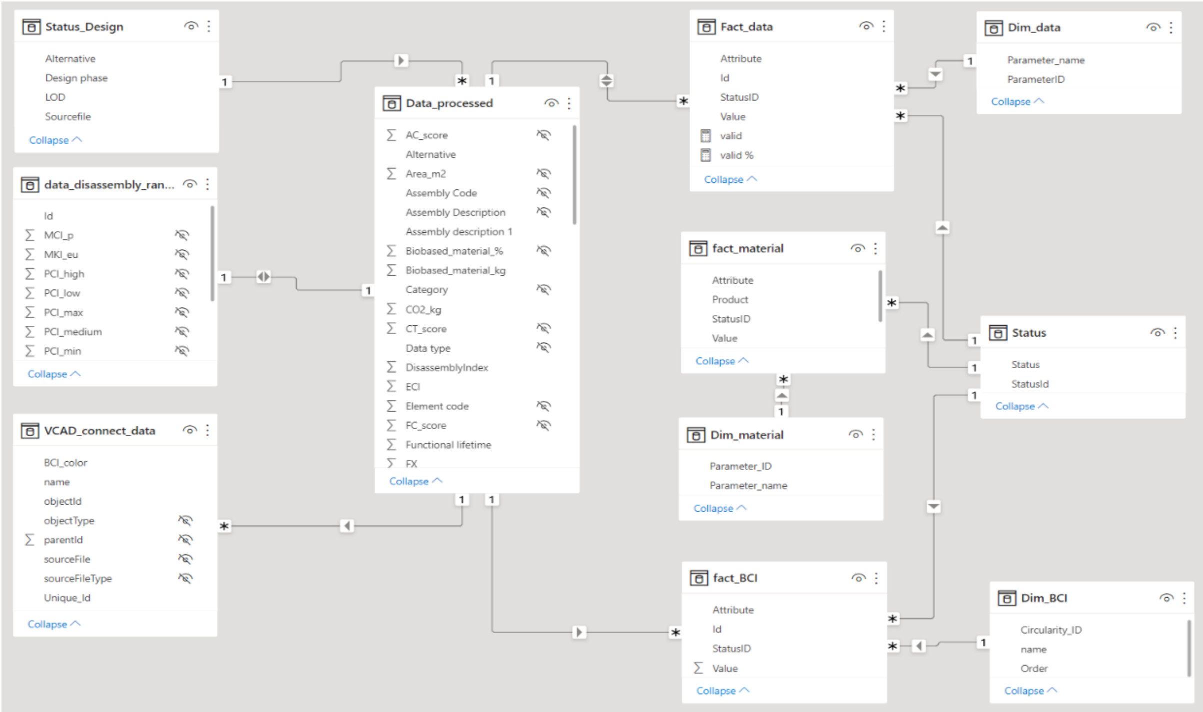


Figure 25: Data model – circular design dashboard

6.3.2. Data transformations

Another technical aspect of the application layer is the data transformations performed with the Power Query Editor. This is an additional data preparation engine that transforms and modifies data before it is loaded into Power BI. The data transformation aims to determine the data quality, so the end-user knows the reliability of the dashboard. Thereby, the input parameters of the Revit model and the Excel material database are checked on completeness, validity, and consistency. In other words, it is analysed if there is any missing data, if the data is in the correct format, and if the value is between expected boundaries.

The steps for the data transformation can be summarised in figure 26. First, the processed data is unpivoted. This means that the data is flattened, so all the parameters of an element are recorded as a single row with their corresponding value. Next, a reference list is created in which states per parameter what the boundaries are and what data type it should be. The original value is checked against the reference value, and the status of the parameter is determined. The result is that for every input parameter, it is determined if the value is missing (0), correct (1), or invalid (2).

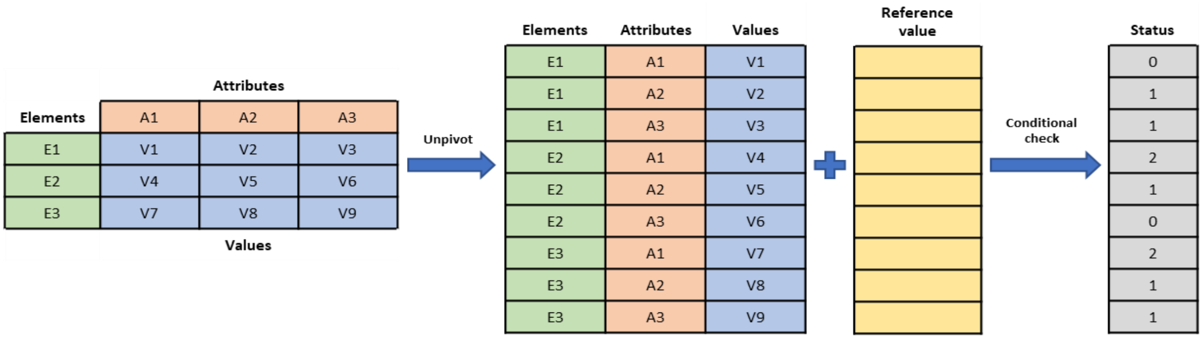


Figure 26: Data transformation for data quality check

6.4. Conclusion synthesis phase

The synthesis phase results in a practical solution of a decision-support framework to automate and integrate the assessment of building circularity in the early design phases. This includes the setup of the data layer, where all the necessary data is collected from Revit and material databases. Also, data analytics with all the operations needed to transform and process the data are presented. Finally, the results are visualised and presented in the application layer in the form of an interactive and dynamic dashboard. This is still a provisional dashboard and will be verified and validated by end-users in the simulation phase. Ultimately, the synthesis phase forms the basis of the second sub-research question:

"How to integrate BIM with data analytics for a decision-support framework for circular building design?"

First, it is meaningful to understand the input needed for the circularity assessment and to make the link between the assessment method and the LOD of the BIM model per design phase. It is not logical to use the standard BCI measurement method throughout the entire early design phase because more information becomes available as the design develops. Therefore, it is decided to use the indicative BCI for the schematic design and the provisional BCI for the detailed design. The indicative and provisional assessment considers the available information per design phase. Data analytics is used to deal with the available data and to predict and assess the circularity of the design at an early stage.

Next, this framework shows that with the implementation of a data layer, an analytical layer, and an application layer, an automated link can be constructed between the design and external material databases. Thereby, data analytics is used to clean, transform, merge, and analyse the data before it is reported in a dashboard to support decision-making. Essential in data analytics is the quality of the data. The data quality starts with the data input, in the BIM model. Therefore, a BIM execution plan is necessary to agree upon the design workflow and to ensure the completeness, consistency, and validity of the data. In this framework, the BIM execution plan safeguards the completeness of the Revit data by setting out the input procedures per design phase. Furthermore, the data extraction with Dynamo, the pre-defined template for the material database, and the data processing with a Python script establish consistency and validity in the data. This is essential because the data is stored in different applications which have to work together. Also, the uniqueness of the data is guaranteed in this framework. The NAA.K.T. material classification creates an unambiguous and unique code which makes it possible to connect the Revit and material data.

Lastly, the system architecture and automation play a big role in the decision-support framework. In this system, the data flow between Revit, Excel, Python, and Power BI is guaranteed and can be automated as well. Therefore, once the system is set up, there are limited manual procedures needed to perform the assessment which simplifies the process. The system functions well as a basis for an automated decision-support framework for circularity assessments in the early design phase.

PART 3 | SIMULATION PHASE

In the next phase, the proposed decision-support framework is demonstrated, verified and validated based on a pilot case. A simulation takes place to demonstrate the dashboard and to see if the actual behaviour of the system met the desired behaviour. The results are presented in the circular design dashboard. The verification process is to ensure the working of the system and that it fulfils the technical requirements, and the validation is to determine the added value of the system and if it the dashboard fulfils the end-user's needs.

7. Circular design dashboard

This chapter presents the end product of the decision-support framework, the dashboard for circular building design. The dashboard is where all the data comes together and will be used by the end-user as a tool to steer on circular building design. The dashboard is demonstrated with a pilot project, which is explained in the first section. After that, the results of the dashboard are presented and the functionality is elaborated.

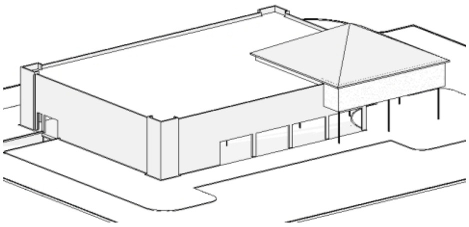
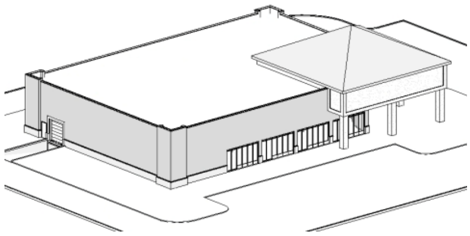
7.1. Case study

The focus of this research is on commercial building constructions. Therefore, a case study of a retail store is chosen as a commercial building. Interest has been aroused by a project of Ahold Delhaize to design and construct a supermarket in Gouda according to circular design principles. There is an increase in awareness of circular retail stores by retail franchises like Lidl and Ahold Delhaize (Ketelaars, 2019). To demonstrate the decision-support framework, a fictive Autodesk Revit tutorial project of a retail store is used (Autodesk, 2022). Figure 27 presents a visual of the project. The Revit project only applies architectural modelling, so the mechanical, electrical, and piping systems are not modelled. This fits well with the scope of this research, which only includes the building structure, skin, and space plan of buildings.

Figure 27: Revit project of a retail store

The original Revit model is adjusted to suit the setup for the decision-support framework. First, the model is adapted according to the BIM protocol for the schematic and detailed design. The original model has LOD300, which fits the detailed design phase. This means that for the schematic design phase, the LOD is downgraded to LOD200, see table 11 for the model characteristics per design phase. Furthermore, two variants are worked out in the detailed design phase to simulate the evaluation of two design options. Thereby, the variants differ with the type of roof. One has a roof of steel sand-which panels with a low degree of demountability, while the other has a timber frame roof that is easily demountable. Moreover, all models are equipped with the right parameters necessary for the circularity assessment.

Table 11: Revit model characteristics

Characteristics	Schematic design	Detailed design
Alternatives	Alternative 0	Alternative 1 & 2
Level of Detail	 LOD200	 LOD300
Design output	Basic alternative modelled as generic elements with approximation of quantities, shape and orientation	Specific design options with specific elements and accurate sizes, shapes and oriantation
Model building elements	• Foundation • Floor • Roof • External & internal walls • Load-bearing structure • Stairs and ramps	• Foundation • Floor • Roof • External & internal walls • Load-bearing structure • Stairs and ramps • Doors & windows • Wall, floor, ceiling, and roof finishing
Non-graphical information & parameters	• Assembly code • NAA.K.T. classification • Functional lifetime	• Assembly code • NAA.K.T. classification • Type of Connection • Accessibility of Connection • Cross-Through • Form confinement • Functional lifetime
Material properties	Generic material properties for global building elements	Product specific properties for accurate building elements

7.2. Dashboard: circular building design

This section presents the end product of the decision-support framework for circular building design. It elaborates on the functionality of the dashboard and how the end-user can make the most of it during circularity analysis. Furthermore, it explains how different visuals can be interpreted and how the visuals can substantiate and support the decision-making process. The dashboard is divided into seven pages each with its own goal. The different pages and functionality are as follows:

- Overview: a reading guide for the dashboard and quick overview of final assessment score.
- Definitions: an explanation of the definitions and circularity measurement method.
- Schematic Design: an evaluation of the individual design alternative in the schematic design.
- Detailed Design: an evaluation of the individual design alternative in the detailed design.
- Comparison: a comparative analysis of the different design alternatives.
- Building Passport: an overview of all the materials and products included in the design.
- Model Health: insight into the data quality of the model.

Page 1: Overview

The first page can be seen as a reading guide of the circular design dashboard. Here is explained what the goal of the dashboard is, who the potential end-users are, and in which design phase it can support the decision-making process. Furthermore, there is a table of content that leads the user to the other pages.

Besides that, this page also presents the end-user with the final score of the circularity assessment and insights into the reliability of the data. In this way, the design team can see immediately what the final circularity scores are without having to go into detail. For the schematic design, the MCI and the indicative BCI are given, and for the detailed design phase, the provisional BCI per variant is given. Also, the key performance indicators regarding data quality are presented so it is directly known if the model data is reliable. It shows the latest data refresh for the model and the completeness and correctness of the input data. For a more detailed insight into the data quality, the end-user is referred to the Model Health page.

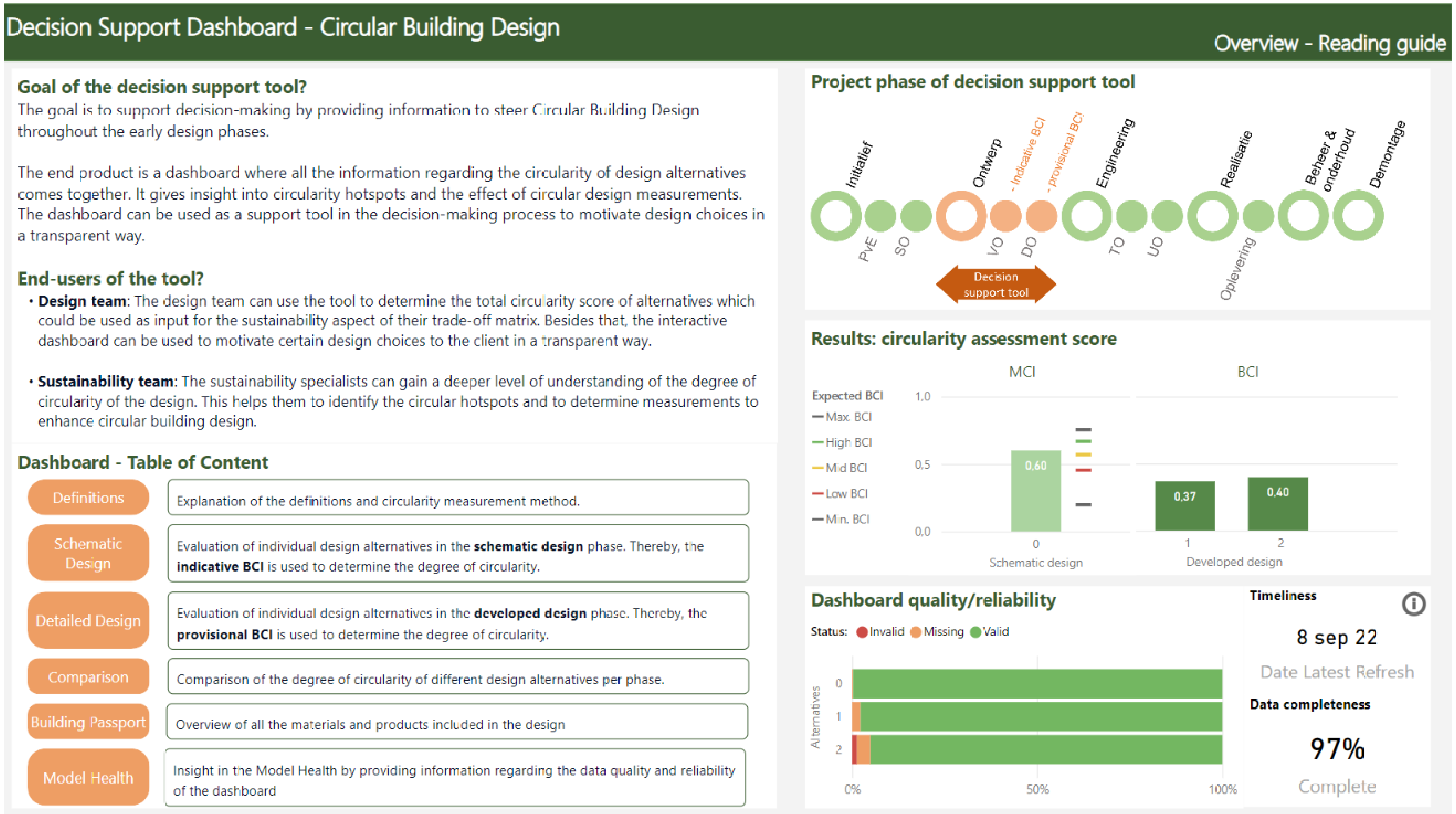


Figure 28: Dashboard page - Overview

Page 2: Definitions

The definitions page has the sole function of providing additional information to the users regarding the building circularity assessment method. This includes a summary of the BCI measurement method of Alba Concepts, with the underlying circularity aspects. Also, a short explanation of the indicative and provisional BCI is presented. This gives the end-user a recap of the two different ways how the BCI assessment is adopted per design phase. Furthermore, the definitions in this dashboard are explained and the legend of the colour scheme for the BIM models is shown.

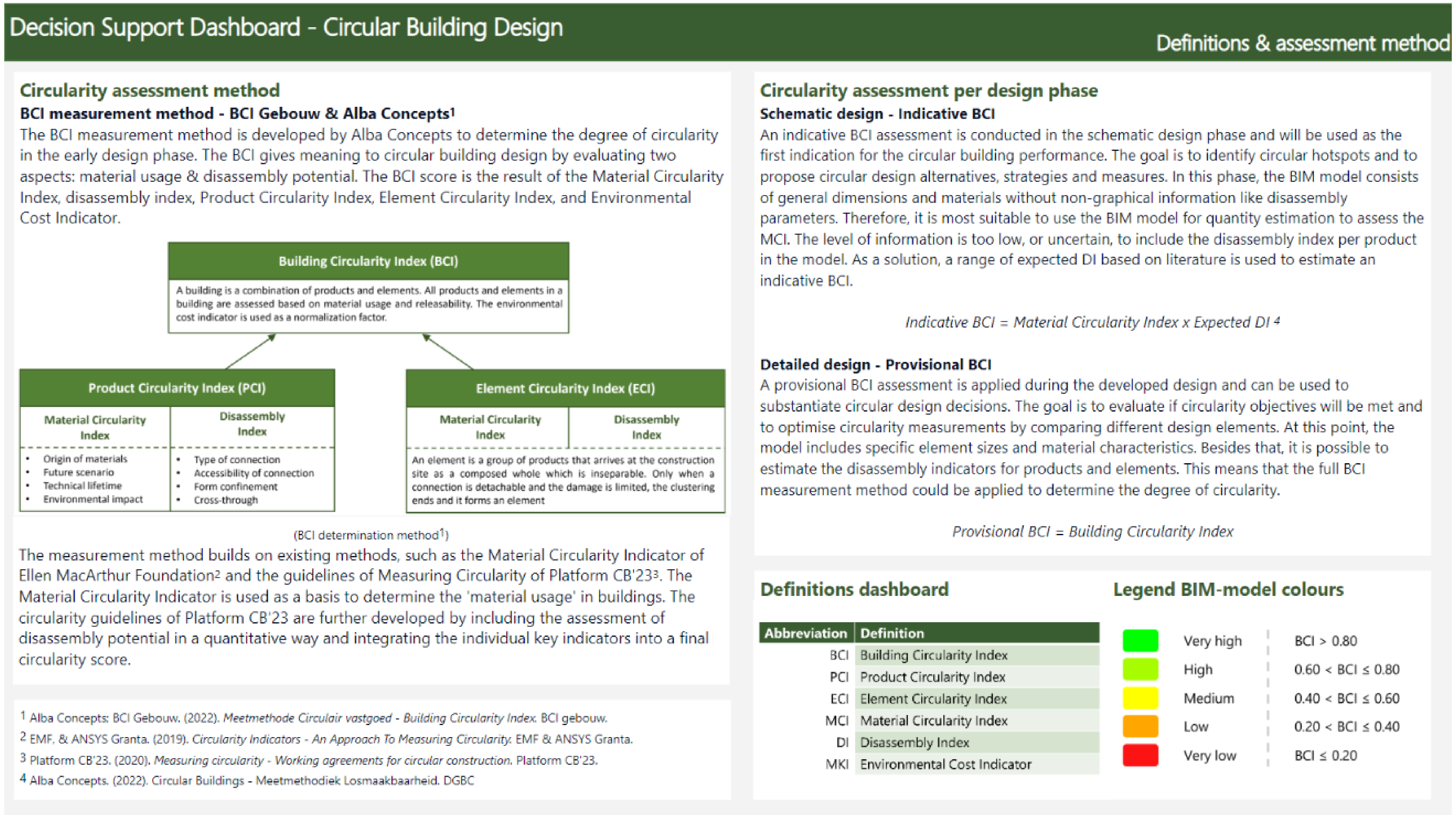


Figure 29: Dashboard page - Definitions

Page 3: Schematic Design

This page is developed to get an indication of the circular building performance in the schematic design. This page assists the design team and sustainability specialists to identify the circular hotspots in the design and proposing circular measures for building elements. Thereby, the following individual circularity components can be analysed:

- Key performance indicators: the overall building circularity scores regarding MCI, environmental impact, and CO_2 emissions.
- System Circularity Index: the building circularity score per building element.
- BIM model: a visualisation of the Revit model to illustrate the assigned elements.
- Material Circularity Indicators: the individual indicators that together form the MCI of products.
- Building Circularity Prognosis: the expected BCI based on the potential disassembly index range.

Additionally, this page has some interactive and dynamic features built in. First, the end-user can filter the data according to their needs, so different building elements can be included in their analysis. Also, when hovering over the environmental cost indicator score, a visual with extra information pops up. It shows a horizontal bar chart with the contribution of the total environmental impact per building element. This makes it possible to determine which building element has a high environmental impact, so contributes more to the final BCI score. In this way, the end-user can determine at which building element the circularity measures would be most effective. Lastly, the exclamation mark by the building circularity prognosis provides additional information. It shows the potential disassembly scenarios, so the end-user knows the underlying assumption for the indicative BCI score.

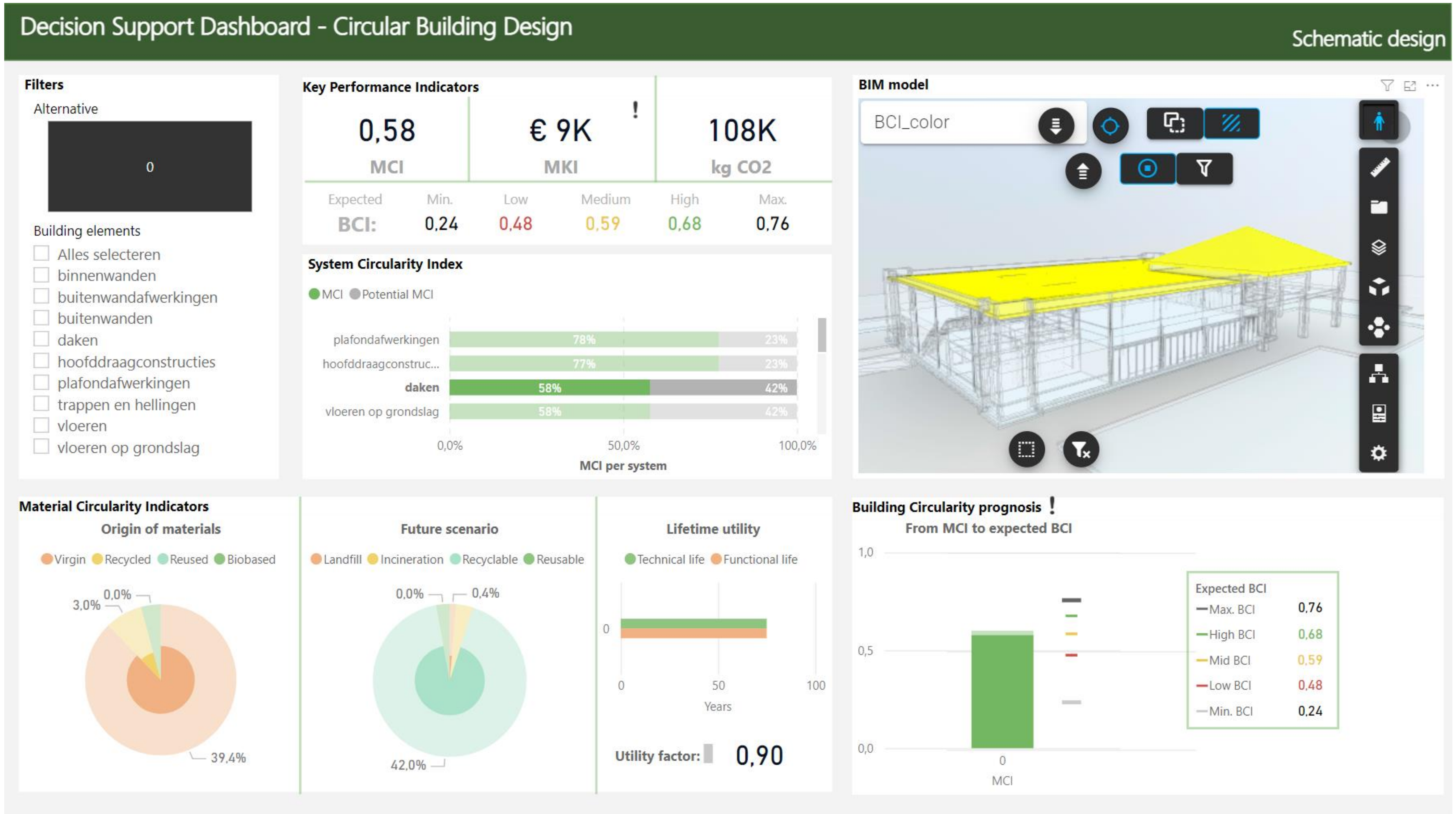


Figure 30: Dashboard page - Schematic Design

Page 4: Detailed Design

The detailed design page is similar to the schematic design, with the same dynamic interactions, features, and filters. The difference is that in this phase, the building circularity indicator does not have to be estimated based on disassembly scenarios, but it can be evaluated from the model data as explained for the provisional BCI. In this way, a full BCI assessment can be performed. Thereby, the 'Building Circularity Indicators' visual presents the different aspects of the BCI measurement method per building element, like the MCI, DI, PCI, and ECI.

This page allows the design team to evaluate if the circularity objectives will be met, while the sustainability specialists can gain deeper insight on how to optimise the proposed circularity measures per alternative or building element.

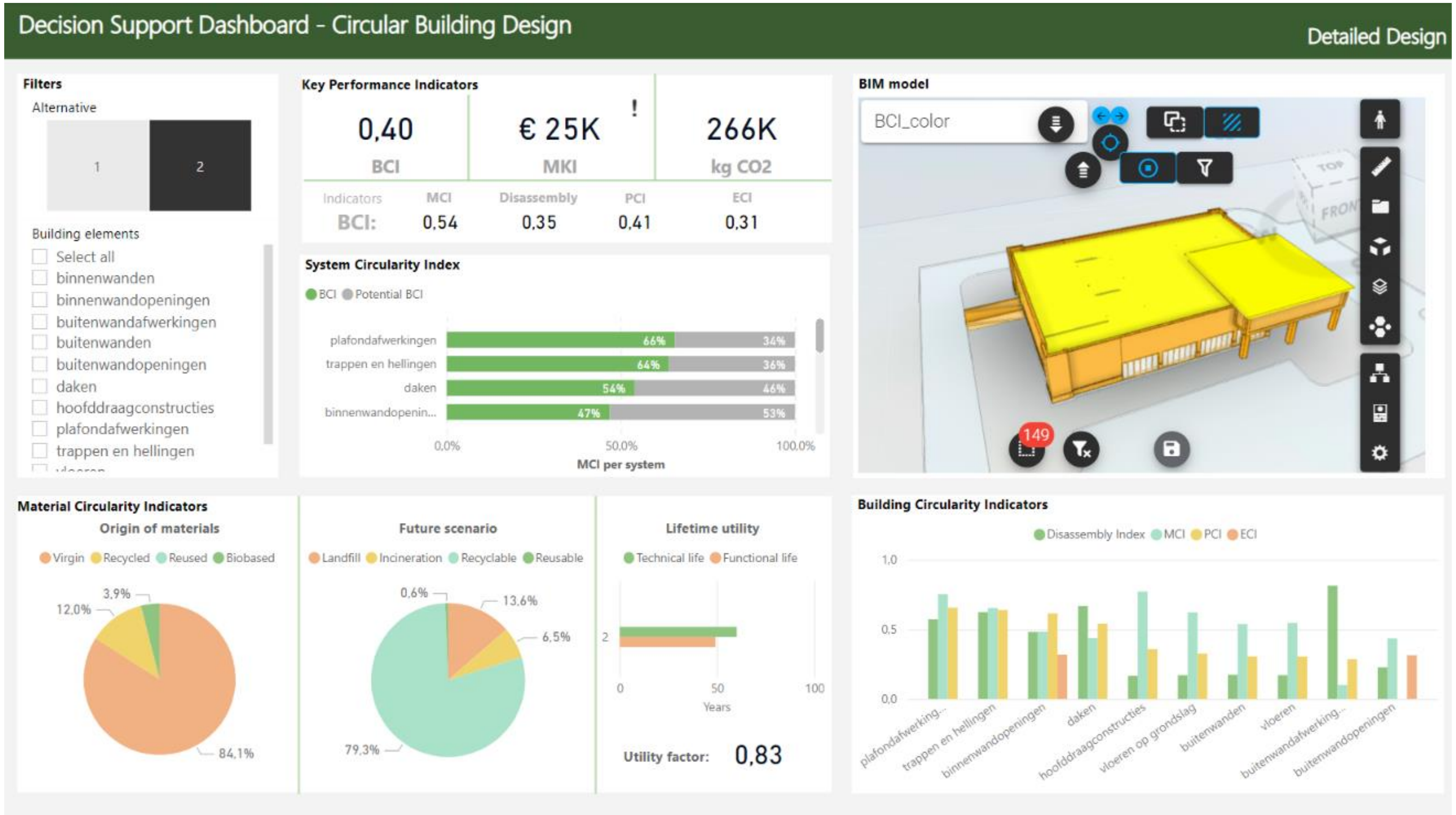


Figure 31: Dashboard page - Detailed Design

Page 5: Comparison Analysis

The fifth page is for a comparative analysis of the design alternatives. This makes it easier for the design team and sustainability specialist to directly compare design alternatives. The filters create the possibility to compare the building as a whole or individual building elements. In this example, a comparison is made between two alternative roof designs. It cannot only be investigated which alternative is more circular but also be reasoned why because of the insight into underlying circularity indicators. For example, in this case, the MCI of alternative 1 is slightly better. However, alternative 2 has a higher disassembly potential which eventually makes it the more circular option. Also, the environmental impact and the CO_2 emissions are substantially lower, which makes it the more environmentally friendly option as well. The goal of this page is to substantiate the decisions that will be made and to start the discussion based on facts.

It should be mentioned that it seems difficult to read the exact score of the individual circularity aspect but more detailed information is visible to the end-user. When the end-user goes over the visuals, the dashboard presents information about the percentage, kilograms, or scores of the associated aspect.

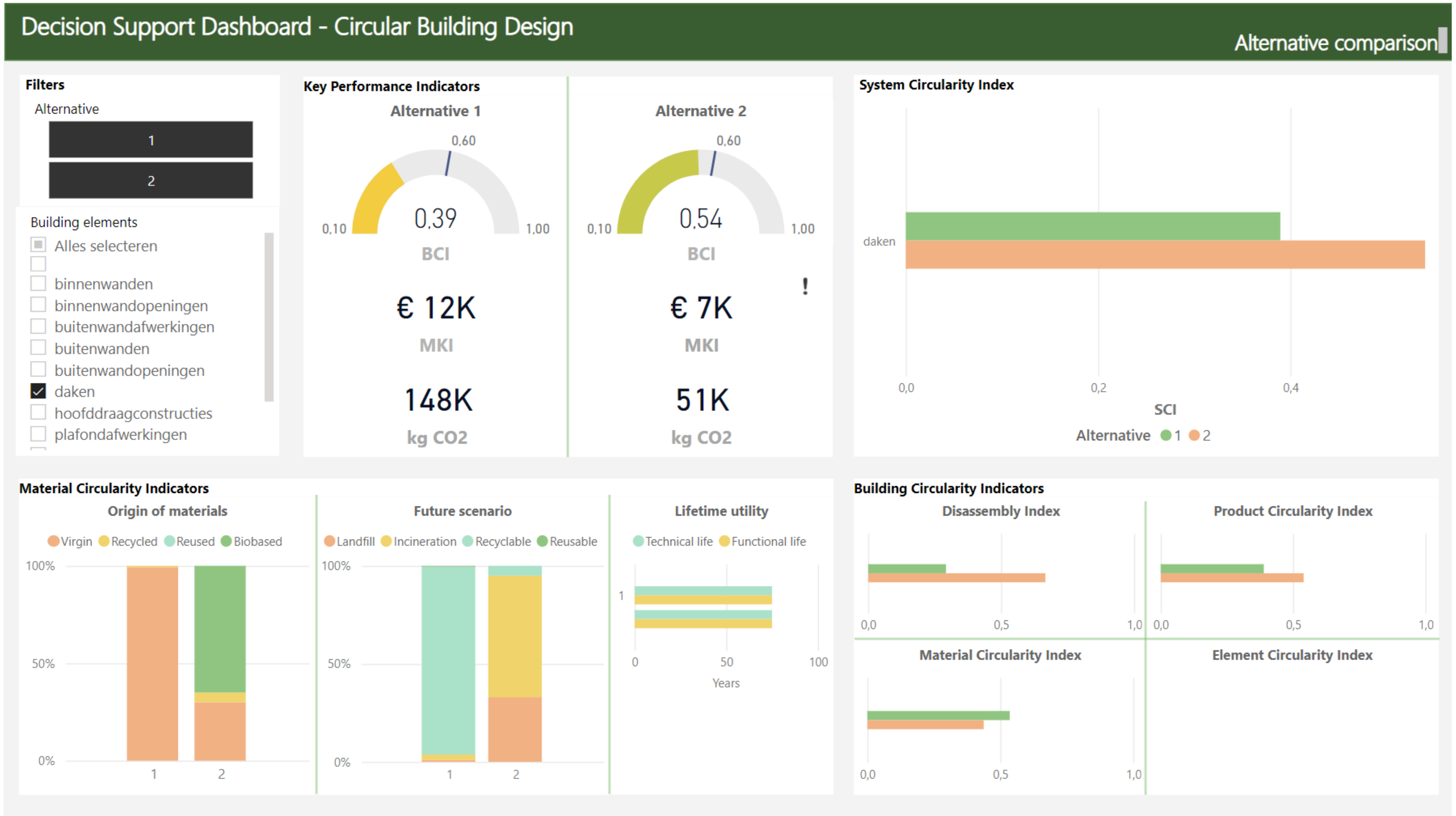
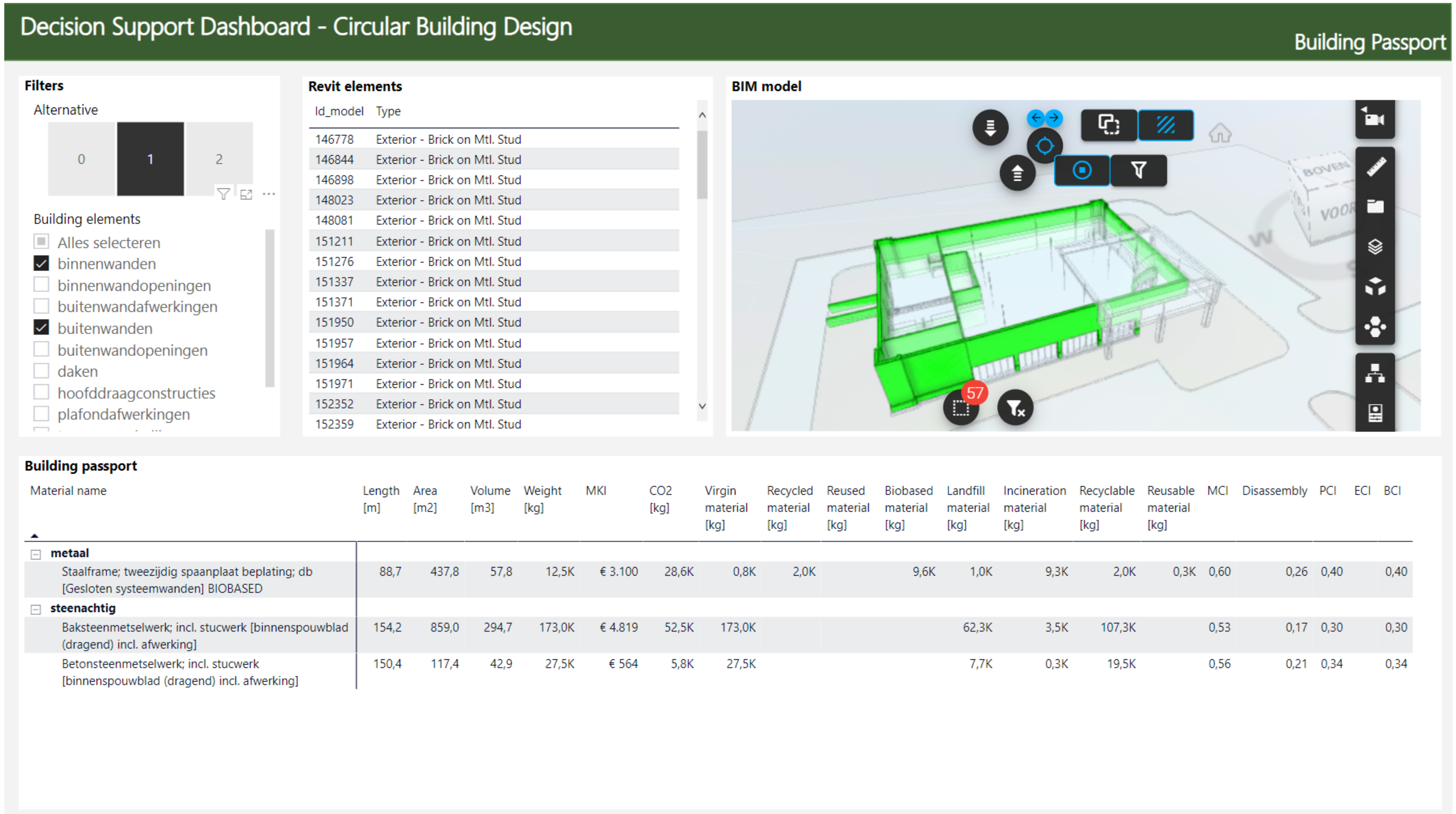


Figure 32: Dashboard page - Comparative Analysis

Page 6: Building Passport

The Building Passport is an overview of all the materials used in the design, together with characteristics like their weight, origin of materials, and future scenarios. The end-user can see from which material certain building elements are built up. It is an additional wish from the end-user to be integrated with the dashboard. The Building Passport is not meant to steer on circular design during the design process. It is meant to stimulate circular building design and gives insight into how much material and products can be reused and recycled at the end-of-life cycle stage.



Material name	Length [m]	Area [m2]	Volume [m3]	Weight [kg]	MKI	CO2 [kg]	Virgin material [kg]	Recycled material [kg]	Reused material [kg]	Biobased material [kg]	Landfill material [kg]	Incineration material [kg]	Recyclable material [kg]	Reusable material [kg]	MCI	Disassembly	PCI	ECI	BCI
metaal																			
Staalframe; tweezijdig spaanplaat beplating; db [Gesloten systeemwanden] BIOBASED	88,7	437,8	57,8	12,5K	€ 3.100	28,6K	0,8K	2,0K		9,6K	1,0K	9,3K	2,0K	0,3K	0,60	0,26	0,40		0,40
steenachtig																			
Baksteenmetselwerk; incl. stucwerk [binnenspouwblad (dragend) incl. afwerking]	154,2	859,0	294,7	173,0K	€ 4.819	52,5K	173,0K				62,3K	3,5K	107,3K		0,53	0,17	0,30		0,30
Betonsteenmetselwerk; incl. stucwerk [binnenspouwblad (dragend) incl. afwerking]	150,4	117,4	42,9	27,5K	€ 564	5,8K	27,5K				7,7K	0,3K	19,5K		0,56	0,21	0,34		0,34

Figure 33: Dashboard page - Building Passport

Page 7: Model Health

The last page is the Model Health page, used to determine the reliability of the dashboard based on the data quality. It provides information about the input data of the Revit model, as well as the material database. The following data quality dimensions can be determined:

- Completeness: the percentage of missing data
- Timeliness: the last time that the data is refreshed
- Validity: check if the values of the input parameters are in the correct data format and if values are within the expected boundaries
- Consistency: check if the material classification code is consistent in the Revit and material data

Furthermore, this page has some interesting interactive features. The visual for the completeness, validity, and consistency of Revit data has a drill-down function. This means that the end-user can go to a deeper layer per alternative. Once they click on an alternative, the data of only that alternative will be presented per parameter, so they know exactly which parameter is missing or invalid. Besides that, there is a dynamic interaction between the BIM model and the bar chart for the Revit data. For example, if the end-user clicks on the invalid data for alternative 2, the corresponding elements will be highlighted in the BIM model. In this way, the design team can provide feedback to the BIM specialist about which parameters are missing or filled in incorrectly.

Moreover, the category of products in the material database is visualised, so the end-user knows if the design consists mainly of generic or manufacturer-specific data. The reason for this is that the data of categories 1 and 2 is not transparent and publicly available, so the design team needs to consider this aspect in their evaluation and assessment as well.

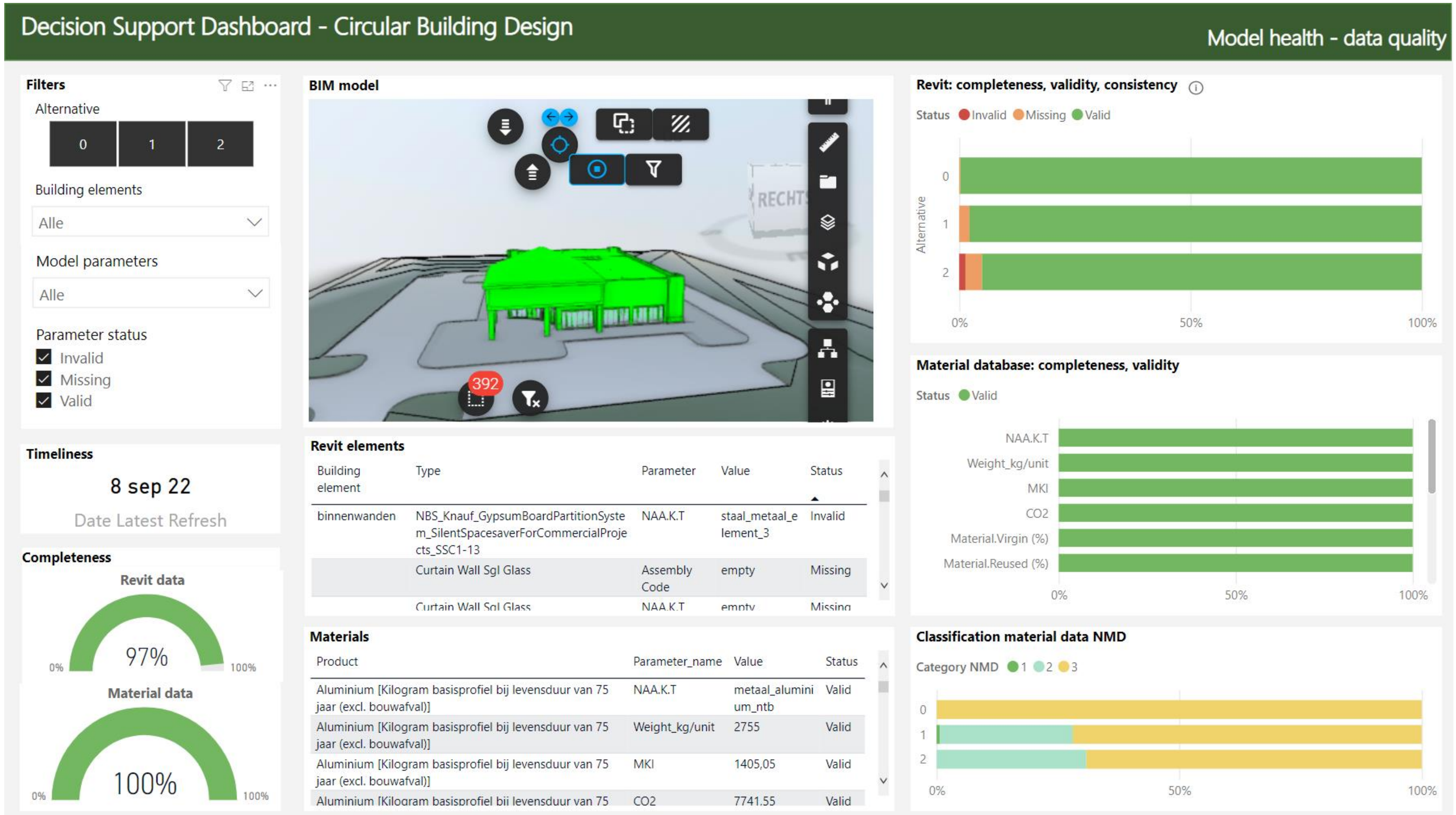


Figure 34: Dashboard page - Model Health

8. Verification and validation

In this chapter, the decision-support framework is verified and the circular design dashboard is validated. The verification is done to check if the framework meets all the technical specifications and if the system runs as intended without any errors. The validation process is based on whether the dashboard captures the needs of the end-user which are expressed as functional requirements in the SRS.

8.1. Verification

The verification process includes all activities associated with the construction of the decision-support framework. Therefore, all three layers of the framework have been subjected to an internal test in an artificial environment. All the data operations in the data, analytical, and application layers are verified step-by-step with the use of the case study. This way, the main question for the verification process can be answered: assuring the correctness of the framework and data flow, and that it operates as intended without producing any errors or crashes. The step-by-step verification of the system determines whether the framework satisfies the technical requirements which are drawn up in the SRS in section 3.3.

Regarding the technical requirements, a reflection is objectively made by the author. The assessment of the requirements results in three possible outcomes: does not satisfy the requirement (1), partially satisfies the requirement (2), and fully satisfies the requirement (3). The result of the verification process is presented in table 12. A more detailed elaboration of the score is given in the paragraph after the table.

Table 12: Verification of the technical requirements

Subject	Technical requirements	Score
System operation	1. The system runs as intended on existing Revit models	**3**
	2. The system produces no errors during the data analytical procedures	**3**
	3. The system removes manual procedures for circularity assessment	**2**
Integration of data sources	4. The system can extract the project data to a database	**3**
	5. The system can link the material data to the corresponding project data	**3**
	6. The system can process the data and perform circularity calculations	**3**
	7. The circular design dashboard can import the data from the database and update the visualisations frequently	**3**
	8. The circular design dashboard can visualise the 3D Revit model	**3**
Data analytic performance	9. The system can regenerate the circularity assessment dynamically	**3**
	10. The system can verify the data quality of the system	**3**
	11. The end-user can change and play with the weight factor of the BCI measurement method	**1**
	12. The end-user can filter the data in the circular design dashboard according to their needs	**3**
Design workflow	13. The system separates the data input and responsibilities from different disciplines	**3**
	14. End-user has access to the data from intermediate steps to control the input data	**2**

System operations

1. The system runs as intended on existing Revit models:
   The system runs as expected on different Revit models when the model is set up correctly. Correctly meaning, with the right data gathering procedures which are captured in a BIM execution plan.
   Side note: if an existing Revit model is set up slightly differently than suggested in the framework, there will be data quality issues. An incorrect setup of the shared parameters leads to empty fields in the quantity export with Dynamo. Also, invalid input for the material classification results in issues when merging the material data with the project data, which leads to an incomplete dataset for further analysis.
2. The system produces no errors during the data analytical procedures:
   The data extraction is completed in Dynamo without any error notification. The Python scripts in the analytical layer also run without errors. Furthermore, Power BI gives no notification of failures by importing and transforming the data.
3. The system removes manual procedures for circularity assessment:
   The system automates all procedures from data extracting in Dynamo, processing the data in Python, and importing the data in Power BI. The Python scripts are scheduled automatically with Windows Task Scheduler and Power BI has features to automate the data import. However, the frequency of updating the data is project dependent. Therefore, manual procedures are necessary to configure and schedule the data updates according to the BIM protocol. Also, the data extraction with Dynamo must be performed manually by the BIM specialist with one click in Dynamo Player.

Integration of data sources

4. The system can extract the project data to a database:
   Different Revit models are tested by extracting the data and comparing the quantity take-off. The system extracts the Revit data with a Dynamo script and export it to Excel consistently with all the required fields and parameters. It automatically exports the file to the assigned folder in the database.
5. The system can link the material data to the corresponding project data:
   The system links the project and material data correctly because of the Python script that creates a keynote file for Revit material classification. Like this, the uniqueness and consistency of the material classification are guaranteed. The data processing Python script ensures that the two data sets are linked and merged correctly for the rest of the analysis.
6. The system can process the data and perform circularity calculations:
   The system processes the data with Python where the datasets are cleaned, merged, analysed, and where most of the circularity calculations are performed. The dynamic circularity calculations and data transformations are performed in Power BI.
7. The circular design dashboard can import the data from the database and update the visualisations frequently:
   The dashboard in Power BI updates the data frequently by the build in function where it scans the underlying datasets and updates the data at predefined intervals or when changes are detected.
8. The circular design dashboard can visualise the 3D Revit model:
   The design is visualised as a 3D model in Power BI with the use of a plug-in of VCAD. The interactive and dynamic features of the 3D model are working correctly.

Data analytic performance

9. The system can regenerate the circularity assessment dynamically:
The final BCI calculations are performed with measures in Power BI. The BCI assessment is regenerated every time the end-user changes the data filters or interactive features. The correctness of the assessment is verified with hand calculations of the roof of alternative 1. The calculations and the results are presented in Appendix E.
10. The system can verify the data quality of the system
The system can present the data quality in the Model Health tab of the dashboard. In this way, the completeness, timeliness, validity, and consistency of the data are presented to the end-user.
11. The end-user can change and play with the weight factor of the BCI measurement method:
This is not achieved because it is chosen to implement the latest version of the BCI measurement method without giving the flexibility to the end-user to play with the underlying weight factors of the method. The reason for this is that there needs to be a common measurement method that is the same for all parties so that there is no misunderstanding. If there are new insights regarding the method, with minor changes to the underlying calculations, it is possible to implement these changes in the data analytical layer.
12. The end-user can filter the data in the circular design dashboard according to their needs:
The filters in the dashboard allows the end-user to filter the data based on the different design alternatives and the individual building components.

Workflow

13. The system separates the data input and responsibilities from different disciplines:
The procedures for data input for the decision-support framework separate the input for Revit data and material data. The BIM specialist is responsible for design-related data in Revit, and the sustainability specialist for the material database. Nevertheless, there needs to be a control mechanism for the sustainability specialist to check if the right material is assigned to the corresponding objects in the design.
14. End-user has access to the data from intermediate steps to control the input data:
The end-user is allowed to see the underlying datasets of the Power BI dashboards. However, they do not have direct access from the dashboard to the data from intermediate steps. In intermediate steps, the data is captured in a database, so arrangements could be taken to determine the accessibility of the database for involved stakeholders.

8.2. Validation

The focus of the validation is more on the end product of the framework, the circular design dashboard in Power BI, as that is the tool the end-user uses to steer on circularity in the design phase. The goal is to determine the added value of the circular design dashboard and fulfilment of the end-user needs, whether it stimulates and supports circular building design in the early design phase, and if it satisfies the user experience. The validation process indicates if the dashboard could be recommended for future implementation within the design workflow of Royal BAM Group, and where further development and improvements are desired. The validation is performed through interactive workshops with potential end-users. The workshops are performed physically at the office. The reason for this is that a physical workshop stimulates the engagement of participants and makes it easier to analyse the non-verbal actions of participants facing challenges when working with the tool. A work plan to guide the workshops and the feedback and results are presented in Appendix E: Verification assessment & Validation workshop.

8.2.1. Setup of the workshop

The workshop is organised in two sessions: one group with the design team and sustainability specialists of Royal BAM Group, and the other with professionals from an external architecture firm partner of Royal BAM Group. Like this, the applicability of the decision-support framework is not limited to only the design workflow of BAM. This broadens the target audience of the framework. The roles of the participants are presented in table 13.

Table 13: Workshop participants

Workshop 1: Royal BAM Group	Workshop 2: Architecture firm
Department head: Sustainability	Architect
Manager: Sustainability and Environmental	Project manager
Tender Manager	Sustainability specialists
Sustainability specialists	
Design leader	

Moreover, the setup of the workshop is divided into two parts: a presentation and a case study. The first part focuses on delivering information to the participants with a presentation about the research in general, the decision-support framework, and the workflow and assessment for circular building design. This part also includes a short tutorial of the dashboard in Power BI with instructions and an explanation of the functionalities. In the second part, the participants engage in a hands-on experience with the dashboard by working on a case study themselves. This is the pilot case explained in the previous chapter. Thereby, the same case study is used in the verification phase. A simulation is performed of a situation that the design team and sustainability specialists could face in a real-time project. This ensures that the participants become acquainted with the dynamic dashboard and all interactive features. The scenarios are presented in the appendix of the workshop. In the end, the circular design dashboard is evaluated with a feedback round and a questionnaire. To summarise, the setup of activities is as follows:

1. Welcome and introduction
2. Presentation of the research, decision-support framework, and design workflow
3. Instructions for circular design dashboard
4. Hands-on experience with a case study
5. Validation of the circular design dashboard
6. Feedback round and questionnaire workshop

8.2.2. Validation results

The validation of the circular design dashboard is assessed in the form of peer reviews and a subjective assessment of the functional requirements of the system. Thereby, it is important to listen to the feedback of participants and their experiences. The peer review is given in feedback rounds which reflects on the general impression of the dashboard, advantages and disadvantages, and the user experience from the practitioners. The subjective assessment is performed with a questionnaire. In this questionnaire, the fulfilment of end-user's needs is determined based on scores on the functional and system requirements from section 3.1.

The validation of the functional and system requirements is performed subjectively. The requirements are ranked by the participants as follows: fail (1), moderate (2), pass (3), good (4), and excellent (5). The final score per requirement is the average score of all the participants. The result of the validation process is presented in table 14.

Table 14: Results validation

Functional requirements	System requirements	Score
1. Motivate design choices between variants in a transparent way	1.1. The tool substantiates design decisions and stimulates the discussion process	4.2
	1.2. The tool evaluates multiple design variants with circular design trade-offs	4.5
	1.3. The tool involves stakeholders through dynamic and interactive reports in a transparent way	4.1
2. Support the design team with feedback on circular building design in the early design phase	2.1. The tool facilitates steering on circular design early in the design process	4.1
	2.2. The tool assesses the building circularity score in a quantitative way	4.5
	2.3. The tool evaluates the circularity for the building as a whole, as well as for specific building components	4.5
	2.4. The tool gives insight into the reliability of the data	4.0
3.Provide sustainability specialists insight into the degree of circularity of the design	3.1. The tool analyses the individual circularity aspects of the design: the material flow, disassembly potential, environmental impact, and lifespan of materials	4.4
	3.2. The tool identifies circular hotspots, both positive and negative	4.3
	3.3. The end-user can specify certain data for comprehensive and detailed analysis	4.3
4. The interface of the tool is suitable for the intended audience	4.1. The tool is user-friendly with an intuitive interface	4.1
	4.2. The tool is applicable for non-experts without technical skills or knowledge of the software	4.4

The peer-review feedback from the feedback rounds and questionnaire are summarised per category below.

1. **Motivate design choices between variants in a transparent way:**
   The end-user is enthusiastic about the possibilities of motivating and substantiating their design choices, especially in the conversation with the client. The objective performance parameters give factual insight into the circularity performance which triggers the right discussions and conversations. The control of data quality gives transparency to the decision substance. Also, the dashboard gives great insight into the contribution of individual circularity aspects per design variant which assists in substantiating the decision-making. The possibilities to evaluate alternatives are good, but this could be improved by briefly introducing the alternatives in the beginning.

2. **Support the design team with feedback on circular building design in the early design phase:**
   The data provides a clear overview of circularity aspects to steer circular building design in the early phases. It presents the design team with feedback on the building circularity performance as a whole but also for individual building elements. Especially, the implementation of the indicative and provisional BCI assessment is a huge benefit because this gives the ability to assess circularity early in the design while not all data is available. This includes smart use of assumptions for disassembly scenarios to present an indication of the final circularity score. Previously, performing a BCI assessment was very time-consuming because all material quantities and properties must be filled in manually for the calculations. Therefore, the

circularity assessment was mostly performed after design choices have been made to save time. With the developed decision-support framework, a big part will be automated which increases the usefulness of the assessment. It will be easier to perform a quick BCI assessment to support design decisions on time. Also, the 3D model is a great way of visualising the results with a coloured 3D model, to get a circularity indication immediately. Furthermore, the insight into the data quality is an excellent addition because it could take the sting out of the discussion about the reliability of data-based decisions.

Although the dashboard gives great support to the design team, there is a need to gather the necessary data in BIM at an early stage. This requires a different way of working than what is usually customary. It requires extra effort to set up the required model variants and to enter the correct parameters for the indicative and provisional BCI. A balance must be found between the time that is needed to prepare a model in detail and the number of alternatives that must be looked at. Therefore, it should be well integrated into the design workflow, whereby all involved parties are willing to do their part.

3. **Provide sustainability specialists with insight into the degree of circularity of the design:** The sustainability specialists are satisfied with the dashboard and the possibilities to investigate the circularity of design alternatives. It gives them great insight into the individual circularity aspects, as well as to compare different design variants. One thing they are worried about is the control mechanism for the input of materials. They suggest implementing a way where they can verify if the right material is assigned in the BIM model. For example, by making data accessible in the intermediate steps, they can verify the material classification at the quantity export. Besides that, the BCI measurement method is one of the most relevant methods to assess circularity quantitatively at this moment. However, it is still under development within the industry and the underlying indicators are decisive in this regard, as is the weight factor. Therefore, it is necessary to continue to assess the latest updates of the assessment method to determine whether the method is suitable, or if changes are necessary.

4. **The interface of the tool is suitable for the intended audience:**
In general, the interface is accepted as user-friendly and simple to use. If you have never used Power BI before, it can be a bit troublesome at the beginning. However, after practising a few times, it is easily mastered. A practitioner proposed to attach instructions or a short video to assist the end-user for the first time. Moreover, the dynamic and interactive features are a big plus for the user experience. It was experienced that these features increase the possibility to perform more detailed analyses, without getting an information overload. Also, the filters work smoothly and are easy to understand. The drill-down functions are good, but the end-users must know how to use them.

8.3. Conclusion simulation

In the simulation phase, the decision-support framework is demonstrated with the use of a fictive case study of a retail store. The simulation gives great insight into how the decision-support framework can be embedded in the current design workflow to support circular building design. The verification process indicates that on the technical level, the system is ready to be implemented in the design workflow whereby it can operate as intended without crashes or error. Also, the validation of the circular design dashboard proves that this tool is suitable to support decision-making in the design process. It fulfils the needs and wishes which were drawn up upfront in the SRS. As a result of this phase, an answer can be given to the third, and last, sub-question:

"How and to what extent does the developed decision-support framework help practitioners?"

Based on the results of the validation, it can be concluded that the decision-support framework with the circular design dashboard would be an excellent tool for the end-user to steer circular building design. The tool was received with great enthusiasm by the end-users and has a large implementation potential for circular design in future projects. The main benefits of the decision-support framework are the decomposition of individual circularity aspects, the applicability of circularity assessments in different design phases, and the insight into the data quality. The decomposition of the total BCI assessment in individual circularity indicators supports the decision-making by substantiating the choices with facts and by pointing out why the circularity score is high or low. The indicative and provisional BCI assessments are also received as interesting because it solves one of the main problems regarding information availability in the design phase. In this way, a framework is proposed for how organisations can steer on circularity early on when information is limited. The circularity assessment method evolves with the design. Furthermore, insight into the reliability of the data is a big plus of this decision-support framework. Data quality is one of the most important aspects of DDDM. Especially in early design phases, where reliability and completeness of data are an issue. So, presenting the data quality gives the end-user a better feeling of how accurate their judgment could be. Besides these three main benefits, there were also more gains of the dashboard, such as interactive and dynamic features to perform more extensive analysis, 3D visualisation of the model to identify hotspots, and the quick comparison of alternatives and building elements.

Moreover, to be effective as a decision-support framework, the system must operate correctly. The verification process shows that the framework fulfils most of the technical requirements. The systems operate almost automatically, while only a few manual procedures must be performed to update the data frequently. Furthermore, the data from different systems can be integrated seamlessly, while no errors occur during the data processing stages. The decision-support framework is ready for implementation in the existing data platforms of organisations.

A side note for the validation workshops is that the personal validation effect could occur. This is a cognitive bias that affects the participants' opinions because of their personal beliefs and involvement in this research. The participants are not completely independent. This could result in the outcome of the validation process is tended more positive than normal because the participants already benefit from the research and therefore are more enthusiastic in advance.

PART 4 | EVALUATION PHASE

The last phase is the evaluation phase. In this phase, the result of the simulation phase and the research project is evaluated. First, the discussion chapter delves deeper into the meaning of the theoretical and practical findings of this research. Also, the limitations regarding the decision-support framework are discussed. After that, the conclusion is presented where the main research question is answered based on the three sub-questions. Finally, recommendations are given for further development of the decision-support framework and the implementation in the current workflow.

9. Discussion and limitations

This chapter provides the discussion and the limitations of this research. First, the interpretation of the results is discussed and the new insights that are gained are presented. Furthermore, the limitations of this research and the corresponding decision-support framework are given.

9.1. Discussion of the results

This research intends to positively contribute to the transition from a linear to a more circular economy. Thereby, the goal was to use DDDM to stimulate and steer on circularity in the early design phase when the impact of circularity measures is most effective. This was accompanied by the objective to develop a decision-support framework for circular building design as a tool for the design team and sustainability specialists. After going through the entire development cycles for this research, it can be concluded that a decision-support framework is constructed that suits the needs and wishes of the end-user to steer on circularity early on. First, an adequate circularity assessment method is found with good applicability in the early design phases. Furthermore, the setup of the framework, with a data, analytical, and application layer, shows the possibility to integrate multiple information systems to assess different design alternatives. The results can be substantiated by the simulation phase, where the validation shows the added value of the tool to steer on circular building design and to support DDDM in the schematic design phase, as well as the detailed design phase.

9.1.1. Circular assessment methods

An important aspect of the decision-support framework is the circularity assessment method. Literature shows that the performance indicators for circularity performance are still under development, while different methodologies are investigating how to systematically and practically assess circular building design (Sassanelli, Rosa, Rocca, & Terzi, 2019). Therefore, the drawbacks or limitations of the assessment methods need to be considered carefully when implementing the decision-support framework. One of the drawbacks is that the BCI measurement method mainly focuses on the aspects: material usage, environmental impact, and disassembly potential. However, circularity encompasses more aspects than just these three. For example, Platform CB'23 is working on a method to implement value retention with indicators to measure techno-functional and economical value in the form of functional and technical performance of products in multiple design stages. Also, adaptive capacity could play a role in circular building design. Currently, the BCI measurement method includes only the disassembly potential of products in their assessment which is more technical adaptability. Another form of adaptability is spatial-functional adaptability where the focus is on the capacity of buildings to change in function and space requirements.

The reader should bear in mind that quantitative measurement of circularity is relatively new, and still in development. Therefore, there are some drawbacks and discussions around the assessment method itself. It is beyond the scope of this research to address the flaws of the circularity assessment method itself. Nevertheless, for this research to assessment method of Platform CB'23 and Alba Concepts seem most suitable and applicable for the Dutch construction industry. Thereby, presenting the underlying indicators of the circularity assessment in the dashboard gives the end-user a more complete picture so that they can also interpret the results of the assessment method based on their judgments.

9.1.2. Data availability in early design stages

It should be mentioned that during this research new insights came to light regarding the availability of data in the early design phases and the input needed for a BCI measurement method. Although the method focuses on circularity at an early stage of the design process, it does have some irregularities regarding the required and available data per phase. In the schematic design, it is uncommon that the design model includes non-graphical information such as building sequence or disassembly parameters. This makes a sound estimation of the individual parameters to determine the disassembly index of products difficult. In the author's opinion, the circularity assessment method should be harmonised with the level of information corresponding to a certain design phase. Therefore, in this research, extra attention is paid to the level of information, the BIM protocol, and the required input data for circularity assessments suitable for the schematic and detailed design phase.

To implement this new insight in the decision-support framework, the application of the BCI measurement method is slightly adapted to fit the model maturity in the schematic and detailed design phase. This results in the proposed framework of performing an indicative and provisional BCI. The indicative BCI only determines the MCI, while combining this with disassembly potential ranges established based on literature. Thereby, the proposed method for the indicative BCI to estimate a potential BCI score is not yet theoretical or practical approved. It is only based on the underlying assessment method of Alba Concepts which is a recognised measurement method by the Dutch construction industry and has been tested in practice. So, the reader should be aware that the solution with the indicative and provisional BCI is a proposed solution to tackle the problem of data availability in early design, but the method is not yet theoretical or practical verified.

Another aspect worth mentioning regarding data availability is how to deal with aspects that are not modelled but do influence the circularity, for example, the reinforcement in concrete. It is uncommon to model reinforcement in early design phases because of a low LOD. Therefore, a possible solution to consider the circularity performance of non-modelled reinforcement is to implement the characteristics in the material database. In the material database, the characteristics of concrete with a certain amount of reinforcement can be added as separate material to include not modelled aspects in the early design stages. The same principle holds when assessing different strength classes of steel or concrete. Sometimes it is easier to adjust the material properties in an external databases than to put a lot of effort into the BIM model to deal with missing elements or to include additional information.

9.1.3. Workflow circular building design

At the end of the study, the participants of the workshops indicated that they see great potential in the tool, but their main concern for the decision-support framework lies with the integration in the current, more linear, design workflow. Currently, it is uncommon to create different variants in BIM and directly evaluate a certain degree of circularity to steer the process. Most of the time, the circularity assessment is performed once the design decisions are made because of the time-consuming process. The circularity assessment focuses more on evaluation than on steering circular building design. Therefore, for the successful implementation of this decision-support framework, changes in the current design workflow are necessary. The participants confirmed that there is a need for a more circular design workflow in general. This study serves as starting point to rethink the transition into a design workflow for circular building design with the current technological potential. In figure 18 in subsection 5.2.2, a new workflow for circular building design is proposed. The participants agreed that to design circular buildings, two main changes are necessary. First, more effort needs to be invested in the development of the models and maintaining a material database early in the process to perform circularity assessments. Second, a more iterative workflow is necessary with more collaboration between the design team, BIM, and sustainability specialists to assess the impact of circularity measures throughout the design. In the end, it will be more time-consuming and costly in the early design phases to develop the BIM model and include circularity components. On the other hand, if they want to achieve their circularity ambitious, they must invest in the early development of models and the benefits will be achieved later on when performing the circularity assessments. Thereby, a balance must be found between the level of detail of design models, the number of alternatives, and the additional information to perform circularity assessments. This means for this research that for the decision-support framework to be effective, the design workflow must change first. Therefore, it would be interesting to see if in the future work processes shift to a circular design workflow, and how the decision-support framework would work out.

9.2. Limitations of the decision-support framework

In this section, the limitations of the decision-support framework are listed:

- <u>Limitations of the used programs and software for the decision-support framework:</u>
  The framework uses Autodesk Revit as the program for the design model. This poses limitations if projects are designed with other software. A proposed solution could be to extract models as IFC files, which is an open file format used for multiple BIM programs. Also, in the application layer are Power BI and VCAD used for visualising and reporting. These are paid business intelligence tools that not every company has. Power BI is integrated with the Microsoft office-365 environment, so it poses limitations for organisations that do not work with Microsoft. Nevertheless, the concept of the framework can still be implemented within other programs.

- <u>Limitations of unrealised functionalities in the decision-support framework:</u>
  There are limitations in the functionalities that are not solved in this version of the framework. For example, the automatic extraction of data with Dynamo at preferred moments in time, where currently the BIM specialist has to run the Dynamo script manually with Dynamo Player. Furthermore, the input for disassembly parameters could be improved. Currently, the BIM specialist needs to fill in the corresponding code but preferably a drop-down list will be presented with the options. Also, the flexibility for the end-user to play with the weight factors of underlying circularity aspects is not implemented yet. This proposes limitations if the client or design team wants to put the focus more on a certain circularity aspect than the others.

- <u>Limitations of access to the material database:</u>
  One of the limitations faced during the synthesis phase was linking the Revit data with material data from the database of Alba Concepts. It was not allowed to create a direct back-end connection with the material database, so all material data must be transposed manually to a local Excel database. Ideally, a direct link with the material database of Alba Concepts would be constructed, so the material data is always up-to-date, and the sustainability specialist does not have to transpose this manually. A solution would be for engineering firms and organisations like Alba Concepts to collaborate during the design process, so a more efficient data structure could be created with direct links between the BIM environment and the material database.

10. Conclusion

This research contributes to the transition to a circular economy by developing a decision-support framework to steer circular building design in the schematic and detailed design phase. Thereby, the development objective is to create a BIM-based framework to assess and evaluate design alternatives with circular assessment methods. The main research question is stated as follows:

"How can Data-Driven Decision-Making support circular building design during the early design phase?"

To answer this question in a structured way, the main research question is divided into three sub-research questions. First, a better understanding of circularity in general and circular assessment methods for buildings is provided. After that, it is investigated how to create a BIM-CE integration and a decision-support framework is developed to integrate BIM and data analytics. Once the framework is finalised, it is verified and validated with end-users to determine how and to what extent the framework will help them to steer on circular building design. This chapter provides answers to the sub-questions first, before it proceeds to answer the main research question.

10.1. Sub-research questions

"How is circularity measured for buildings in the early design phase?"

To answer the first sub-question, a literature review is conducted. First, research is done on CE in general and circular design principles because this forms the basis for circular assessment methods. After that, different assessment methods are explored and examined which suit best for the early design phases.

First, circularity is an emerging trend in the construction industry. The Dutch construction industry is ambitious in the transition towards a more circular economy where it wants to be fully circular by 2050. Currently, there is not yet a consensus on strategies for circular building design and circular assessment methods, while there is a need for harmonised measurement methods for the industry. However, the principles of circularity are generally accepted by all the different schools of thought, which makes it possible to find a thread through the various circular building design strategies and circularity assessment methods. In terms of circularity, it is acknowledged by most assessment methods and principles that the flow of materials during the full lifecycle is a good start to measure circularity. Additionally, according to the Design for X principles, Platform CB'23 and the BCI of Alba Concepts, the design for disassembly is also essential to include in the circularity assessment. Alba Concepts came up with the BCI measurement method, a generally accepted method to assess the disassembly potential quantitatively, while other methods only include qualitative assessment methods for demountability. Interesting about the assessment method of Alba Concepts is that it aligns well with the circular design guidelines of Platform CB'23. These guidelines are based on the working agreements and guiding principles from Platform CB'23, which is trustworthy and representative of the Dutch construction industry.

In this research is the BCI measurement method of Alba Concepts adopted. The method is maybe not perfect, since it is still in development and some adjustments are still necessary. Still, it gives a good indication of the degree of circularity of a project in the design phase. The method captures individual circularity performance indicators and merges them into a final score, which makes it possible to quantitatively assess design alternatives and steer on circular building design. Figure 35 presents the hierarchy of the BCI method. The BCI is built up of the Material Circularity Index, Disassembly Index, Product Circularity Index, and Element Circularity Index. Thereby, a building is composed of products and elements, where elements are a group of inseparable subproducts that arrive at the construction site as a composed whole. The BCI gives meaning to the concept of circularity through three main aspects: material usage, disassembly potential, and environmental impact. The BCI measurement method can act as a measurement and control instrument which makes it suitable to steer on circular building design in the early stages.

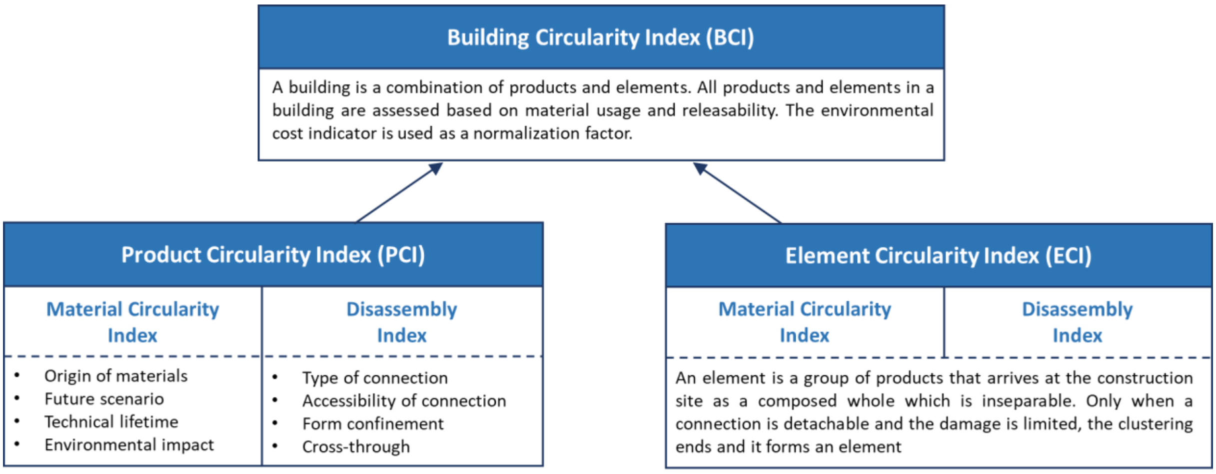


Figure 35: Building Circularity Index of Alba Concepts (Alba Concepts, 2018)

For assessing circularity in early design phases, it is meaningful to understand the input needed for the circularity assessment and the LOD of the BIM model per design phase. The data availability differs per design phase, which makes it not logical to use the standard BCI measurement method throughout the entire design phase. Therefore, it is proposed to use the indicative BCI for the schematic design and the provisional BCI for the detailed design. The indicative and provisional assessment considers the level of information per design phase. The indicative BCI assessment is conducted based on the MCI and an expected range of the disassembly potential, while the provisional BCI is conducted according to the full BCI measurement method with available disassembly parameters. Data analytics is used to deal with the available data and to predict and assess the circularity of the design at an early stage.

"How to integrate BIM and data analytics for a decision-support framework for circular building design?"

The second sub-question is partly answered by the literature study but also by the development of a practical solution to integrate BIM and circularity assessments. First, different streams for the integration of BIM and CE are investigated. After that, a decision-support framework is constructed to stimulate and evaluate circular building design.

After the literature study, it is concluded that an appropriate solution for BIM-based circularity assessment is by constructing an automated connection between BIM and external material databases within a data platform. For this research, this is the most suitable assessment method with opportunities to develop an efficient decision support framework for circular building design. A decisive factor was the high automation potential in data platforms, the potential to scale up for more complex projects, and the possibility to develop an interactive and dynamic dashboard in an external application convenient for the design team and sustainability specialists. The interactive and dynamic dashboard has the advantage to engage the end-user and stimulate circular design and creating a better understanding of complex data for more extensive analyses.

First, an exploratory study is conducted with interviews to determine the SRS for the decision-support framework. Thereby, the needs and wishes of the end-user are identified and translated to technical and functional requirements. After that, the requirements are translated into a practical solution to support circular building design. A decision-support framework is constructed that consists of a data, analytical, and application layer. See figure 36 for the concept of the framework and the used applications. The data layer collects the necessary data, the analytical layer accommodates the connection between different data sources, processes the data, and performs the calculations, and the circular design dashboard is developed in the application layer. Like this, an automated connection is created between BIM and an external material database, the circularity assessments are performed within the database, and the results are visualised in an interactive and dynamic dashboard to support the decision-making of the end-user.

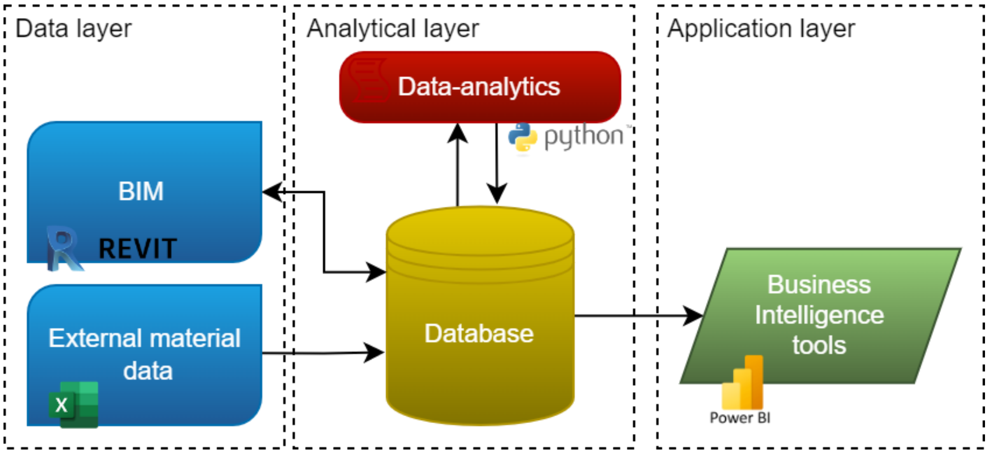


Figure 36: Decision-support framework with applications

Essential in data analytics is the quality of the data. The data quality starts with the data input, in the BIM model. Therefore, a BIM execution plan is necessary to agree upon the design workflow and to ensure the completeness, consistency, and validity of the data. In this framework, a BIM execution plan safeguards the completeness of the Revit data by setting out the input procedures per design phase. Furthermore, the data extraction with Dynamo, the pre-defined template for the material database, and the data processing with a Python script establish consistency and validity in the data. This is essential because the data is stored in different applications which have to work together. Also, the uniqueness of the data is guaranteed in this framework. The NAA.K.T. material classification creates an unambiguous and unique code that makes it possible to connect Revit and material data.

"How and to what extent does the developed data-driven decision-support framework help practitioners?"

This sub-question can be answered through verification and validation in the simulation phase. In this phase, the added value of the decision-support framework is validated with workshops for potential end-users. It is determined if the framework fulfils the needs and wishes that were drawn up in the SRS of the analysis phase.

The validation process shows that the decision-support framework and circular design dashboard would be a great solution for the end-user to steer on circular design with large implementation potential for future projects. The benefits of the framework are divided into the following four categories:

1. <u>Motivate design choices between variants in a transparent way</u>: the dashboard allows the end-user to substantiate design choices with objective circularity performance indicators. Besides that, the evaluation of the data quality contributes to the transparency and reliability of decision-making.

2. <u>Support the design team with feedback on circular building design in the early design phases</u>: the decision support framework gives the end-user a method, with indicative and provisional BCI, to assess the circularity in the schematic and detailed design phase. Furthermore, the circularity of a building can be assessed as a whole, or for individual building components.

3. <u>Provide sustainability specialists with insight into the degree of circularity of the design</u>: the dashboard allows sustainability specialists to investigate the circularity of design alternatives. Especially, the insight into the individual circularity indicators is a great addition because it decomposes the final score and therefore more effective circularity measures can be proposed targeting specific aspects.

4. <u>A suitable interface of the tool for the intended audience</u>: the interface of the dashboard is adjusted to the technical skills of the end-user. This makes to dashboard user-friendly and simple to use. Furthermore, the interactive and dynamic features of the dashboard contribute to a better user experience because more detailed analyses can be performed.

Moreover, to be effective as a decision-support framework, the system must operate correctly and as expected. This is verified by the verification process which shows that most of the technical requirements are fulfilled. The automation of the process is guaranteed, only a few manual procedures have to be performed to update the data frequently. The decision-support framework is ready for implementation in the existing data platforms of the organisations.

10.2. Main research question

"How can Data-Driven Decision-Making support circular building design during the early design phase?"

The answers to the sub-questions form the final answer for the main research question. There are two important aspects to support DDDM for circular building design: a circular assessment method and a framework for the data architecture. The first sub-question shows that the BCI measurement method of Alba Concepts is a suitable method to quantitatively assess circularity in the early design phase. Thereby, only small adjustments regarding the data input are necessary to apply the method in the schematic and detailed design phase. Furthermore, the second sub-question presents a framework of information systems and data flows to facilitate DDDM. This research shows a method that makes it possible to integrate circularity assessments in the data architecture and design processes to successfully support circular building design. This is substantiated by the development of a decision-support framework. The results of the decision-support framework are demonstrated with the use of a pilot project. The third sub-question indicates the usefulness and effectiveness of the framework through the verification and validation process by practitioners.

To conclude, this research presents a decision-support framework that can be implemented in a project to steer circular building design in the schematic and detailed design phase. The framework deals with the limited information available per design stage and proposes a new workflow to incorporate circularity assessments in each phase. Furthermore, the data analytic operations are mostly automated which is beneficial to perform quick and easy circularity assessments to evaluate design choices. Practitioners have verified and validated that this dashboard effectively supports circular decision-making in the design process. Thereby, the higher objective of this study to positively contribute to the transition to a more circular economy is met.

11. Recommendations and reflection

This research and decision-support framework are used to stimulate and support circular design decisions. Thereby, insight is gathered to improve the design workflow, stimulate DDDM for circular building design, and to further develop the decision-support framework. This chapter presents the recommendations for future research and a brief reflection on the research process.

11.1. Recommendations

First, the implementation of the decision-support framework for circular building design requires some adjustments in the current workflow of Royal BAM Group. For successful implementation, it is recommended to include the data input procedures for circularity aspects in the BIM protocol for projects that attach great importance to sustainability and circularity. Furthermore, it is recommended to integrate the data architecture of the decision-support framework into the data analytical platform of the company. The quantity take-off of the project data and the material database must be exported to a central data warehouse within the organisation. The quantity take-off and material database could be used for other analyses as well, so the central data warehouse safeguards a single source of truth. In the data warehouse, data analytical operations can be performed to process the data. With the integration of the decision-support framework in the current data analytical platform, the process for automatically assessing circularity can be standardised and centralised for all projects.

Next, there is still plenty of research to be done on circular design strategies and assessment methods. Extension and improvement of the circular assessment methods are interesting topics. Also, future research can focus on how circularity benchmarks could be integrated into the tender procedure of projects. This will create awareness for circular ambitions and increases the demand for circular design strategies and steering tools. Implementing circular standards and benchmarks in the construction industry could accelerate the goal of being fully circular by 2050.

Furthermore, the proposed circularity assessment method, the indicative and provisional BCI, could be further developed. In the early design phase, the availability of data is limited which introduces uncertainty in the circularity assessment. Currently, the schematic design phase only deals with uncertainty through a range of disassembly potential. Future research can focus on the use of data from multiple projects to determine a bandwidth, or safety margins, per design phase to analyse the uncertainty of the circularity assessment. In this way, a trend line analysis can be performed throughout the design, so you do not only steer on circularity but also control if circularity objectives will be met.

Besides the recommendations regarding the research and implementation of the decision-support framework, it is recommended to improve the decision-support framework itself as well.

- <u>Data platform:</u> Currently, a local database is created where all data is captured in Excel files. It would be interesting to improve and scale up the data architecture of the decision-support framework to a cloud-based data platform. For example, using a SQL database to store, clean and process data from multiple sources in an efficient and centralised way. SQL database is a relational database suitable for back-end data storage and data processing. In this way, a data platform can be set up to store all project data in a cloud-based database and from where all other analyses can be performed.

- <u>Additional improvements to the dashboard:</u> From the workshops in the simulation phase, it turned out that there are some additional wishes from the end-user for the improvement of the next version of the dashboard. It would be nice to implement a page that makes it easy to compare several materials for one specific building element. Thereby, the possibility to assign different materials to an element in Power BI instead of creating multiple alternatives in Revit. This does require a different setup of the data analytical model. Furthermore, an interesting solution would be to highlight which parts in the model were updated when the data is refreshed, so the sustainability specialists know where to focus on.

11.2. Reflection

This last section reflects on the process of this research. The reflection is performed in a threefold structure with a reflection on the literature review, research methodology, and research results.

The literature study was helpful for the continuation of the research. First of all, it became more understandable what the current status was of the transition to a circular economy and circular building design quantitatively. Secondly, even though circularity assessments are still in development, there was enough information available about the circularity measurement method suitable for this research. The theory about circular assessment methods provided a good handle during the development of the decision-support framework. Furthermore, the theory for integration of BIM and circularity assessments was limited and no research did a systematic investigation. However, this gap was filled with research on state-of-the-art BIM and circularity integration and with systematic research on comparable integration approaches of BIM and sustainability aspects.

The reflection on the research methodology focuses on the data gathering of material data, connecting project and material data, and the validation workshops. First, gathering the material data took more time than expected because the information was not publicly accessible. Luckily, Royal BAM Group had a partnership with Alba Concepts which made it possible to gain insight into the data. However, it was not allowed to create a back-end connection with the database. This resulted in the material database having to be constructed manually as an alternative solution. Besides that, difficulties are faced in connecting the project data with material data because. The reason for this was that there was no standard and consistent name convention used in Revit and the material database, and finding a suitable way to assign material classification in Revit took longer than expected. In the end, the challenges are solved by implementing the NAA.K.T. material classification and the creation of a Revit keynote for the material list. Furthermore, in the validation workshops, the personal validation effect could occur, which is a cognitive bias that affects the participants' opinions because of their personal beliefs and involvement in this research. The participants are not completely independent. This could result in the outcome of the validation process is tended more positive than normal because the participants already benefit from the research and therefore are more enthusiastic in advance.

Lastly, reflecting on the results of this research, they do fulfil the expectations at the beginning of this process because an effective decision-support framework is constructed to steer on circular building design. Thereby, the reaction and feedback of end-users are above expectations. It feels good that there is so much appreciation for the results and that there is a lot of interest in the circular design dashboard and the demand for further implementation of the framework in projects.

References

Akanbi, L. A., Oyedele, L. O., Omoteso, K., Bilal, M., Akinade, O. O., Ajayi, A. O., . . . Owolabi, H. A. (2019). Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. *Journal of Cleaner Production, 223*, 386-396. Retrieved March 2022

Akhimien, N. G., Latif, E., & Hou, S. (2021). Application of circular economy principles in buildings: A systematic review. *Journal of Building Engineering, 38*. Retrieved March 2022

Alba Concepts. (2018). *Circulair Bouwen*. Retrieved March 2022, from Alba Concepts: https://albaconcepts.nl/circulairbouwen/

Alba Concepts. (2019). *CIRCULAR BUILDINGS - MEETMETHODIEK LOSMAAKBAARHEID.* DGBC. Retrieved May 2022

Alba Concepts; BCI gebouw. (2022). *Meetmethode Circulair vastgoed - Building Circularity Index.* 's-Hertogenbosch: BCI gebouw. Retrieved March 2022

Amory, J. (2019). *A GUIDANCE TOOL FOR CIRCULAR BUILDING DESIGN.* Delft: Delft University of Technology. Retrieved March 2022

Askar, R., Bragança, L., & Gervásio, H. (2022). Design for Adaptability (DfA)—Frameworks and Assessment Models for Enhanced Circularity in Buildings. *MDPI, 5*(1). Retrieved March 2022

Autodesk. (2022). *Tutorials*. Retrieved June 2022, from Knowledge Network Autodesk: https://knowledge.autodesk.com/support/revit/learn-explore/caas/CloudHelp/cloudhelp/2021/ENU/Revit-GetStarted/files/GUID-9E9688A2-0645-4F8E-9D96-F1B76291A6C6-htm.html

BAMB. (2019). *Material Passports*. Retrieved March 2022, from BAMB2020: https://www.bamb2020.eu/topics/materials-passports/

Barnes, P., & Davies, N. (2019). *BIM in Principle and in Practice.* London: ICE Publsihing. Retrieved July 2022

Bergen, T. v., & Driever, D. (2019). Creating a better world: circularity in real estate and construction. *Real Estate Predictions 2019*. Retrieved August 2022

BIM Forum. (2021). *Level of Development Specification - Part 1, Guide & Commentary.* Retrieved March 2022, from BIM Forum: https://bimforum.org/lod/

BIM Loket. (2020). *BIM Loket*. Retrieved June 2022, from NL/SfB: https://www.bimloket.nl/p/664/Over-NLSfB

BIM Loket. (2021). *Wat is BIM?* Retrieved March 2022, from BIM Loket: https://www.bimloket.nl/p/134/Wat-is-BIM

BIM Loket. (2022). *BIM Loket - 1. NAA.K.T. Eenduidige materiaalbenaming*. Retrieved June 2022, from BIM Loket: https://www.bimloket.nl/p/682/1-NAAKT-Eenduidige-materiaalbenaming

Bolpagni, M., Gavina, R., Ribeiro, D., & Arnal, I. P. (2022). Shaping the Future of Construction Professionals. In M. Bolpagni, R. Gavina, & D. Ribeiro, *Industry 4.0 for the Built Environment* (Vol. 20, pp. 1-28). Porto: Springer. Retrieved March 2022

Borrmann, A., König, M., Koch, C., & Beetz, J. (2018). *Building Information Modeling.* Springer. Retrieved March 2022

Brand, S. (1995). *How Buildings Learn: What happens after they're built.* Penguin Putnam Inc. Retrieved March 2022

Brundtland, G. H. (1987). *Our Common Future.* Oslo: The World Commission on Environment and Development. Retrieved March 2022

Brynjolfsson, E., Hitt, L. M., & Kim, H. H. (2011). *How does data-driven decisionmaking affect firm performance?* SSRN. Retrieved March 2022

Cambier, C., Galle, W., & de Temmerman, N. (2020). Research and Development Directions for Design Support Tools for Circular Building. *MDPI, 10*. Retrieved March 2022

Charef, R. (2022). The use of Building Information Modelling in the circular economy context: Several models and a new dimension of BIM (8D). *Cleaner Engineering and Technology, 7*. Retrieved March 2022

Construction Users Roundtable. (2004). Collaboration, Integrated Information, and the Project Lifecycle in Building Design, Construction and Operation. *CURT Publication No. WP-1202.* Retrieved June 2022

Debacker, W., & Manshoven, S. (2016). *D1 synthesis of the state-of-the-art: key barriers and opportunities for materials passports and reversible building design in the current system.* BAMB. Retrieved March 2022

Deloitte. (2021). *Industry 4.0*. Retrieved March 2022, from Deloitte: https://www2.deloitte.com/nl/nl/pages/energy-resources-industrials/articles/about-industry-4-0.html

Di Biccari, C., Abualdenien, J., Borrmann, A., & Corallo, A. (2019). A BIM-Based Framework to Visually Evaluate Circularity and Life Cycle Cost of buildings. *IOP Conf. Series: Earth and Environmental Science.* Atlanta: IOP Publishing. Retrieved March 2022

Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources, Conservation and Recycling, 122*, 163-171. Retrieved March 2022

Durmisevic, E. (2006). *Design for disassembly as a way to introduce sustainable engenieering to building design & construction.* Delft: Delft University of Technology. Retrieved August 2022

Dutch Green Building Council. (2018). *Albert Heijn opent eerste circulaire supermarkt van Nederland*. Retrieved August 2022, from DGBC: https://www.dgbc.nl/nieuws/albert-heijn-opent-eerste-circulaire-supermarkt-van-nederland-1479

Ellen MacArthur Foundation. (2013a). Towards the circular economy Vol. 1. *1*. Retrieved March 2022

Ellen MacArthur Foundation. (2013b). Towards the circular economy Vol. 2. *2*. Retrieved March 2022

EMF, & ANSYS Granta. (2019). *Circularity Indicators - An Approach To Measuring Circularity.* EMF & ANSYS Granta. Retrieved March 2022

Emmanuel, J. A. (2021). BIG DATA ANALYTICS: UNDERSTANDING ITS CAPABILITIES AND POTENTIAL BENEFITS FOR NIGERIA'S CONSTRUCTION INDUSTRY. *Environmental Review, 8*(2), 59-72. Retrieved Februari 2022

Gallopoulos, N. E., & Frosch, R. A. (1989). Strategies for Manufacturing. *Scientific American, 261*, 144-152. Retrieved March 2022

Guy, B., & Ciarimboli, N. (2008). *Design for Disassembly in the Built Environment: A Guide to Closed-Loop Design and Building.* Pennsylvania: The Pennsylvania State University. Retrieved March 2022

Habib, H. M., & Kadhim, E. (2020). Employ 6D-BIM Model Features for Buildings Sustainability Assessment. *IOP Conference Series: Materials Science and Engineering.* Retrieved March 2022

Hollberg, A., Kiss, B., Rock, M., Soust-Verdaguer, B., Wiberg, A. H., Lasvaux, S., . . . Habert, G. (2021). Review of visualising LCA results in the design process of buildings. *Building and Environment, 190*. Retrieved March 2022

Hopkinson, P., Chen, H.-M., Zhou, K., Wang, Y., & Lam, D. (2019). Recovery and reuse of structural products from end-of-life buildings. *Engineering Sustainability* (pp. 119 - 128). ICE Publishing. Retrieved March 2022

Ingemarsdotter, E., Jamsin, E., Kortuem, G., & Balkenende, R. (2019). Circular strategies enabled by the internet of things—A framework and analysis of current practice. *Sustainability, 11*(20). Retrieved March 2022

Jalaei, F., Jrade, A., & Nassiri, M. (2015). Integrating decision support system (DSS) and building information modeling (BIM) to optimize the selection of sustainable building components. *Journal of Information Technology in Construction, 20*, 399-420. Retrieved April 2022

Jonkers, H. M. (2021). *Reader CIE4100 - Materials and Ecological Engineering.* Delft: Delft University of Technology. Retrieved March 2022

Kayaçetin, N. C., Versele, A., & Verdoodt, S. (2022). Evaluation of Circular Construction Works During Design Phase: An Overview of Valuation Tools. In J. R. Littlewood, R. J. Howlett, & L. C. Jain, *Sustainability in Energy and Buildings 2021* (Vol. 263, pp. 89-100). Springer. Retrieved March 2022

Kedir, F., Bucher, D. F., & Hall, D. M. (2021). A Proposed Material Passport Ontology to Enable Circularity for Industrialized Construction. *European Conference on Computing in Construction.* Zurich. Retrieved March 2022

Ketelaars, R. (2019). *TOWARDS CIRCULAR REMODELING IN THE RETAIL SECTOR.* Eindhoven: Eindhoven University of Technoloogy. Retrieved August 2022

Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation & Recycling, 127*, 221-232. Retrieved March 2022

Kohlhammer, J., Proff, D. U., & Wiener, A. (2018). *Visual business analytics: effektiver Zugang zu Daten und Informationen.* dpunkt. verlag. Retrieved April 2022

Linder, M., Boyer, R. H., Dahll:of, L., Vanacore, E., & Hunka, A. (2020). Product-level inherent circularity and its relationship to environmental impact. *Journal of Cleaner Production, 260*. Retrieved March 2022

McDonough, W., & Braungart, M. (2002). *Cradle to Cradle: Remaking the Way We Make Things.* Tantor Audio. Retrieved March 2022

Miu, I. (2020). *Fundamental Characteristics and Concept of Material Passports.* Twente: University of Twente. Retrieved March 2022

Morkunaite, L., Naber, F. A., Petrova, E., & Svidt, K. (2021). An Open Data Platform for Early-Stage Building Circularity Assessment. *Proc. of the Conference CIB W78*, (pp. 11-15). Retrieved March 2022

Morris, A. (2021, Juli). *Descriptive Analytics Defined: Benefits & Examples*. Retrieved Februari 2022, from NetSuite: https://www.netsuite.com/portal/resource/articles/erp/descriptive-analytics.shtml#:~:text=Descriptive%20analytics%20helps%20companies%20understand,future%20outcomes%20and%20possible%20actions.

Morseletto, P. (2020). Targets for a circular economy. *Resources, Conservation & Recycling, 153*. Retrieved March 2022

Munaro, M. R., Tavares, S. F., & Bragança, L. (2020). Towards circular and more sustainable buildings: A systematic literature review on the circular economy in the built environment. *Journal of Cleaner Production, 260*. Retrieved March 2022

Nadj, M., Maedche, A., & Schieder, C. (2020). The effect of interactive analytical dashboard features on situation awareness and task performance. *Decision Support Systems, 135*. Retrieved April 2022

NATSPEC. (2013). *NATSPEC BIM Paper BBP 001 - BIM and LOD.* Construction Information Systems Limited. Retrieved March 2022

NMD. (2020). *Toetsingsprotocol Opname data in de Nationale Milieudatabase.* Stichting Nationale Milieudatabase. Retrieved June 2022, from https://milieudatabase.nl/wp-content/uploads/2020/07/Toetsingsprotocol-juli-2020.pdf

NMD. (2022). *Gids Milieuprestatieberekeningen.* Rijswijk: Stichting Nationale Milieudatabase. Retrieved March 2022, from Nationale Milieu Database : https://milieudatabase.nl/milieuprestatie/milieuprestatieberekening/?cn-reloaded=1

Nobre, G. C., & Tavares, E. (2021). The quest for a circular economy final definition: A scientific perspective. *Journal of Cleaner Production, 314*. Retrieved March 2022

Nuñez-Cacho, P., Górecki, J., Molina-Moreno, V., & Corpas-Iglesias, F. A. (2018). What gets measured, gets done: Development of a circular economy measurement scale for building industry. *Sustainability, 10*(7). Retrieved March 2022

NxtGen Houses. (2021). *Building layers*. Retrieved March 2022, from Nxtgen houses: https://nxtgenhouses.com/how-buildings-learn/

O'Neill, R. V., DeAngelis, D. L., Waide, J. B., & Allen, T. F. (1986). *A Hierarchical Concept of Ecosystems.* Princeton: Princeton University Press. Retrieved March 2022

Platform CB'23. (2020a). *Measuring circularity - Working agreements for circular construction.* Platform CB'23. Retrieved March 2022

Platform CB'23. (2020b). *Leidraad: Paspoorten voor de bouw.* Platform CB'23. Retrieved June 2022, from https://platformcb23.nl/images/downloads/2020/paspoorten-voor-de-bouw/Platform_CB23_Leidraad_Paspoorten_voor_de_bouw_versie_2.0.pdf

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). *CIRCULAR ECONOMY: MEASURING INNOVATION IN THE PRODUCT CHAIN.* The Hague: PBL Netherlands Environmental Assessment Agency. Retrieved March 2022

Provost, F., & Fawcett, T. (2013). Data Science and its Relationship to Big Data and Data-Driven Decision Making. *Big Data, 1*(1), 51-59. Retrieved Febrauri 2022

Rahla, K. M., Bragança, L., & Mateus, R. (2019). Obstacles and barriers for measuring building's circularity. *IOP Conference Series: Earth and Environmental Science. 225.* Atlanta: IOP Publishing. Retrieved March 2022

Rahla, K. M., Mateus, R., & Bragança, L. (2021). Implementing Circular Economy Strategies in Buildings — From Theory to Practice. *Applied system innovation, 4*(26). Retrieved March 2022

Ramasamy, A., & Chowdhury, S. (2020). Big data quality dimensions: a systematic literature review. *Journal of Information Systems and Technology Management, 17*. Retrieved June 2022

Rigamonti, L., & Mancini, E. (2021). Life cycle assessment and circularity indicators. *The International Journal of Life Cycle Assessment, 26*(10), 1937-1942. Retrieved March 2022

Rios, C. F., Chong, W. K., & Grau, D. (2015). Design for Disassembly and Deconstruction - Challenges and Opportunities. *International Conference on Sustainable Design, Engineering and Construction* (pp. 1296 - 1304). Arizona: Elsevier. Retrieved March 2022

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Visualization of environmental potentials in building. *Building and Environment, 140*, 153-161. Retrieved March 2022

Royal BAM Group. (2019). *Levels of Design and Maturity Assessment.* Intern document. Retrieved June 2022

Royal BAM Group. (2020). *Circulair bouwen (proces)plan.* BAM. Retrieved June 2022

Saadé, M., Erradhouani, B., Pawlak, S., Appendino, F., Peuportier, B., & Roux, C. (2022). Combining circular and LCA indicators for the early design of urban projects. *International Journal of Life Cycle Assessment*, 1-19. Retrieved March 2022

Saidani, M., Yannou, B., Leroy, Y., Cluzel, F., & Kendall, A. (2019). A taxonomy of circular economy indicators. *Journal of Cleaner Production, 207*, 542 - 559. Retrieved March 2022

Salthe, S. N. (1993). *Development and evolution: complexity and change in biology.* Massachusetts: Mit Press. Retrieved March 2022

Santiago, P. (2022). Achieving Sustainability in Construction Through Digitally Informed Decisions. In M. Bolpagni, R. Gavina, & D. Ribeiro, *Industry 4.0 for the Built Environment* (Vol. 20, pp. 247 - 269). Porto: Springer. Retrieved March 2022

Sassanelli, C., Rosa, P., Rocca, R., & Terzi, S. (2019). Circular economy performance assessment methods: A systematic literature review. *Journal of Cleaner Production*, 440-453. Retrieved March 2022

SBR. (2011). *Levensduur van bouwproducten, methoden voor referentiewaarden.* Rotterdam: SBR. Retrieved June 2022

Stobierski, T. (2019). THE ADVANTAGES OF DATA-DRIVEN DECISION-MAKING. *Harvard Business School*. Retrieved March 2022

Thomas, E., & Bowman, J. (2020). *Harnessing the data advantage in construction.* FMI Corporation & Autodesk. Retrieved Februari 2022, from https://a.storyblok.com/f/64835/x/137c281eda/harnessing_the_data_advantage_in_construction.pdf

Thomson, L. A. (2017). The Seven Pitfalls of Data-Driven Decision-Making (And How to Avoid Them). *BYU Marriott Alumni Magazine*. Retrieved March 2022

van Stijn, A., Eberhardt, L. M., Jansen, B. W., & Meijer, A. (2021). A Circular Economy Life Cycle Assessment (CE-LCA) model for building components. *Resources, Conservation & Recycling, 174*. Retrieved March 2022

Verberne, J. (2016). *Building Circularity Indicators – An approach for measuring circularity of a building.* Eindhoven: University of Technology Eindhoven. Retrieved March 2022

Vliet, M. M. (2018). *Disassembling the steps towards building circularity - redeveloping the building disassembly assessment method in the building circularity indicator.* Eindhoven: Eindhoven University of Technology. Retrieved March 2022

Wadan, R. (2020, April). *How is the current state of Big Data Analytics in Controlling?* Retrieved Februari 2022, from Towards Data Science: https://towardsdatascience.com/how-is-the-current-state-of-big-data-analytics-in-controlling-1273c725ac6a

Walzberg, J., Lonca, G., Hanes, R. J., Eberle, A. L., Carpenter, A., & Heath, G. A. (2021). Do We Need a New Sustainability Assessment Method for the Circular Economy? A Critical Literature Review. *Frontiers in Sustainability, 1*. Retrieved March 2022

Willskytt, S., Böckin, D., André, H., Tillman, A.-M., & Ljunggren, S. (2016). Framework for analysing resource-efficient solutions. *12th Biennial International Conference.* Kyoto: EcoBalance. Retrieved March 2022

Xue, K., Hossain, U., Liu, M., Ma, M., Zhang, Y., Hu, M., . . . Cao, G. (2020). BIM Integrated LCA for Promoting Circular Economy towards Sustainable Construction: An Analytical Review. *MDPI, 13*. Retrieved March 2022

Zhang, N., Han , Q., & de Vries, B. (2021). Building Circularity Assessment in the Architecture, Engineering, and Construction Industry: A New Framework. *Sustainability, 13*. Retrieved March 2022

Zhang, N., Han, Q., de Vries, B., & Zhai, J. (2021). A BIM-based Building Circularity Assessment tool for the early design stage. *Proc. of the Conference CIB W78*, (pp. 11-15). Retrieved March 2022

Zorzi, I. d. (2019). *NL-SfB codering*. Retrieved June 2022, from CAD & Company: https://cadcompany.nl/kennisbank/bim/nl-sfb/

APPENDICES

Appendix A: Market analysis – Applications & software

Table 1: Market analysis applications

	Source	Data mining	Analysis	Visualisation
1	Autodesk Revit/Navisworks	Assembly/Relatics	Power BI	
2	Autodesk Revit/Navisworks	BIM 360 (option to integrate BI tools and Python)		
3	Autodesk Revit	Dynamo		
4	Autodesk Revit	Dynamo		Power BI
	Autodesk Revit			Power BI
	Autodesk Revit	Dynamo	Python	Power BI
5	Revit → IFC	Python (incl. packages for visuals/interactive dashboards)		

Table 2: Market analysis explanation

	Application stream	Info	Pros	Cons
1	Company specific application environment (BAM)	Data application workflow that is current used within BAM, based on a common data environment	Integrated in application architecture of company to ensure smooth interoperability Shared database company wide	Company specific, not generally applicable in the industry High cost for software and applications
2	Autodesk BIM-environment	BIM 360 as base for common data environment and modelling and circularity assessment with the use of several Autodesk applications (Revit, Navisworks, BIM360)	BIM360 provides the same project user experience to all the stakeholders in the BIM project process during all the phases Shared database with access to project data to anyone at any time	High cost for software and applications
3	Revit environment	Modelling of design in Revit and directly linking external databases and performing circularity assessment with Dynamo. Dynamo is used for data extraction, analysis, and visualisation	Single software packages for modelling and circularity assessment (Dynamo comes free with Revit software) Dynamo has the ability to automate the assessment process	Static representation of the data and not user-friendly for non-technical users Limited possibility to adjust for what you want to know about the data Slow performance and huge RAM/CPU usage if database becomes big Only applicable for Revit users, so technical skills required
4	Automated link of Revit with external data analytic tools	Using dynamo to export the data from the design, dynamo or data analytics tools to analyse the data, while visualising the report with BI Power BI is used as example, but other BI tools are possible as well Different setups for data mining, analysing and visualising possible, so therefore multiple streams	Dynamo can include Python scripting providing wider applicability in exporting files (or store in SQL database/integrating in other software) Business Intelligence tools to improve data analytics are user-friendly to make rapid visualisations without much prior technical knowledge Power BI plug-ins to visualise and link 3D model to data (Revit DB link)	License cost for BI tools, although Power BI does have a free version and the pro version cost are limited Power BI is integrated in Microsoft environment, so more suitable for companies that also use Microsoft Limited performance if data sources become very large, processing speed will decrease
5	Open-Source environment,	Open-Source alternative using IFC exports from Revit and analysing and visualising with Python without additional applications	No application costs Open-Source so high general applicable because everybody can make use of it Almost infinite possibilities of visualisations and packages to analyse data	High level of IT knowledge to develop and adjust tool Difficult to visualise Revit 3D model in dashboard Software development is not core business for construction company, so prefer to outsource or to purchase tools/applications for easier analytics

Appendix B: Information documents

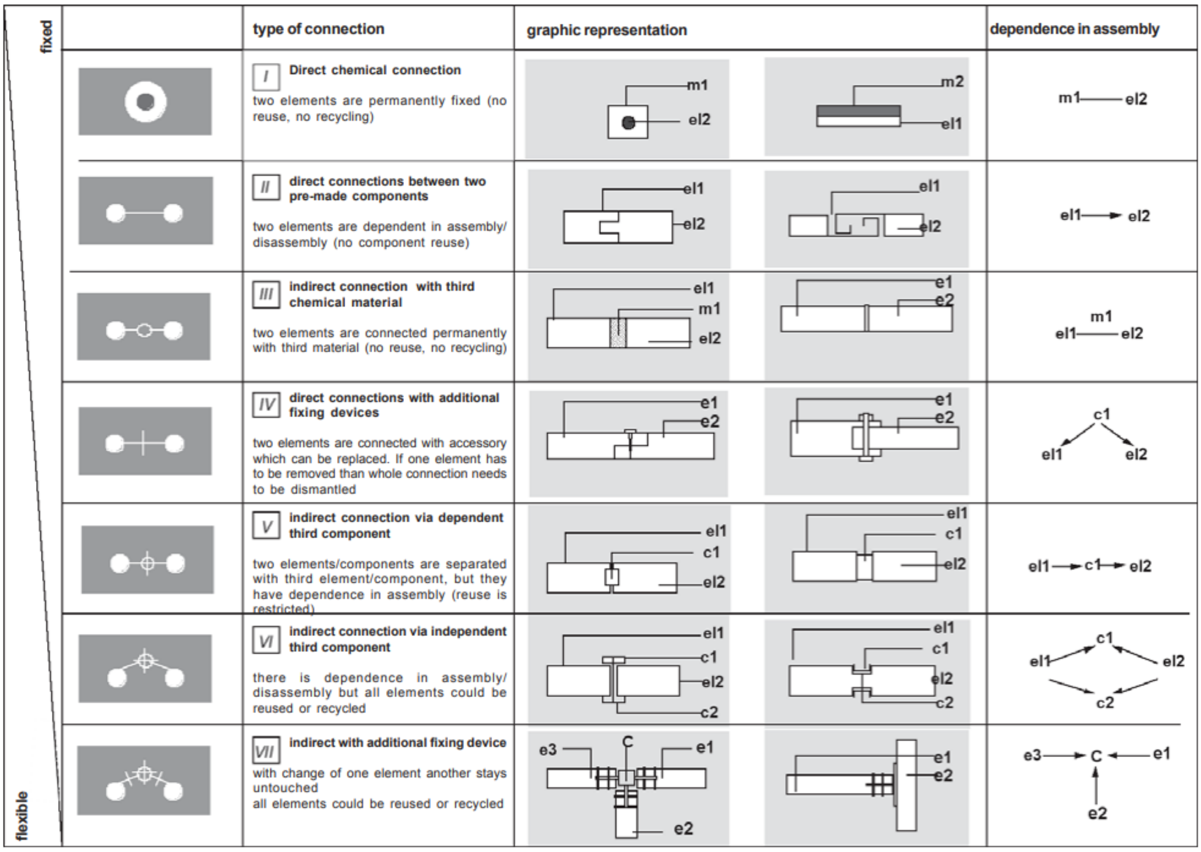
Level of Development

Table 3: Summary LOD (BIM Forum, 2021)

	LOD 100 Conceptual	LOD 200 Approx. geometry	LOD 300 Precise geometry	LOD 400 Fabrication	LOD 500 As-built
Analysis	Analysis based on volume, area and orientation by application of **generalised** performance criteria assigned to **other** Model Elements.	Performance analysis of selected systems by application of **generalized** performance criteria assigned to the **representative** Model Elements.	Performance analysis of selected systems by application of **specific** performance criteria assigned to the **representative** Model Element.	Performance analysis of systems by application of **actual** performance criteria assigned to the Model Element.	Performance measured from installed systems.
Cost Estimating	Development of a cost estimate based on **current** area, volume or similar **conceptual** estimating techniques (e.g., square metres of floor area, hospital bed, etc.).	Development of cost estimates based on **approximate** data provided and **quantitative** estimating techniques (e.g., volume and quantity of elements or type of system selected).	Development of cost estimates suitable for procurement based on the **specific** data provided.	Costs are based on the **actual** cost of the Model Element at buyout.	Operation and maintenance costs measured from installed systems.
Project scheduling	Project phasing and determination of **overall** Project duration.	For showing ordered, time-scaled appearance of **major** elements and systems.	For showing ordered, time-scaled appearance of **detailed** elements and systems.	For showing ordered, time-scaled appearance of **detailed specific** elements and systems **including construction means and methods**.	Maintenance scheduling derived from installed systems.
Coordination	N/A	**General** coordination with other Model Elements in terms of its size, location and clearance to other Model Elements.	**Specific** coordination with other Model Elements in terms of its size, location and clearance to other Model Elements including **general** operation issues.	Coordination with other Model Elements in terms of its size, location and clearance to other Model Elements including **fabrication, installation** and **detailed** operation issues.	N/A
Other authorised uses	Additional Authorised Uses of the Model Element developed to **LOD 100**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of *AIA E203-2012*.	Additional Authorised Uses of the Model Element developed to **LOD 200**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of *AIA E203-2012*.	Additional Authorised Uses of the Model Element developed to **LOD 300**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of *AIA E203-2012*.	Additional Authorised Uses of the Model Element developed to **LOD 400**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of *AIA E203-2012*.	Specific Authorised Uses of the Model Element developed to **LOD 500**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of *AIA E203-2012*.

Disassembly parameters

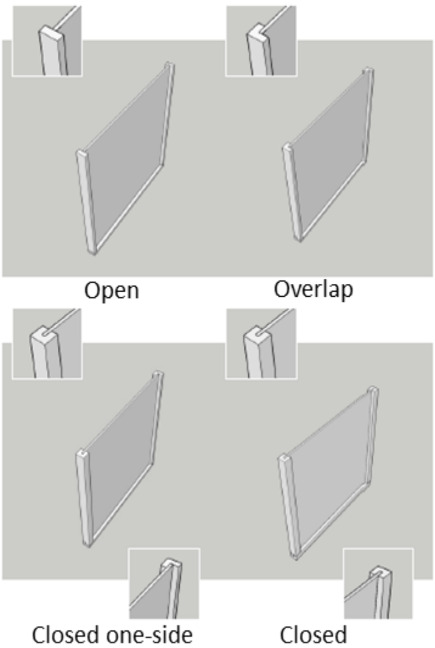
Type of connection:



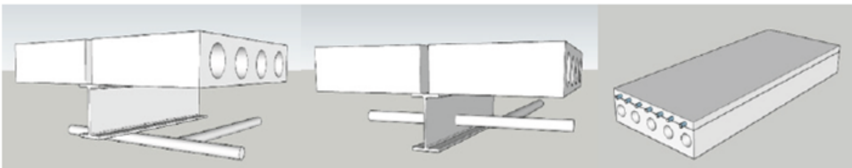
	type of connection	graphic representation	dependence in assembly
fixed	I Direct chemical connection two elements are permanently fixed (no reuse, no recycling)	m1, el2 / m2, el1	m1—el2
	II direct connections between two pre-made components two elements are dependent in assembly/ disassembly (no component reuse)	el1, el2 / el1, el2	el1→ el2
	III indirect connection with third chemical material two elements are connected permanently with third material (no reuse, no recycling)	el1, m1, el2 / e1, e2	m1 el1—el2
	IV direct connections with additional fixing devices two elements are connected with accessory which can be replaced. If one element has to be removed than whole connection needs to be dismantled	e1, e2 / e1, e2	c1 el1 el2
	V indirect connection via dependent third component two elements/components are separated with third element/component, but they have dependence in assembly (reuse is restricted)	el1, c1, el2 / el1, c1, el2	el1→c1→ el2
	VI indirect connection via independent third component there is dependence in assembly/ disassembly but all elements could be reused or recycled	el1, c1, el2, c2 / el1, c1, el2, c2	c1 el1 el2 c2
flexible	VII indirect with additional fixing device with change of one element another stays untouched all elements could be reused or recycled	e3, C, e1, e2 / e1, e2	e3→ C ← e1 ↑ e2

Figure 1: Seven principles of connections (Durmisevic, 2006)

Form confinement



Cross-through



Modular zoning   Intersection   Integration

Figure 2: Form confinement (left), Cross-through (right) (Alba Concepts, 2019)

Appendix C: Semi-structured interviews

List of participants

Table 4: List of participants

	Organisation	Role	Subject
Stakeholders: decision-support framework			
Participant 1	Royal BAM Group	Head of Department: Digital Construction Program	Digitalisation & decision-support tools
Participant 2	Royal BAM Group	Project leader BIM	Building Information Management
Participant 3	Royal BAM Group	Specialist Digital Construction	Information Management & data analysis
Participant 4	Alba Concepts	Consultant Circularity	BCI measurement method
Participant 5	Royal BAM Group	Project leader Sustainable Buildings	Sustainability and Circular design
End-user: circularity dashboard			
Participant 6	Royal BAM Group	Manager Sustainability and Environment	Circularity in the design process / Program of Requirements
Participant 7	Royal BAM Group	Manager Sustainability IP	
Participant 8	Royal BAM Group	Design leader – Civil	
Participant 9	Benthem Crouwel NACO	Design team / architect	

Interview structure

Not all questions are used in every interview. The questions are selected depending on the profession and role of the interviewee.

- Introduction:
  - Personal introduction
  - Background and education
  - Professional experience and role within the company

- Thesis overview
  - Subject of the master thesis
  - Concept decision-support framework
  - Goal of the interview

- Questions: sustainability/circularity
  - How is circularity included in the design process within BAM?
    - How to deal with measuring Circularity in different design phases?
    - What design tools/guidelines are there for circularity within BAM?
    - What needs are there in terms of design tools for circular building design?
  - How are the material properties regarding circularity collected/registered within BAM?
    - Which sustainability or circularity databases does BAM use, own material database or NMD for example?
  - What measurement methods to determine circularity are in place?

        - Are there certain bottlenecks/points for improvement that are encountered when determining circularity during the design?
    - What is the relationship between the design team and the sustainability specialists?
        - To what extent does the sustainability specialists influence the design?
    - What is the current process of performing a BCI assessment?
        - What information is needed and what are the information sources?
        - How is the BCI assessment used to steer on design process, and how is feedback delivered to BAM?
    - How to deal with detailed data from the environmental database while the preliminary design in BIM is not so detailed?

- Questions: Building Information Modelling – Information management
    - To what extent are sustainability assessments linked with BIM?
        - What are the challenges with assessing BIM-based sustainability analysis?
    - To what extent is the BCI calculation automated or integration with the BIM model?
        - Where can optimization be achieved in the current workflow/bottlenecks of automation
        - Are there bottlenecks or opportunities for improvement/automation encountered in the BCI calculation?
    - How do BIM specialists deal with the Level of Development in BIM models?
        - What preferences do BIM specialist have in how to deal with new parameters in the model?
        - What is the common classification for material names/properties?
    - How to make sure that the information/data is up to date for analysis?

- Questions: Decision support system / circularity dashboard
    - What is the current data architecture like within BAM?
        - How does the information flow between systems?
        - What are the pros and cons of the data architecture within BAM?
    - At which moment in the design process do decisions need to be supported by the dashboard?
        - How is the decision-making process during design stages?
        - What is the preferred frequency of updating the data?
    - Are there any issues/bottlenecks in implementing current Power BI dashboards or design tools?
    - Do you have any requirements and wishes that you would like to see reflected in a decision support tool in terms of circularity?
    - Are there any requirements/wishes from the Digital Construction department for the data-driven dashboard?

Summary results interview

Table 5: Interview results

Subject	Success	Problems	Needs	Notes
Design phase	Sustainability and (sometimes) Circularity part of tender procedures and recognised as criteria in the design phase	Design decisions based on experience, personal interest, and qualitative assessment, not data-driven with quantitative approach Change in work process needed for data-driven design tools, not everybody wants to work data-driven Reactive instead of pro-active: assessment methods at the end of the design but not included in trade-off for development of alternatives Problem on how to deal with uncertainties in data and important aspects not included in the model, data availability per design phase	Support design decisions in early design phase when less (accurate) data is available Design team: final score of design performances (incl. circularity) to rank design alternatives Insight in the reliability of the model on which decisions need to be based (data quality/dashboard health) Ways to visualise in the early design which changes benefit the design and what the impact is (to improve decision-making & stakeholder communication)	BAM is not always involved in the early design phase, but comes into play during detailed design Do not blindly trust data, but use data as a tool to gain insight and to start a discussion about possible solutions The result of the tool gives insight in importance of circularity indicators for future design process
Circularity	Industry acknowledges the importance of circularity and the transition to a circular economy is one the move Implementation of Circularity goals, performance indicators, guidelines, and processes for circular building design Circularity assessment performed in design phase for pilot projects	Circularity procedures and methods are in development and sometimes knowledge is lacking with stakeholders Discussion on relative importance of weight factors of circularity indicators (disassembly index vs. material circularity index) Availability of circularity data of materials, and availability/reliability of disassembly data in early design stage Manual procedures of input for circularity assessment / time-consuming assessments Circularity assessment of design is outsourced to external company, company returns feedback/advise on how to improve circularity (not own analysis). Also, results of circularity assessment are in the form of a qualitative report with some quantitative numbers but no opportunity to gain insight in the model and assessment	Quantitative methods to assess circularity in the early design phase and that suits the level of information per phase Possibility to calculate the circularity assessment within the company Circularity assessment in early design phase based on BIM-model to reduce manual input Adjustment of the weight factors between material circularity index and disassembly index Include Environmental Cost Indicator for more comprehensive assessment	Not the intention to have organisation specific circularity database, but to make use of national database (NMD/NIBE) Change in design workflow is necessary because circularity assessment is performed once the design is almost finished, while involvement earlier on is preferred
Decision support framework (content)	Trade-off tool that supports and verify the circularity ambitions in initial design phase (qualitative) Quantitative way of including circularity with assessment of module D in LCA Implementation of business intelligence tools for decision-making is upcoming	Support tools are developed out of personal interest, but important that tool is a must-have to a certain problem Linking/connection of material list/quantities with corresponding item from circularity database (differentiation in product and material codes) Clustering of elements with same properties Lack of expertise in other area which complicates understanding of each other (BIM vs. sustainability)	Insight in comparison of circularity aspects of alternatives to better substantiate decision making Variant comparison on different abstraction level, so also variants within one design Insight in the whole project instead of specific objects of a project Visualises the possible impact of design changes in the tool, and not in the Revit model	It is not necessary to have 100% reliability of the tool, but is important that it is an improvement of current work procedure
Interface (communication)	Standardised format for dashboards in Power BI Power BI proves to be easily applicable in the organisation with good user-interface	Clear visuals of circular hotspots and comparison of alternatives is lacking Standardisation model input requirements from other departments Dashboards only provide information, but eventually you want data to become controlling and steering	Easily applicable for end-users – low technical skills required Logical and structured way of dashboard layout, without information overload Pop-ups of circularity aspects that trigger users into action Interactive to engage with end-user and to steer data-driven decisions Dynamic visualisations to gain deeper level of understanding to improve trade-offs and discussions	Communicate with and involve end-users during development of dashboard
Running environment (documentation)	Data Lakehouse to extract and store data (in development) Data architecture to link 3D-model with external databases and software	Operational speed, importing huge BIM-models gives delay Standardisation of data storage and data processing	Interoperable with other applications and software in current application environment Scalable for future projects Security: who has access, change management	Current Data Lakehouse and application environment of BAM out of scope for research Do not use multiple tools within an organisation with the same function

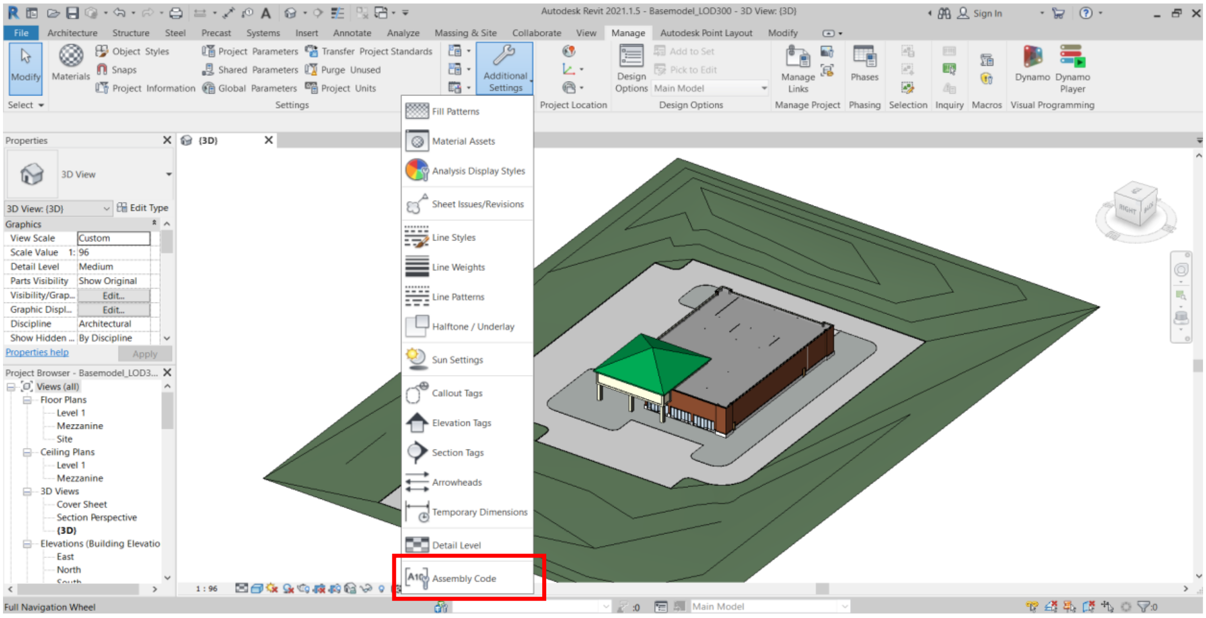
Appendix D: Framework design

Data collection

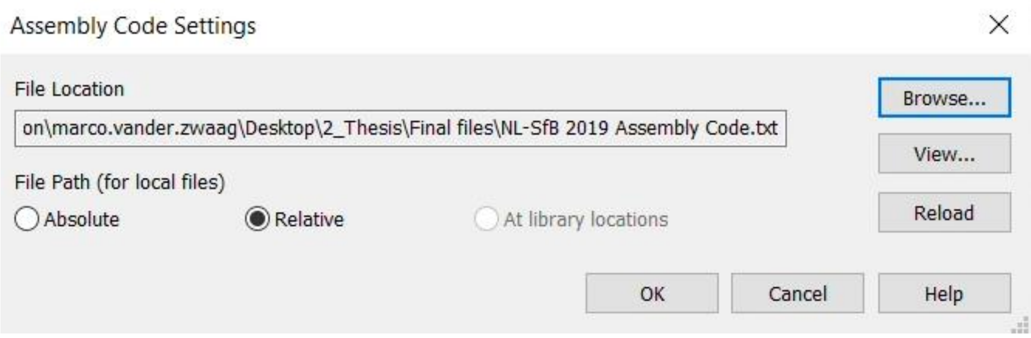
Assembly code

The procedure to load a specific assembly code file to use the assembly code parameter as type parameter for model elements is as follow. Note, the NL-SfB classification file can be found in the additional folder of data for this thesis. These files can be placed in a shared area on the network of the organisation.

1. Autodesk Revit → Manage tab → Settings panel → Additional Settings drop-down → Assembly Code



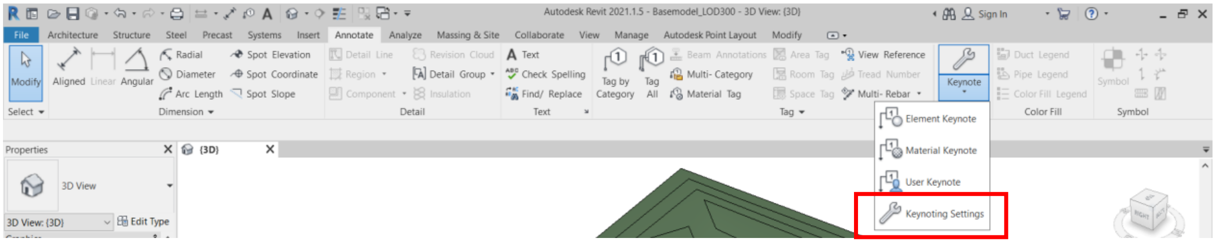
2. Browse and load NL-SfB classification text file



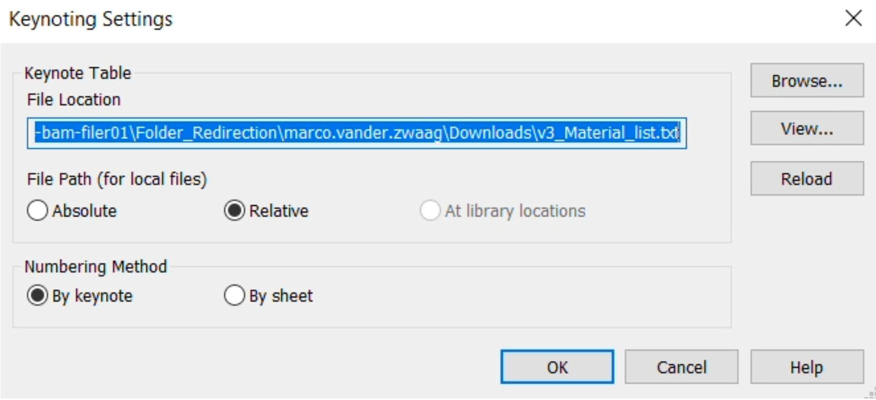
NAA.K.T material classification

The procedure to load the Revit keynote for material classification is similar as the Assembly code. Attention, the keynote text file is constructed and exported in Python in the analytical layer. The path location is the same as the folder to which the Python exports the data in the database. So, depends on the setup of the database.

1. Autodesk Revit > Annotate tab > Tag panel > Keynote drop-down > Keynote Settings



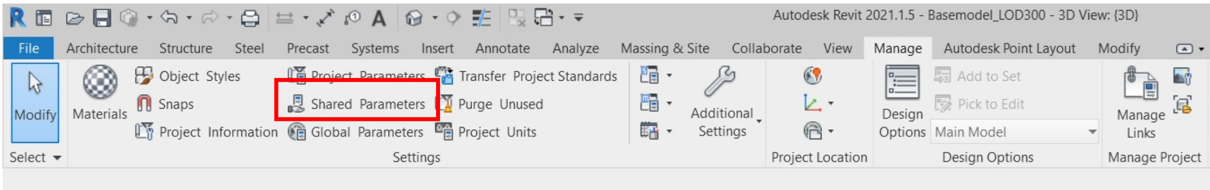
2. Browse and import keynote text file from the database



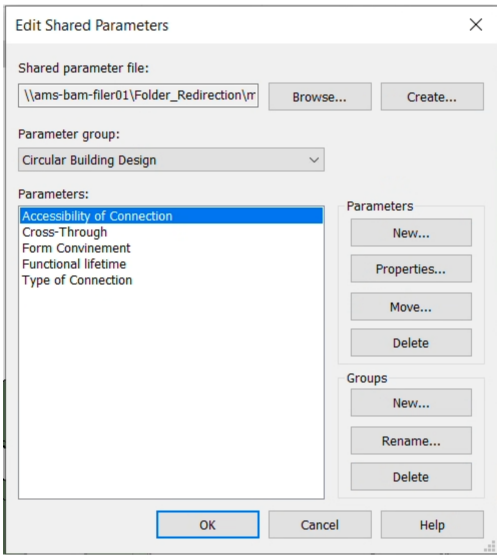
Disassembly parameters

The disassembly parameters are set up in a shared parameter file, so it can be accessed from multiple projects. The shared parameter file is a definition of a container for information of the defined disassembly parameters. The shared parameter file can also be found in the folder of additional data for this research.

1. Autodesk Revit > Manage tab > Settings panel > Shared Parameters



2. Add and import the shared parameters in the Revit project



Data extraction

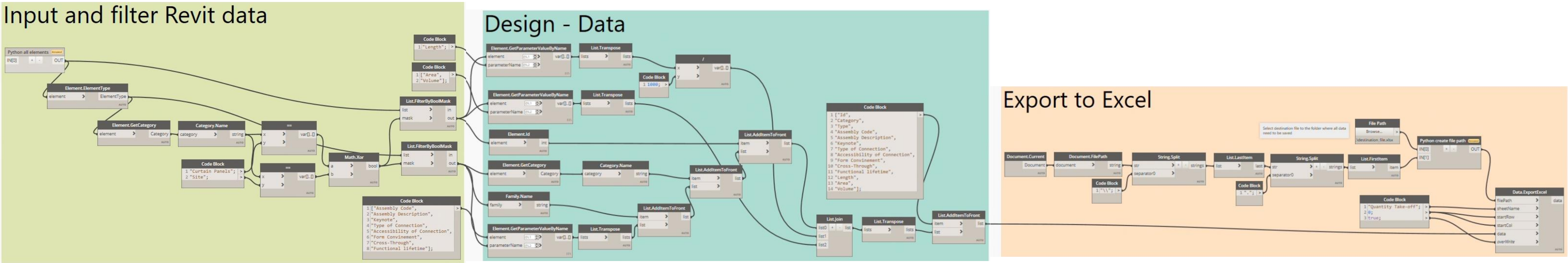
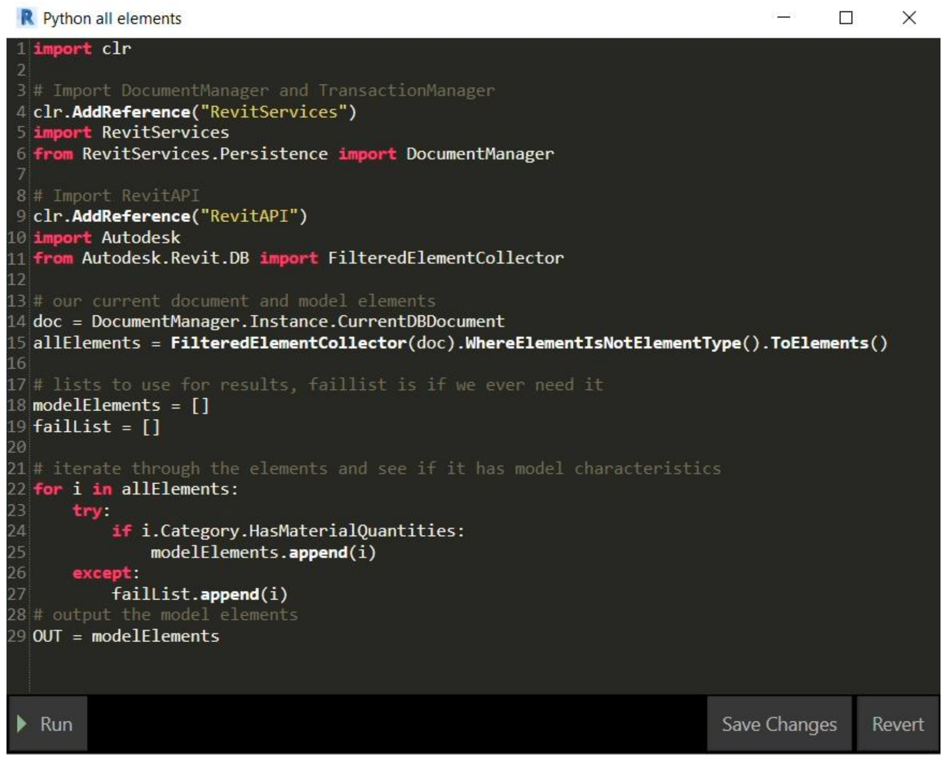
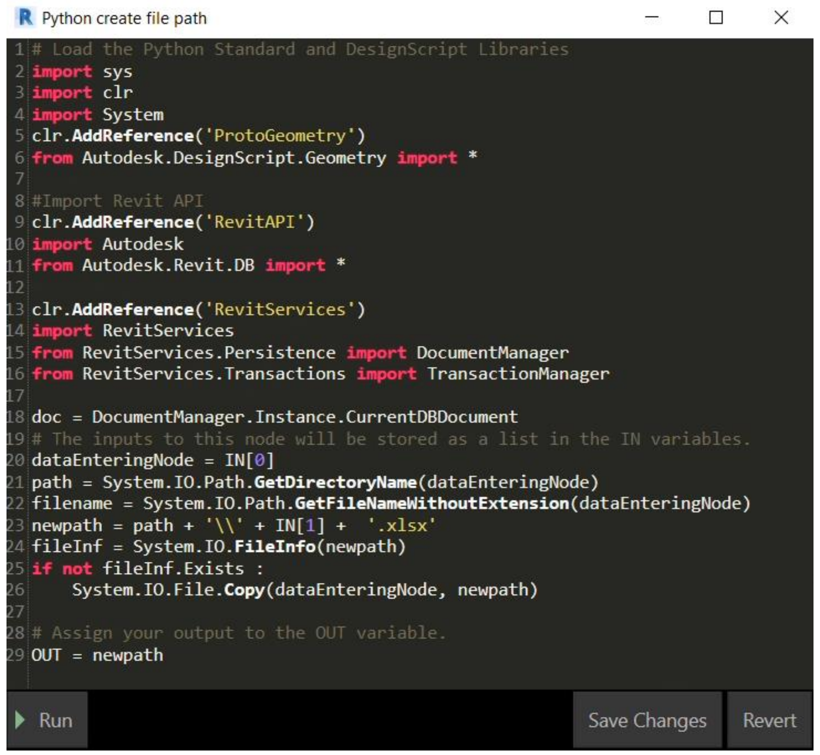


Figure 3: Data extraction script - Dynamo




```python
import clr

# Import DocumentManager and TransactionManager
clr.AddReference("RevitServices")
import RevitServices
from RevitServices.Persistence import DocumentManager

# Import RevitAPI
clr.AddReference("RevitAPI")
import Autodesk
from Autodesk.Revit.DB import FilteredElementCollector

# our current document and model elements
doc = DocumentManager.Instance.CurrentDBDocument
allElements = FilteredElementCollector(doc).WhereElementIsNotElementType().ToElements()

# lists to use for results, faillist is if we ever need it
modelElements = []
failList = []

# iterate through the elements and see if it has model characteristics
for i in allElements:
    try:
        if i.Category.HasMaterialQuantities:
            modelElements.append(i)
    except:
        failList.append(i)
# output the model elements
OUT = modelElements
```




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

#Import Revit API
clr.AddReference('RevitAPI')
import Autodesk
from Autodesk.Revit.DB import *

clr.AddReference('RevitServices')
import RevitServices
from RevitServices.Persistence import DocumentManager
from RevitServices.Transactions import TransactionManager

doc = DocumentManager.Instance.CurrentDBDocument
# The inputs to this node will be stored as a list in the IN variables.
dataEnteringNode = IN[0]
path = System.IO.Path.GetDirectoryName(dataEnteringNode)
filename = System.IO.Path.GetFileNameWithoutExtension(dataEnteringNode)
newpath = path + '\\' + IN[1] +  '.xlsx'
fileInf = System.IO.FileInfo(newpath)
if not fileInf.Exists :
    System.IO.File.Copy(dataEnteringNode, newpath)

# Assign your output to the OUT variable.
OUT = newpath
```

Figure 4: Python nodes Dynamo

Data processing

Automation of Python scripts

The run the Python scripts periodically or at fixed moments, Windows Task Scheduler is used. This can be done for the Python script to translate the material database to a Revit keynote and for the data processing script. The procedure to set this up is as follow:

1. Safe the Python scripts as a Python file (.py)
2. Create a Batch file to run the Python script
    - Safe a notepad with a file name and the “bat” extension

```
#location of Python3
call C:\Users\marco.vander.zwaag\Anaconda3\condabin\activate.bat

#location of Python script
cd "C:\Users\marco.vander.zwaag\Docuements\Thesis BAM\Submission
\Decision-support framework"

#Python file
python Python_data_processing.py

pause
```

Figure 5: Batch file to run Python script

3. Schedule the Python script in Windows Task Scheduler
    - Open Windows Task Scheduler
    - Create Basic Task
    - Create trigger when to execute
    - Action: start a program
    - Browse to the batch file that runs the Python script

Creating Revit material textfile

The goal of this Python script is to transpose the material database to a Revit keynote file. In this way, all the materials can be assigned as a material classification parameter in Revit with a drop-down menu.

In [1]:
```
import pandas as pd
import numpy as np
```

Import data

Import material database and convert NAA.K.T classification to unique element NAA.K.T. classification by creating a suffix for all duplicate material classifications.

In [2]:
```
database = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv
```

In [3]:
```
options = ['Product', 'Element']
data = database[database['Producttype'].isin(options)]
```

In [4]:
```
uniq = np.unique(data['NAA.K.T'])

for i in uniq:
    count = 0
    base = i
    for row in data.itertuples():
        if data.at[row.Index, 'NAA.K.T'] == base:
            data.at[row.Index, 'NAA.K.T'] = base + '_' + str(count)
            count = count + 1
```

Create textfile for material list in Revit

Create a text file which can be linked as keynote in Revit. The setup is in layers in order to create the drop-down feature.|

Layer 1: lowest layer of the text file with all the individual material classifications

n [12]:
```
data.loc[data['Phase'] == 'Schematic', 'Placeholder'] = '0_' + data.loc[data['Phase
data.loc[data['Phase'] == 'Developed', 'Placeholder'] = '1_' + data.loc[data['Phase
```

In [6]:
```
file1 = data[['NAA.K.T', 'Product', 'Placeholder']]
```

Layer 2: the intermediate layer to categorise all the individual products based on the name and characteristcs/application

In [7]:
```
uniq_ph = np.unique(file1['Placeholder'])
data_txt = []

for i in uniq_ph:
    data_txt.insert(0, {'NAA.K.T':i, 'Product':'','Placeholder':"_".join(i.split("_

file2 = pd.DataFrame(data_txt)
```

Layer 3: the highest layer to categorise all the products based on the design phase

In [8]:
```
uniq_ph2 = np.unique(file2['Placeholder'])
data_txt2 = []

for i in uniq_ph2:
    if i[0] == '1':
        data_txt2.insert(0, {'NAA.K.T':i, 'Product':'','Placeholder':'Developed de
    else:
        data_txt2.insert(0, {'NAA.K.T':i, 'Product':'','Placeholder':'Schematic de

data_txt2.insert(0, {'NAA.K.T':'Developed design', 'Product':'','Placeholder':''})
data_txt2.insert(0, {'NAA.K.T':'Schematic design', 'Product':'','Placeholder':''})

file3 = pd.DataFrame(data_txt2)
```

In [9]:
```
txtfile = pd.concat([file3, file2, file1])
```

Export the data

In [10]:
```
txtfile.to_csv('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv/Document
```

Example of the txtfile. This is the correct format for a Revit keynote file which creates a drop-down window with the material list.

In [11]:
```
txtfile
```

Out[11]:

	NAA.K.T	Product	Placeholder
0	Schematic design		
1	Developed design		
2	1_steenachtig		Developed design
3	1_metaal		Developed design
4	1_hout		Developed design
...	...	...	...
32	hout_zachthout_generiek_0	Europees zachthout; massief, gelamineerd; db [...	1_hout_zachthout
33	glas_helder_element_1	Prefabricated window element [inside]	1_glas_helder
36	beton_generiek_ihw_0	In situ betonvloer, 20% puingranualaat; incl. ...	1_beton_generiek
37	hout_hardhout_generiek_0	Dak elementen, houten ribben, steenwol, spaanp...	1_hout_hardhout
38	metaal_staal_element_3	Systeemwand met driedubbele rogipsplaat en ste...	1_metaal_staal

67 rows × 3 columns

Python data processing

The goal of this Python script is to proces the data in the database. Thereby, the different datasets will be merged and cleaned. Also, the Building circularity assessment calculations are performed.

In [1]:
```
import pandas as pd
import numpy as np
import os
import fnmatch
```

Import material and Revit data from database

Import material data, rename columns, and create subsets for the element and corresponding subproduct data

In [2]:
```
database = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv
database = database.rename(columns = {'MKI':'MKI_unit','CO2':'kgCO2_unit','Materia
```

In [3]:
```
options = ['Product', 'Element']
data = database[database['Producttype'].isin(options)]
subdata = database[database['Producttype'].isin(['Subproduct'])]
```

Create unique material classification codes for all products: NAA.K.T. classification

In [4]:
```
uniq = np.unique(data['NAA.K.T'])

for i in uniq:
    count = 0
    base = i
    for row in data.itertuples():
        if data.at[row.Index, 'NAA.K.T'] == base:
            data.at[row.Index, 'NAA.K.T'] = base + '_' + str(count)
            count = count + 1
```

Import the Revit data (Excel-files extracted with Dynamo). The script automatically searches for all Revit data files in the folders.

In [5]:
```
#Locate all Revit files in the folder where Revit data is exported
directory_path = 'C:\\Users\\marco.vander.zwaag\\OneDrive - Royal BAM Group nv\\Do
folder = os.listdir(directory_path)
filenames = fnmatch.filter(folder, '*.xlsx')
```

In [6]:
```
revitdata = {}
for i in range(len(filenames)):
    file = os.path.join(directory_path, filenames[i])
    df = pd.read_excel(file, sheet_name='Quantity Take-off')
    df['filename'] = filenames[i]
    revitdata[i] = df

revit = pd.concat(revitdata, ignore_index=True)
revit = revit.rename(columns = {'Keynote':'NAA.K.T','Length':'Length_m', 'Area':'A
```

Import additional tables Creating a table with the parameters and scores of the disassembly index according to the BCImeasurement method of Alba Concepts.

In [7]:
```
AC = {'Code':['AC1','AC2','AC3','AC4','AC5'], 'AC_score':[1.0,0.8,0.6,0.4,0.1]}
TC = {'Code':['TC1','TC2','TC3','TC4','TC5'], 'TC_score':[1.0,0.8,0.6,0.2,0.1]}
CT = {'Code':['CT1','CT2','CT3'], 'CT_score':[1.0,0.4,0.1]}
FC = {'Code':['FC1','FC2','FC3'], 'FC_score':[1.0,0.4,0.1]}
df_TC = pd.DataFrame(TC)
df_AC = pd.DataFrame(AC)
df_CT = pd.DataFrame(CT)
df_FC = pd.DataFrame(FC)
```

Import data to specify the alternatives and corresponding Revit models, and the disassembly range for the indicative BCI assessment.

In [8]:
```
LOD = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv/Docu
disassembly_range = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM
LOD['filename'] = LOD['Sourcefile'].str.rsplit('.', 1, expand=True).rename(lambda x
```

Clean data

Data cleaning by creating unique element data, and identifying and fixing the incomplete datasets. Creating a unique Id for all data by adding the alternative number to the Revit element Id.

In [9]:
```
revit['filename'] = revit['filename'].str.rstrip('.xlsx')
```

In [10]:
```
revit["Id"] = revit["Id"].astype(str) + '_' + revit['filename']
```

Identifying missing data in the two datasets: material data and revit data

In [11]:
```
data[data.isnull().any(axis=1)].head()
```

Out[11]:

	Asssembly Code	Phase	Category NMD	Producttype	Element code	Product	NAA.K.
0	00.01.1	Schematic	3	Product	NaN	Betonmortel C20/25 XC2, 0% puingranulaat, CEM ...	beton_generiek_ntb_
1	00.01.2	Schematic	3	Product	NaN	Betonmortel C30/37 XC2, 0% puingranulaat, CEM ...	beton_generiek_ntb_
2	00.01.3	Schematic	3	Product	NaN	Baksteen [Kilogram basisprofiel bij levensduur...	steenachtig_generiek_ntb_
3	00.01.4	Schematic	3	Product	NaN	Europees naaldhout; duurzame bosbouw [Kilogram...	hout_generiek_ntb_
4	00.01.5	Schematic	3	Product	NaN	Europees loofhout; duurzame bosbouw [Kilogram ...	hout_generiek_ntb_

Not all material has element codes because only this is only assigned to elements and subproducts, so this is not a problem. Furthermore, the material data has no value for elements because elements are a group of subproducts. Therefore, the missing element values can be determined based on aggregations of subproducts.

Filling in the missing values for elements regarding technical lifetime, total weight, MKI and CO2 per unit. The weight, MKI, and CO2 is based on underlying subproducts of the elements. For the technical lifetime, the BCI measurement method suggest to choose the minimum lifetime of the individual subproducts

In [12]:

```
#Fill in the technical lifetime, total weight, MKI, and CO2 per unit for all the e
elements = np.unique(subdata['Element code'])

for i in elements:
    data.loc[data['Element code'] == i, 'Weight_kg/unit'] = sum(subdata.loc[subdat
    data.loc[data['Element code'] == i, 'MKI_unit'] = sum(subdata.loc[subdata['Ele
    data.loc[data['Element code'] == i, 'kgCO2_unit'] = sum(subdata.loc[subdata['E
    data.loc[data['Element code'] == i, 'Tech_lifetime_yr'] = min(subdata.loc[subd
```

For the revit data, it is expected that there is missing data in the columns of Length, area, or volume because not all elements have both parameters. More important is the missing data that does not have an assembly code or NAA.K.T. classification. This data could not be fixed in Python, because it is project dependent and the BIM specialist has to upgrade the model. Moreover, the data will not be removed because it is important in the next stage (reporting in Power BI) to visualise the data quality.

In [13]:
```
revit.info()
```

```
<class 'pandas.core.frame.DataFrame'>
RangeIndex: 408 entries, 0 to 407
Data columns (total 15 columns):
 #   Column                       Non-Null Count  Dtype  
---  ------                       --------------  -----  
 0   Id                           408 non-null    object 
 1   Category                     408 non-null    object 
 2   Type                         408 non-null    object 
 3   Assembly Code                400 non-null    float64
 4   Assembly Description         400 non-null    object 
 5   NAA.K.T                      400 non-null    object 
 6   Type of Connection           306 non-null    object 
 7   Accessibility of Connection  306 non-null    object 
 8   Form Convinement             306 non-null    object 
 9   Cross-Through                306 non-null    object 
 10  Functional lifetime          408 non-null    int64  
 11  Length_m                     327 non-null    float64
 12  Area_m2                      318 non-null    float64
 13  Volume_m3                    389 non-null    float64
 14  filename                     408 non-null    object 
dtypes: float64(4), int64(1), object(10)
memory usage: 47.9+ KB
```

In [14]:
```
revit[revit['NAA.K.T'].isnull()].head()
```

Out[14]:

	Id	Category	Type	Assembly Code	Assembly Description	NAA.K.T	Type of Connection
114	191870_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
115	191872_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
116	191880_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
117	191882_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
271	191870_Basemodel_LOD300_2	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN

Merging data

Replacing the disassembly factor codes in the Revit data with corresponding values from the disassembly dataframe

In [15]:
```
data_frames = [df_AC, df_TC, df_CT, df_FC]
```

```
columns = ['Accessibility of Connection', 'Type of Connection', 'Cross-Through', 'I

for i in range(4):
    revit = pd.merge(revit, data_frames[i], left_on= columns[i], right_on='Code', I

revit.drop(['Code_y','Code_x'], inplace=True, axis=1)
```

```
C:\Users\marco.vander.zwaag\AppData\Local\Temp\ipykernel_16576\654153352.py:5: Fut
ureWarning: Passing 'suffixes' which cause duplicate columns {'Code_x'} in the res
ult is deprecated and will raise a MergeError in a future version.
  revit = pd.merge(revit, data_frames[i], left_on= columns[i], right_on='Code', ho
w='left', suffixes=('_x', '_y'))
```

Merge the revit quantity take-off datasets and material data

In [16]:

```
#Merge circular data on revit data
merged = pd.merge(revit, data, left_on='NAA.K.T', right_on='NAA.K.T', how='left')
```

Merge the data with corresponding LOD

In [17]:

```
merged = pd.merge(merged, LOD, left_on='filename', right_on='filename', how='left')
```

Building circularity assessment (calculations)

Data processing of the merged database. The existing database is extended with calculated columns necessary for the circularity assessment.

It is determined what the value is of the corresponding unit of the products. For example, in the material database is the unit for hollow core slabs in m2, so the function calls the area as quantitiy as unit measurement

In [18]:

```
def unit_measure(df):
    if df['Unit'] == 'm':
        return df['Length_m']
    elif df['Unit'] == 'm3':
        return df['Volume_m3']
    elif df['Unit'] == 'm2':
        return df['Area_m2']
    elif df['Unit'] == 'unit':
        return 1

merged['unit_measure'] = merged.apply(unit_measure, axis = 1)
merged['Weight_kg'] = round(merged['unit_measure'] * merged['Weight_kg/unit'], 1)
merged['MKI_eu'] = round(merged['unit_measure'] * merged['MKI_unit'], 1)
merged['CO2_kg'] = round(merged['unit_measure'] * merged['kgCO2_unit'], 1)
```

Calculations of the parameters for BCI. The LFI for elements is determined with the MKI of subproducts as weightfactor.

In [19]:

```
#Calculate FX value per product
merged['FX'] = 0.9 / (merged['Tech_lifetime_yr'] / merged['Functional lifetime'])
```

In [20]:

```
#Calculate LFI value per product and per element
merged.loc[pd.isna(merged['Element code']), 'LFI_p'] = (merged['Virgin_material_%']

for i in elements:
    df = subdata[subdata['Element code'] == i]
    df = df.reset_index()
```

```
    MKI_numerator = 0
    MKI_denominator = 0
    for index, row in df.iterrows():
        MKI_numerator = MKI_numerator + row['MKI_unit']*row['Virgin_material_%'] +
        MKI_denominator = MKI_denominator + row['MKI_unit']
    merged.loc[merged['Element code'] == i, 'LFI_e'] = 1/MKI_denominator * MKI_num
```

In [21]:
```
#Calculate MCI value per product and element
merged['MCI_p'] = np.maximum(0, (1.0 - merged['LFI_p'] * merged['FX']))
merged['MCI_e'] = np.maximum(0, (1.0 - merged['LFI_e'] * merged['FX']))
```

In [22]:
```
#Calculate Disassembly Index per product and element
merged['LIs'] = 2 / (1/merged['AC_score'] + 1/merged['TC_score'])
merged['LIc'] = 2 / (1/merged['CT_score'] + 1/merged['FC_score'])
merged['DisassemblyIndex'] = 2 / (1/merged['LIc'] + 1/merged['LIs'])
```

In [23]:
```
#Calculate PCI
merged['PCI'] = np.sqrt(merged['MCI_p'] * merged['DisassemblyIndex'])
```

In [24]:
```
#Calculate ECI
merged['ECI'] = np.sqrt(merged['MCI_e'] * merged['DisassemblyIndex'])
```

Calculations of the origin of materials and future scenario in kg per product.

In [25]:
```
#Transform the origin of materials and future scenario from % to kg per product
transform = ['Virgin_material_%','Reused_material_%','Recycled_material_%','Biobas
transform_kg = ['Virgin_material_kg','Reused_material_kg','Recycled_material_kg','
transform_unit = ['Virgin_material_unit','Reused_material_unit','Recycled_material_

for i in elements:
    df = subdata[subdata['Element code'] == i]
    df = df.reset_index()
    for j in range(len(transform)):
        kg_material = 0
        weight_total = 0
        for index, row in df.iterrows():
            kg_material = kg_material + (row['Weight_kg/unit']*row[transform[j]])/
            merged.loc[merged['Element code'] == i, transform_unit[j]] = kg_materi
```

In [26]:
```
for i in range(len(transform)):
    merged.loc[pd.isna(merged['Element code']) ,transform_kg[i]] = round(merged[tr
    merged.loc[merged['Element code'] > 0 ,transform_kg[i]] = round(merged[transfo
```

Drop unnecessary columns

In [27]:
```
merged = merged.drop(['Virgin_material_unit','Reused_material_unit','Recycled_mate
```

Disassembly range

Calculations for the indicative BCI assessment which uses a range of disassembly scenarios to estimate the expected circularity in the schematic design phase.

In [28]:
```
data_range = merged.loc[merged['LOD'] == 'LOD200', ['Id','MKI_eu', 'LOD', 'MCI_p']
```

In [29]:
```
data_range = pd.merge(data_range, disassembly_range, left_on='LOD', right_on='LOD'
```

In [30]:
```
data_range['PCI_min'] = np.sqrt(data_range['MCI_p'] * data_range['Min. DI'])
```

```
data_range['PCI_low'] = np.sqrt(data_range['MCI_p'] * data_range['Low DI'])
data_range['PCI_medium'] = np.sqrt(data_range['MCI_p'] * data_range['Medium DI'])
data_range['PCI_high'] = np.sqrt(data_range['MCI_p'] * data_range['High DI'])
data_range['PCI_max'] = np.sqrt(data_range['MCI_p'] * data_range['Max. DI'])
```

In [31]:
```
data_range = data_range.drop(['LOD', 'Min. DI', 'Low DI', 'Medium DI', 'High DI',
```

Export of the data

Export the data in Excel in the database. The processed data is captured in the main data sheet and the data ranges for the indicative BCI in the data range sheet.

In [32]:
```
output = 'C:\\Users\\marco.vander.zwaag\\OneDrive - Royal BAM Group nv\\Documents\'

with pd.ExcelWriter(output) as writer:
    merged.to_excel(writer, sheet_name="main_data", index=False, header=True)
    data_range.to_excel(writer, sheet_name="data_range", index=False, header=True)
```

Appendix E: Verification assessment & validation workshop

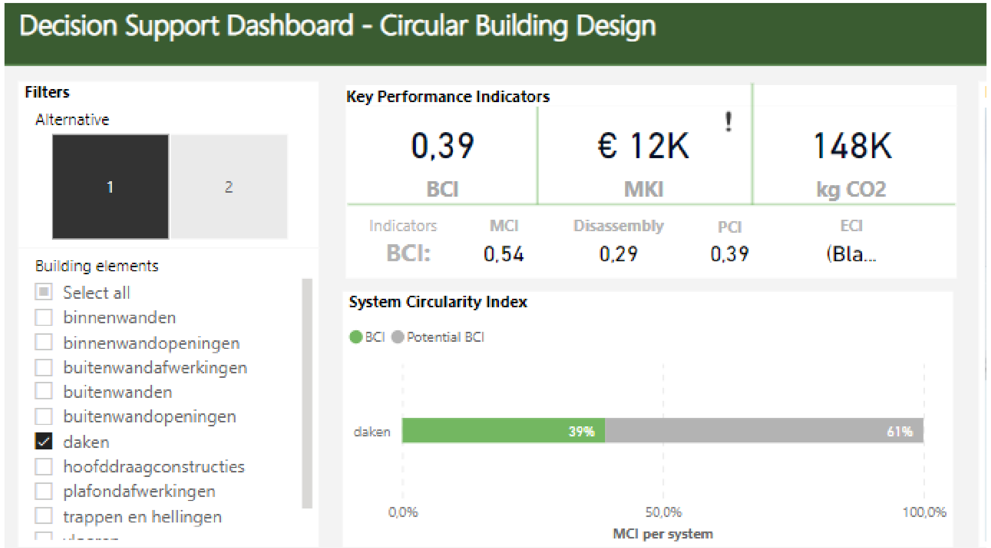
Verification of BCI assessment with hand calculations

Roof alternative 1 consists of two types of elements, a canopy roof and flat roof. The element properties of the roof are presented in the table below. The figure next to this presents the results according to the BCI assessment of the decision-support framework.

Table 6: Element properties

	Canopy roof	Flat roof
Product	Sandwich paneel trapeziumvormige, staal + EPS	Cellenbeton
Area	381.2 m^2	1163.9 m^2
MKI per m2	€3.13	€8.85
% virgin material	69%	100%
% landfill	2%	1%
% incineration	34%	2%
Technical lifetime	75 year	75 year
Functional lifetime	75 year	75 year
Accessibility of Connection	0.8	0.4
Type of Connection	0.8	0.1
Cross-Through	1	0.4
Form Convinement	0.4	1

Figure 5: Results BCI assessment



The hand calculations on the next page show the same results as the circular design dashboard. Therefore, it can be concluded that the data analytic operations in the decision-support framework are correct.

Element 1: canopy roof

Material Circularity Index:

$$F(X_{p1}) = \frac{0.9}{\frac{l_t}{l_w}} = \frac{0.9}{\frac{75}{75}} = 0.9$$

$$LFI_{p1} = \frac{v_p + l_p + i_p}{2} = \frac{0.69 + 0.02 + 0.34}{2} = 0.525$$

$$MCI_{p1} = \max\left(0, \left(1 - LFI_{p1} * F(X_{p1})\right)\right) = (1 - 0.525 * 0.9) = 0.5275$$

Disassembly Index:

$$DI_{con1} = \frac{2}{\frac{1}{FC_{p1}} + \frac{1}{CT_{p1}}} = \frac{2}{\frac{1}{0.4} + \frac{1}{1}} = 0.5714$$

$$DI_{cmp1} = \frac{2}{\frac{1}{TC_{p1}} + \frac{1}{AC_{p1}}} = \frac{2}{\frac{1}{0.8} + \frac{1}{0.8}} = 0.8$$

$$DI_{p1} = \frac{2}{\frac{1}{DI_{con1}} + \frac{1}{DI_{cmp1}}} = \frac{2}{\frac{1}{0.5714} + \frac{1}{0.8}} = 0.667$$

Product Circularity Index

$$PCI_{p1} = \sqrt{MCI_{p1} * DI_{p1}} = \sqrt{0.5275 * 0.667} = 0.593$$

$$MKI_{tot1} = €3.13 * 381.2\text{m}^2 = €1193.1$$

Element 2: flat roof

Material Circularity Index:

$$F(X_{p2}) = \frac{0.9}{\frac{l_t}{l_w}} = \frac{0.9}{\frac{75}{75}} = 0.9$$

$$LFI_{p2} = \frac{v_p + l_p + i_p}{2} = \frac{1 + 0.02 + 0.01}{2} = 0.515$$

$$MCI_{p2} = \max\left(0, \left(1 - LFI_{p2} * F(X_{p2})\right)\right) = (1 - 0.515 * 0.9) = 0.5365$$

Disassembly Index:

$$DI_{con2} = \frac{2}{\frac{1}{FC_{p2}} + \frac{1}{CT_{p2}}} = \frac{2}{\frac{1}{1} + \frac{1}{0.4}} = 0.5714$$

$$DI_{cmp2} = \frac{2}{\frac{1}{TC_{p2}} + \frac{1}{AC_{p2}}} = \frac{2}{\frac{1}{0.1} + \frac{1}{0.4}} = 0.16$$

$$DI_{p2} = \frac{2}{\frac{1}{DI_{con2}} + \frac{1}{DI_{cmp2}}} = \frac{2}{\frac{1}{0.5714} + \frac{1}{0.16}} = 0.25$$

Product Circularity Index

$$PCI_{p2} = \sqrt{MCI_{p2} * DI_{p2}} = \sqrt{0.5365 * 0.25} = 0.366$$

$$MKI_{tot2} = €9.95 * 1163.9\text{m}^2 = €10{,}417.0$$

Building Circularity Index:

$$BCI = \frac{1}{\sum_{i=1}^{n} MKI_n} * \sum_{i=1}^{n}\left(\left(MKI_p * PCI_p\right) + \sum_{i=1}^{p} MKI_p * ECI_e\right) = \frac{1}{1193.1 + 10417.0} * (1193.1 * 0.593 + 10417.0 * 0.336) = 0.39$$

Validation Workshop

Workshop plan:

Table 7: Workshop plan

Workshop: Circulair ontwerpen		
Workshop Datum: 30-09-22	**Doel workshop** Informeren deelnemers over circulair ontwerpen en validatie van circulariteit dashboard	**Deelnemers** - Duurzaamheid managers & specialisten - Ontwerpteam + ontwerpleider - Architecten
Opstelling ruimte: BAM Gouda zaal 6.56	**Op te roepen gedrag:** - Informeren, participeren en reflecteren over decision-support framework voor circulair bouwen - Bewustwording mogelijkheden BIM & Circulariteit	

Tijd	**Onderwerp-agendapunt**	**Wat moet dit punt opleveren?**	**Welk gedrag wordt van de deelnemers verwacht (+/-)?**	**Aanpak (werkvorm)/ door wie**	**Benodigdheden**
starttijd 13:00 (10 min)	Welkom en inleiding	Welkom, Doel van de bijeenkomst Voorstelronde	luisteren, commitment		Validatie formulier en pen uitdelen
13:10 (15 min)	Presentatie	Informatieoverdracht, overzicht PvE	Luisteren en vragen stellen	Powerpoint op groot scherm	Scherm, aansluiting eigen laptop, PowerPoint presentatie
13:25 (10 min)	Instructie Dashboard	Uitleg dashboard	Luisteren en vragen stellen	Power BI dashboard delen scherm	Power BI dashboard,
13:35 (5 min)	Opstarten dashboard bij deelnemers	Systeem starten & dashboard weergeven	Deelnemen op de link	Via een link openen.	Laptop deelnemers, Uitnodiging link voor dashboard
13:40 (5 min)	Pauze				

13:45 (20 min)	Simulatie van een case met bepaalde opdrachten	Gebruikservaring van de eindgebruikers	Participatie aan de case	Een casus: simulatie met opdrachten die betrekking hebben op circulair ontwerpen	PowerPoint met case beschrijving en vragen, laptop deelnemers + toegang dashboard
14:05 (15 min)	Validatie	Reflectie over de werking van het system, voldoet het aan de wensen van de gebruiker	Invullen score formulier. Fysiek op papier ter plaatse of nader hand digitaal	Feedback ronde over de casus en het dashboard	
14:20 (10 min)	Evaluatie workshop en tips proces begeleiding	Tips & tops	Actief meedoen, commitment	Rondje langs de deelnemers - Hoe was de workshop - Hoe was mijn rol - Tips en trucs Board met 4 kwadranten: - Wat ging goed, wat kan beter? - Inhoudelijk, proces begeleiding	Post-its, groot papier om kwadranten op te maken
Eindtijd 14:30	Einde				

Workshop: simulation scenarios

- Schematic design:
  The client informs the design team that they strive to a building circularity performance of 60% or higher. The client wants to know if this is achievable with the current design, and where circular measures could have to most impact to increase the circularity of the design. Thereby, the design team knows based on their expert judgement that the disassembly potential of this building is low. With this information, they are able to make an initial estimation based on the indicative BCI to determine if the circularity objective could be achieved. Besides that, with the information on the dashboard, they can determine the building elements with the highest impact by pointing out the elements with the highest environmental impact. They can conclude that circularity measures for this building element would potentially be most effective. Furthermore, they have been asked by the client what the possible future scenarios are for these building elements, so he gets an indication for the second lifecycle of materials in this design.
  - Questions:
    - Is a BCI score of 60% or higher a realistic objective for this design?
    - At which building element do the circularity measures have most impact thus are probably most effective?
    - What are the future scenarios for materials from this category of building elements?
- Detailed design:
  In the detailed design phase, the participant is going to perform a deeper analysis for two different roof alternatives. They have to determine which alternative is most circular, and also substantiate their decisions based on facts from the dashboard. Furthermore, they have to show the client which aspects of the design score lowest. They can visualise this based on the 3D model and highlight the worst building elements. Also, they were asked to inform the client how much of the exterior walls could be recycled or reused for future projects, and what kind of material this is.
  - Questions:
    - Which roof variant will be advised to the client, and substantiate why?
    - Show the client the building elements with a low circularity score (BCI < 40%)?
    - What type of material is the exterior wall built of, and how much is recyclable for future projects?
- Model Health:
  The dashboard shows that there are some issues with the data quality of alternative 2. The design team is asked to investigate the reliability of the data. First, they have to determine if the data is up-to-date and complete. Once they know if there is data missing or incorrect, they have to investigate which parameters are filled in invalid in the model. Moreover, with the use of the 3D model visualisation, they are able to show the building elements with invalid parameters, which could be useful as feedback for the BIM specialist to improve in the model.
  - Questions:
    - Is the data up-to-date and how much percentage is missing?
    - Which parameters were entered incorrectly by the BIM specialist and what are the associated building elements?