BIM-based framework for circularity and environmental impact assessment during the design stage

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by

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Summary

Introduction

The Linear Economy (LE) model is based on take-make-dispose, which exploits the natural resources for producing products and disposing these products to landfill or energy incineration at the end of the useful life of the products. The model is highly unsustainable due to its negative impact on the environment, such as greenhouse gas emissions causing climate change. The growing consumption rate and scarcity of resources, along with the adverse environmental effects, has called for a change in the current model. The Circular Economy (CE) in the built environment has gained attention due to the current unsustainable linear model. The CE model closes the loop of the LE model by considering waste obtained at the end of the useful life of the products as a resource. To assess the transition from LE to CE, there is a need to quantify the benefits and impacts of the strategies and principles applied to make the paradigm shift. 'Circularity Indicators or Metrics' can help measuring these benefits and impacts.

Problem Analysis

There are several indicators to measure the transition towards the CE in the built environment, but no consensus has been reached. Thus, a standardized methodology for measuring CE in the built environment is not yet streamlined. Based on previous literature, the design decisions during the preliminary stage of the design should consider circularity performance and environmental impact as key indicators. Traditionally, these assessments are performed at the end of the design stage, limiting their use for making design decisions. Also, the determination method (LCA assessment) does not include measurement of circularity principles. Hence, there is a need to develop a framework or a tool to perform the assessment during design stage. Making changes to the design at the end of the design process is time-consuming and expensive. In recent years, Building Information Modelling (BIM) has shown its potential in the construction industry. However, there is limited research on its effectiveness to enhance sustainability driven by CE.

Research Objective and Question

The objective of the research was divided into three parts: determine the necessary CE metrics related to product circularity performance and environmental impact during the design stage;

develop a framework and a tool to conduct assessment during design stage; and determine a method to support designers to make design decisions based on the assessment and project requirements. To meet the objective of the research, the research question is framed as follows:

"How can a BIM-based framework enable designers in the built environment to assess the material circularity and environmental impact of their design and make design decisions throughout the design stage?"

To answer the main research question, sub-research questions were formulated as follows:

1. What is the link between circular economy and sustainability? How can we apply the circular economy principles in the built environment?
2. (a) What are the necessary indicators for assessing circularity and environmental impact in the built environment?
   (b) What are the existing methods to perform the assessment?
3. (a) How can BIM support the design making process?
   (b) What are the current integration approaches and challenges between BIM and the assessment methods?
4. How to design a framework that integrates BIM and the circular economy assessment to facilitate circularity and environmental impact of building designs?
5. What are the implications for providing a BIM-based assessment framework for the designers in decision-making during the design phase?

Research Methodology

The study adopts the design-based research (DBR) approach to answer the research questions. The adopted approach aims to solve the identified problem by designing, developing, and implementing the solution in the real-world setting. A type of DBR approach is the double-diamond method which was adopted for the research. The method is divided into two main phases with four sub-phases. The four sub-phases in the model include discover, define, develop, and deliver. 'Discover' is the first sub-phase where a literature review was carried out to identify the CE metrics and the possible BIM-integration approaches. In the 'define' sub-phase, a selection of the metrics necessary to be assessed during the design stage and the existing BIM- integration challenges and possible solutions were defined. The third and fourth sub-phases focused on developing a BIM integration framework and implementing the framework by developing a tool and validating the tool through a case study and workshop.

Literature Review

A literature review was carried out in two parts, namely, to identify the indicators necessary for assessing circularity and environmental impact of products in the built environment and to identify the BIM integrated assessment approaches and their challenges. The former was identified by performing literature study on CE and sustainability concepts, circularity building principles and life-cycle assessment and its allocation methods. Based on this around 16 indicators (table 1) were identified as the necessary indicators for assessing circularity and environmental impact assessment. The latter was obtained by performing literature study on

BIM and the current BIM based LCA, LCC and circularity assessments. Based on the literature study, three main BIM-integrated approaches: a) Performing assessment in external software tools, b) Linking BIM model with external database containing the required information and performing assessment and c) Creating parameters to store assessment information within BIM environment to perform the assessment were identified.

Circularity Indicators	Environmental Impact Indicators	Environmental Impact Indicators
Quantity of input materials: virgin, recycled, reused materials	Climate change -Global Warming (GWP)	Human toxicity (HTP)
Quantity of output materials: recyclable, reusable, recoverable, landfill	Ozone layer depletion (ODP)	Freshwater aquatic ecotoxicity (FAETP)
Disassemby potential	Acidification (AP)	Marine aquatic ecotoxicity (MAETP)
Recycling efficiency	Eutrophication (EP)	Terrestrial ecotoxicity (TETP)
Utility	Photochemical oxidation (POCP)	Depletion of fossil fuels and abiotic raw materials (ADP)

Table 1: Indicators for measuring CE

Building Circularity and Environmental Impact Assessment Framework

A framework was proposed to conduct the assessment during the design stage as shown in figure 2. Autodesk Revit was identified as one of the most widely used BIM design tool. The software was used as the design tool for the research. A prototype in Revit using Dynamo, a visual programming platform, was developed for conducting the assessment. A multi-criteria decision making (MCDM) using TOPSIS method was performed on the obtained assessment results for the products to make a trade-off between circularity performance and environmental impact and obtain the best alternative product for the design. A case study and workshop validate the proposed framework. The criteria for evaluation include, the applicability of the framework, accuracy of the developed tool for the assessment, usability of the tool and its implication to make a balanced design choice and its contribution towards sustainability and circularity consciousness.

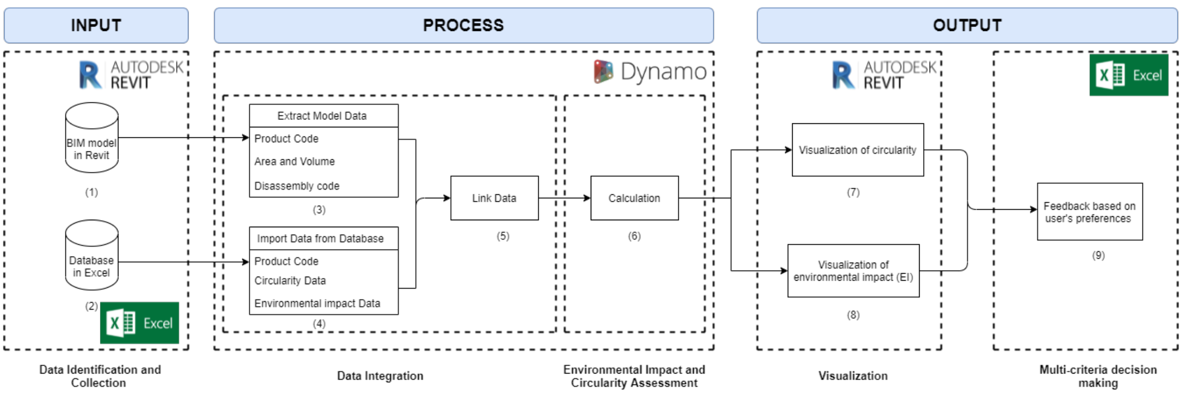

Figure 2: Proposed Framework

Findings

Based on the implementation of the developed tool and workshop, it was observed that tool can be applied to real-time projects and had the ability to support designers to make sound decisions based on circularity and sustainability criteria. It had 95 - 100 % accuracy when compared to other commercial tools. During the workshop it was perceived that over the period of time the developed tool improves the designer's consciousness on circularity and sustainability.

The major challenge in application of the BIM-based assessment framework is the database. Existing database needs to be restructured to a standard format to include circularity data apart from the environmental impact data. The proposed framework is applicable if the selected products are available in the database. Hence, for easier implementation by construction companies the database should include variety of products (sustainable, bio-based, traditional and secondary) available in the market. This will help the companies select products from the database and perform accurate assessments. The other issue identified is the diversity in the environmental impact assessment methods. Each country have their specific calculation rules and impact categories making products manufactured in different countries incomparable.

Limitations of the research

Some of the major limitations of the research include:

1. The research does not consider socio-economic aspect of sustainability.
2. The research was only applied in Revit.
3. The environmental impact calculation is specific to the Netherlands.
4. The developed tool is validated from limited user's point of view and the benefits and drawbacks are based on limited responses.

Scope for future research

Based on the finding and limitations of the research, recommendations are proposed for future research. Due to the limited scope of research, various factors such as the socio-economic factors are not considered in the current research. Hence, it is recommended to include Life cycle costing(LCC) and Social Life cycle assessment (S-LCA) along with Life cycle assessment (LCA)and Circularity indicators. For researchers analysing the BIM based environmental impact assessment, it is recommended to assess the products based on element category (wall, column, door, floor etc.) and compare the change in results to the existing method and its impact on decision-making process. It is also recommended to explore other MCDM methods and compare the impact on the select of alternative product/design variant and integrate the most beneficial method with BIM. The research did not evaluate the influence of the framework on time, hence it is recommended to determine whether the proposed framework saves or consumes more time. The limitation of the research is that the tool is developed for Revit users, however, in future the framework should be applied for other design tools such as SketchUp and Rhino.

Similary, certain recommendations are provided for future implementation of the framework in practice. The time constraint for the research limited the development of the database and it is recommended to explore the benefits of developing the database in SQL. It is also recommended to determine a standard method to obtain product information from suppliers to obtain reliable assessment results.

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Preface

This master thesis report is the outcome of the seven-month graduation research conducted at the Delft University of Technology (TUD) in collaboration with Witteveen+Bos. The research marks the final stop to my two years of Master's journey. My passion for a sustainable world made me learn about the Circular Economy concept in the Built Environment. During my Master's at TU Delft, I amplified my knowledge on the concept of Circular Economy, focusing on circular design strategies, circular procurement, and key performance indicators (KPIs) for sustainability. All these factors cultivated an interest in carrying out my graduation thesis in the field of Circular Economy. While looking for a research topic, Circularity Indicators grabbed my focus. The knowledge on BIM and its potential abilities made me combine Circularity Indicator assessment with BIM, thus framing the research topic as a "BIM-based framework for circularity and environmental impact assessment during the design stage".

Looking back throughout the journey of my Master and mainly MSc. thesis, I would like to take a moment to express my gratitude to people for their enormous support and assistance. First of all, I would like to thank **Rajiv Hotchandani** and **Janet van de Watering** from Witteveen+Bos for allowing me to conduct this research. A special thanks to Janet van de Watering who agreed to supervise me and took time from her busy schedule to support and direct me through the process. Further, I would like to extend my gratitude to other colleagues from Witteveen+Bos for actively participating in the workshop for validating my research.

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In addition, I would like to thank my parents for their constant support, immense belief and scarifices for me. Most importantly, I could not have completed this thesis without the support of my friends here at Delft and back in India, who encouraged me at each and every step and brought in happy distractions to drive my mind outside of my research. Finally, I thank God for being a good listener and hearing my prayers to complete my Master's journey.

I hope you enjoy reading the thesis report!

Nireeksha Shivakumar August 27, 2021

Chapter 1

Introduction

This chapter presents the context of the research. The research focused on assessing the circular economy CE within the design process. The chapter starts with the theoretical background on the CE concept. An explanation on the research context is made followed by problem analysis and knowledge gap.

1-1 Theoretical Background

The growing population along with a changing consumption rate has arisen the use of natural resources and their associated environmental impacts [4]. The United Nations Environment Program (UNEP) has stated that the world population will grow to 9 billion people by 2050, thereby increasing the rate of resource consumption greater than their generation rate. The construction sector contributes to this critical challenge by consuming resources and energy required during different stages, which includes the production of materials, construction, operation and maintenance, and demolition. In the European Union, the construction industry is the largest consumer of materials and energy [5]. The building sector accounts for about 50% of material consumption and 40% of total energy [4, 6]. Apart from being the largest consumer of resources and energy, the built environment is responsible for contributing 40% of all greenhouse gas emission and around 25% of waste generation [4, 7].

The Built Environment is crucial for global economic development. The current global economic system is based on the linear model of 'take-make-use-dispose' as mentioned in figure 1-1. 'Take' refers to exploiting raw materials from the earth's crust, 'make' represents production, and 'dispose' is portrayed by waste incineration plants and landfills [4, 7]. The current model is unsustainable as 79Gt of raw materials are being consumed globally and more than 40% of Greenhouse Gas (GHG) emissions are due to the consumption of raw materials and their related activities [8]. This growing consumption and scarcity of resources have called for a transition from a linear economy LE to a circular economy CE [5].

Contrary to the linear economy model, the circular economy model adopts a more sustainable approach of 'take-make-use-reuse and recycle' [9]. The CE concept is viewed as a promising approach that can operate at the macro-vel (nation, cities, and regions), meso-level (industrial parks) and micro-level (companies, products and consumer) to achieve sustainable development, and thus overcome the environmental, economic, and social problems of the current linear economic system [5, 10]. The CE model closes the loop of the linear economy by considering waste as a resource, thereby reducing dependencies on global resource markets [1, 11]. Thus, the CE model can reduce the current issues arising from the construction sector. Implementing CE principles is seen as a movement towards meeting sustainable development goals [12]. To tackle the current issue of climate change, the Paris Agreement was adopted in

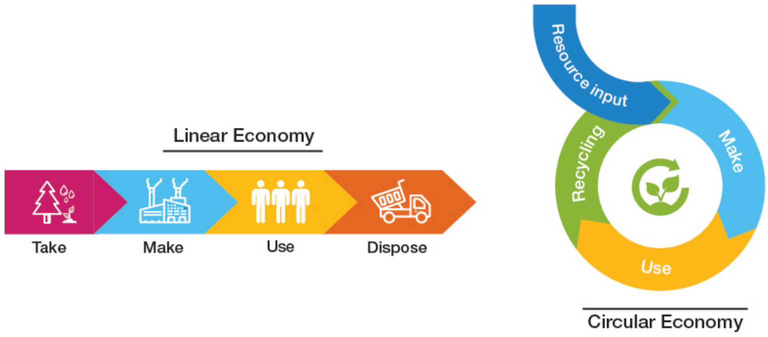


Figure 1-1: Linear Economy and Circular Economy

2015. The Paris Agreement is one of the major international agreements under the UNFCCC (United Nations Framework Convention on Climate Change) to limit global warming to well below 2 degree Celsius (preferably 1.5 degree Celsius), compared to pre-industrial levels [13]. The agreement is signed by 196 countries including Netherlands and every country has set their target and is working towards achieving the goal. Recognizing the benefits that the CE can make towards creating a resilient and sustainable future, the Netherlands has set targets for the country that 49% of carbon dioxide emission should be decreased by 2030 in comparison to 1990 and by 95% in 2050 and consumption of primary raw materials should be less than 50% in 2030 and the country should be fully circular by 2050 [14].

1-2 Research Context

To be able to make this paradigm shift, various strategies have been proposed. The concepts behind these strategies mainly include constructing demountable structures, maximizing the service life, reducing energy, and R-strategies (primarily reduce, reuse, and recycle), and so on [15]. The benefits and impact due to these strategies are often measured using circularity indicators [16]. Thus, circularity monitoring frameworks and indicator tools are used to provide an indication of how much the principle of the circular economy is applied to a product. Many indicators are exploited to quantify and evaluate the circularity level by academic researchers and industry practitioners; however, they are still at an early development stage [16].

The most widely used indicator to measure the level of circularity in the built environment is R-framework (primarily reduce, reuse, and recycle). Melanie et al. (2019)[17] recognizes that not only circularity needs to be assessed but also the environmental implications of circularity of materials. This was justified by an example that the energy demand for recycling can drastically increase at a high rate and might offset the environmental gains obtained from recovering the secondary materials. The author concluded that monitoring both material efficiency and environmental impacts as well as defining targets is a key for the successful implementation of the CE in the built environment. To assess the environmental benefit and impact of implementing CE strategies, several researchers in the past have recommended using life cycle thinking (LCT) approach to evaluate the scenarios [18, 19, 20, 21]. Life-cycle assessment (LCA) is the most widely adopted methodology that operationalizes LCT. LCA is used to evaluate the environmental impacts of buildings during the entire life cycle [6, 22]. It is the most widely accepted assessment tool in the building industry to evaluate sustainability concepts. Currently, initiatives have been taken to measure the benefits and impact of CE strategies such as recyclability and reusability in terms of environmental impact in LCA. However, they do not indicate the quantity of products or materials that can be reused or recycled at the end-of-life. Lonca et al. (2018) [23] recognized the need to achieve a sustainable circular economy and recommended selecting assessment methods accordingly. Recently, the platform CB '23 recognized that the increasing desires concerning the information about the degree of circularity in the construction sector and existing methods are insufficient to meet the needs. They developed a method that covers the objectives of construction: (a)protect material stock, (b) protect the environment, and (c) protect the existing value [15]. However, the method is still in infancy and cannot be used for circularity assessment [15].

To facilitate these assessments various studies suggest integrating Building Information Modelling (BIM) with assessment tools. Previous studies show that during the design stage, BIM can be used to identify material flows at different life-cycle stages and LCA can be used to assess the environmental performance at different stages for adopting the circular economy principle [24]. Additionally, BIM based circularity assessment has also been attempted in the past [25]. For instance, the Madaster platform offers to import 3D BIM models into their database to perform circularity assessment [5]. Di Biccari et al. (2019)[25] developed a BIM-based framework in Revit to visualize circularity and life cycle costing of the building design in 3D form.

1-3 Problem Analysis

In the construction industry, during the early design phase decision-makers such as architects and design engineers, whose expertise does not lie within the CE approach, need indicator tools to support them in exploiting the value of the CE approach especially in selecting the design alternatives and materials [25, 15]. Saidani et al (2017)[26] recognized the need to develop frameworks, methods, and tools to assess the circularity potential of a product during the design phase and recommended this as a first step to efficiently improve the circularity practices. However, a standard method and tool is still lacking in the construction industry to perform such assessments during the design stage.

Attempts have been made to integrate BIM and LCA, yet there is a lack of interoperability and supporting technologies and frameworks. The most widely used method for the assessments is exporting BoQ from BIM to perform assessments. Such a process is complex, time-consuming and reduces efficiency as it is prone to human error because of numerous manual steps. In the construction industry, the assessments are performed at the end when all the necessary information is available, but it is too late for decision-making [27]. Usually, these assessments are not carried out by designers and need to depend on experts which is again time-consuming. Thus, there is a need to provide an assessment platform for the designers to perform the assessment of their design based on CE and sustainability principle with BIM software tools. Performing the assessment during the design phase will enable the designers to use the assessment score of the design in the decision-making process. This way, the designers can focus on the conceptual design and at the same time track the potential effects of materials and design decisions.

1-4 Knowledge Gap

Based on the literature study and problem analysis, the knowledge gap consists of two parts. Firstly, the indicators for measuring transition towards CE. Previous literature emphasized in attaining sustainable circular economy, however there is no standardized method to achieve the objective due to several indicators and assessment methods. Organizations are responsible for choosing their measurement method. Due to the various indicators and assessment methods, it is necessary to determine the critical indicators for making design decision and their measurement method. Secondly, the integration of assessments with BIM has proven to be promising. However, there is a lack of interoperability to integrate the assessment with BIM. Thus, this research focuses on reviewing circularity and environmental impact indicators and assessment methods and how they can be linked with BIM during the design process for making design decision throughout the design stage.

Chapter 2

Research Objective

This chapter introduces the objective of the research and research questions and describes the scope of the research in the following paragraphs. Figure 2-1 represents the structural outline of the research.

2-1 Research objective

The objective of the research is to propose a BIM-based framework to enable assessment of environmental impact and circularity performance of products in a building to support the designers for making design decisions based on the assessment during the design phase. The research aims to develop an automated assessment and multi-criteria decision-making tool to provide feedback to the designers through visualization. A research question is formed to achieve the objective of the research and answer the problem identified in Chapter 1. The research question for the research is as follows:

How can a BIM-based framework enable designers in the built environment to assess the material circularity and environmental impact of their design and make design decisions throughout the design stage?

To answer the main question, the following sub-questions are formed (SQ's):

1. What is the link between circular economy and sustainability? How can we apply the Circular Economy principles in the Built environment?
2. (a) What are the necessary indicators for assessing circularity performance and environmental impact in the built environment?
   (b) What are the existing methods to perform the assessment?
3. (a) How can BIM support the design-making process?
   (b) What are the current integration approaches and challenges between BIM and circularity economy assessment?

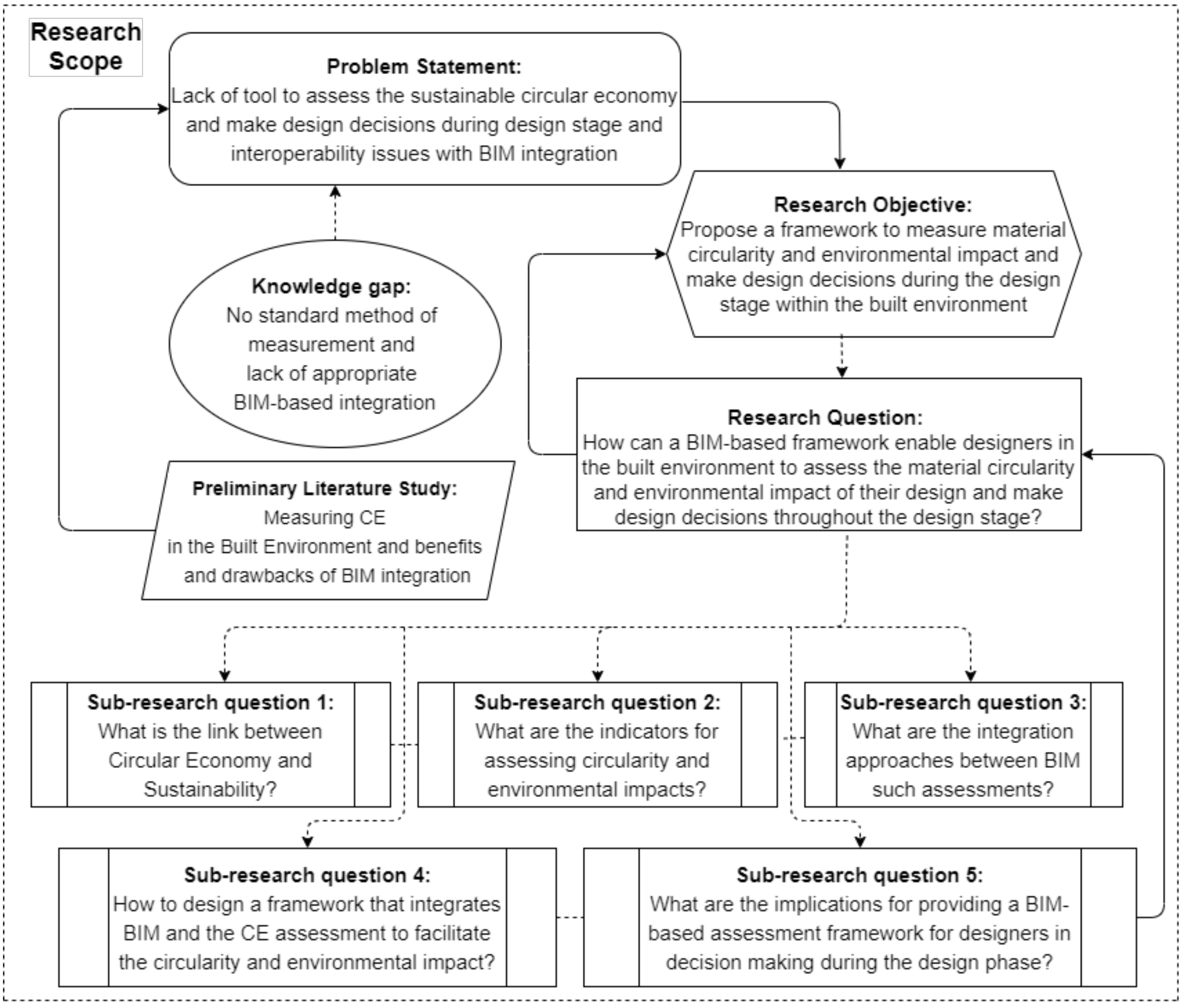


Figure 2-1: Research process

4. How to design a framework that integrates BIM and the circular economy assessment to facilitate the circularity and environmental impact of building designs?

5. What are the implications for providing a BIM-based assessment framework for the designers in decision-making during the design phase?

The first sub-question (SQ1) is necessary to understand the concept of the Circular Economy in the Built environment and sustainability. This sub-question helps to understand the relation between sustainability and the CE and the importance of adopting CE principles. The second sub-question (SQ2) is necessary to identify the indicators used to measure circularity performance and environmental impact. The second part of the sub-question focuses on the methods and tools to perform assessment and comprehend the tools used in the Dutch construction industry. The third sub-question (SQ3) helps to understand the role of BIM in the construction industry and review possible integration methods for the assessment with BIM. The three sub-questions lay the theoretical foundation for the study. The fourth sub-question (SQ4) focuses on developing a model that integrates BIM and circular economy assessment. This is an important step for the prototype development and to answer the main research question. The fifth sub-question (SQ5) focuses on the consequences due to the implementation of the framework. The information gained by answering all the sub-questions will help to answer the main research question.

2-2 Research Scope

The concept of Circular Economy in the construction industry is vast and given the time limit for completing the master thesis, it was found necessary to narrow down the scope of the research.

1. The area of research is thus narrowed down to measuring the circular economy in the built environment during the design stage. The reason is that the design process offers room for changing and adapting the building characteristics and process. In the later stages, the cost for changes increases, while the impact of these changes reduces [28]. Therefore, the design process is when circular design methods should be introduced and measured. It makes this phase the most impactful phase in the life-cycle of a building [29].

2. The research focuses on the building sector in the Dutch construction industry. The building sector has a major environmental impact and has the largest improvement potential to reduce the impact by implementing circular practices. The concept of CE in the built environment is still considered to be in the early stage of development and its implementation in the industry requires further research [30].

3. There are several indicators that can be used to measure the CE. However, only the material efficiency and environmental aspects of the CE concept is considered in the study. To measure the progress towards CE, it is necessary to understand the link between environmental and circularity performance to prevent burden shifting [8, 31]. It is not necessary that applying circular strategies reduces environmental impact. Hence, it is important to develop a framework that can measure the degree of circularity of a system and how the system's circularity affects the environmental impact, and thus prevent a biased method of measuring circularity [32]. Additionally, the assessment methods explored are the ones commonly used in the Netherlands.

4. The research considers the perspective of designers and sustainability consultants only. The designers are the people involved in the design of buildings and include architects, structural designers and BIM modellers. The advisors can be circularity and sustainability consultants who perform assessment of the building design. It is possible to determine and minimize 70% of the environmental impact during the design phase [8]. When circularity and sustainable strategies are assessed together, it creates a conflict during decision-making on selecting the most suitable practice and lets the decision-makers choose most optimal designs that can balance both. Thus, the research aims to support designers in assessing their designs in terms of CE aspects and increase their knowledge and awareness about circularity, material efficiency, and environmental impact that their designs carry.

Chapter 3

Research Methodology

The chapter presents the research approach and the research method adopted in the study. The data gathering methods for the research are discussed. Lastly, the thesis model is presented.

3-1 Research Approach

Design-based research (DBR) developed by Brown and Collins in 1992 was adopted for the study. Wang et al. (2005)[33] defined DBR as a methodology aimed to improve educational practices through iterative design, development, analysis, and implementation, based on collaboration among practitioners and researchers in the real-world setting to produce design principles and theories. The research approach is characterized as a mixed-method research approach as it addresses the problem by bridging the gap between theoretical research and practice in educational research [34]. Therefore, the design-based approach is chosen as it is in line with the identified problem, objectives, and questions of the research.

Design-based research exhibits the following characteristics:1) addresses the complex problem and solves the real-world problems by extending existing theories and refining design principles 2) grounded in both theory and real-world settings 3) no separation between developing a theory and testing the theory, rather the two are intertwined 4) conducted in an interactive, iterative and flexible way 5) lead to shareable theories that can be communicated between practitioners and educational researchers [35, 36, 37, 33]. These characteristics can be seen in this research. The research fulfils the first characteristics as it results in the creation of an artifact that addresses a complex problem that is related to the solution of a relevant industry problem. The industry problem will be addressed by providing the designers with a framework and a tool to perform an assessment of design alternatives based on environmental impact and circularity level and the artifact developed will act as proof of concept contributing to the theoretical research, thus supporting the second characteristics. The third and fourth characteristics can be seen as the research involves the development of a tool that is tested and validated in a reflective way. As per the fifth characteristics, the design process will be documented to see the outcome of the design and how it impacts the existing principles and what types of changes have been made. This will also help other designers and researchers interested in the same field to further examine the results in relation to their context and needs.

3-2 Research Method

As mentioned earlier, a design-based research approach is adopted to answer the research questions. The design approach consists of various methods. The double-diamond method is a type of design process model developed by the British Design Council in 2005 [38] is used as the research method for the study. The method was adapted from the divergence-convergence model [39]. The method consists of four phases with two main stages. The two diamonds form the stages of the model. The four phases include discover, define, develop, and deliver. The two diamonds represent the process of exploring a problem widely (divergent thinking) and then narrowing the action or solution (convergent thinking) to solve the problem.

The double-diamond method used in the research is visually shown in figure 3-1. The first diamond includes the 'discover' and 'define' phase. The 'discover' phases mark the start of the project. This phase focuses on problem identification, data gathering and defining the expected result. This phase helps in understanding the problem from a broader perspective. The 'define' represents convergent thinking by focusing on interpretation and alignment of objectives to be achieved. In the second phase, the challenges and possible solution direction to the problem will be defined.

The second diamond includes the develop and deliver phase. The 'develop' phase marks the development period where design-led solutions are developed. In this stage, the possible solutions will be explored further to design and develop a solution to the problem. The 'deliver' phase forms the final quarter of the developed solution which will be tested, validated, and proposed to the market. The main activity in this phase is evaluating the solution. After this stage, the result of the research is obtained. The design process is an iterative process.

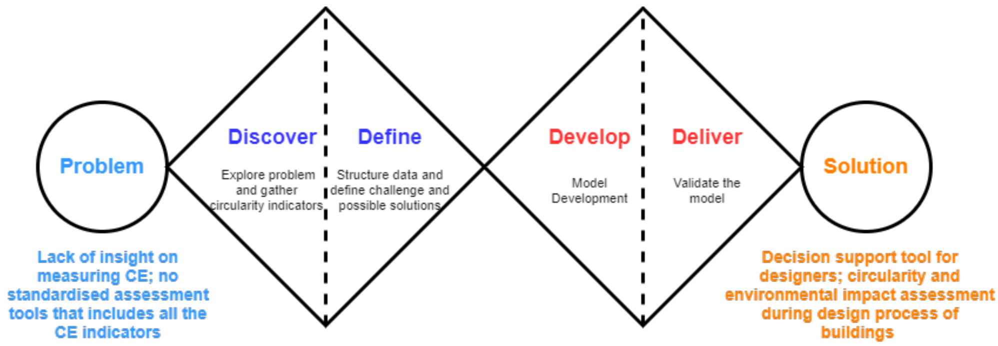


Figure 3-1: Double-diamond method (own illustration)

This means that during the process to solve the underlying problem, it is possible to learn or uncover something more about the issue which can make the process resume to understand the problem based on the newly gained knowledge and determine the potential solution. The other reason for the iterative process is that with the innovation of new digital technologies it is always possible to improve the provided solution for the given problem. The double-diamond method is most suitable for the research as the first diamond of the process helps in clearly understanding the problems faced by the users and then exploring the potential solutions within the solution space. The second diamond will help in developing and implementing the developed solution and check if it works for the users. The process can be repeated with the changing technologies to improve the proposed solution or arrive at a new solution.

3-3 Data Gathering

The data gathered for the research include desk research, semi-structured interviews, and case studies. For each phase in the research, different methods are used to gather the data. Figure 3-2 is a visual representation of the research phases, their content and the means of data gathering. In the following sections, each phase in the research model is elaborated and how the data is gathered is explained.

3-3-1 Stage 1 - Discover and Define

As mentioned earlier, the first stage consists of two phases, discover, and define. In the first phase, the problem of the research is explored. In design-based research, insights into theoretical and practical problems are necessary. Hence, an extensive literature study is carried out to get an insight into the theoretical problem and exploratory interview is conducted to get an insight into the practical problem. The sources for desk research mainly include recent scientific papers, journals, technical reports, conference papers, and research studies. The

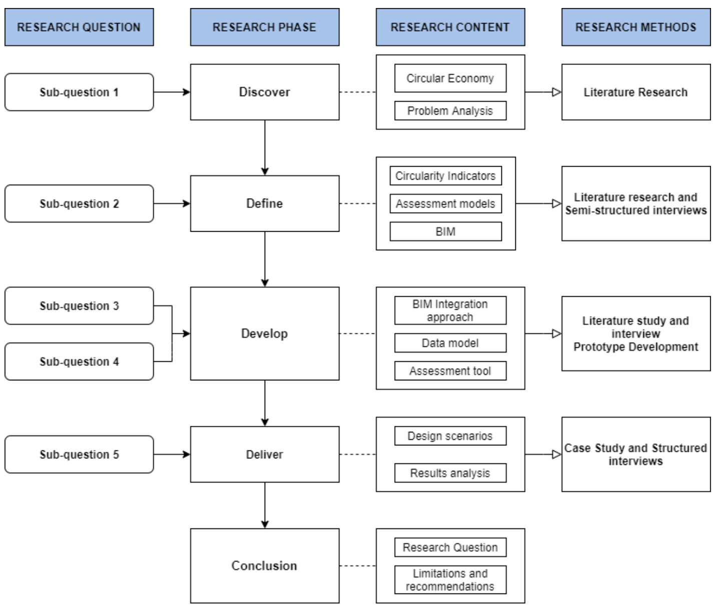


Figure 3-2: Research model

second phase focuses on defining the direction to the solution by narrowing the focus of the research. This phase answers the first and second sub-questions (SQ1 and SQ2) by defining the term the 'Circular Economy' and its relationship with sustainability, material circularity and environmental impacts indicators, the current state-of-the-art in terms of existing measurement methods and tools for material circularity and environmental impact and the commonly used tools and methods in practice by industry experts. The data gathering model adopted is desk research.

3-3-2 Stage 2 - Develop and Deliver

The second stage includes 'develop' and 'deliver'. In this stage, the framework is developed and validated. In the develop phase, a mixture of literature study and semi-structured interview to understand the possibility and challenges for integrating such assessment in BIM is performed. A mixture of desk research and interviews are necessary to identify and compare the practical observations with the literature. By semi-structured interviews, the interoperability of BIM with assessment tools in the industry is studied. The interviews are focused on specialists whose expertise lies in the field of digital innovation and BIM. This will answer the third sub-research question (SQ3). By this time, all the necessary information for the development is gathered. A data model is designed and developed, thus answering the fourth sub-question (SQ4). The last phase of the model is focused on validating the developed model by testing the model using a case study and conducting workshop for expert feedback. With this step, the fifth sub-question (SQ5) is answered.

Chapter 4

Literature Study

The chapter introduces the concept of Circular Economy in the Built environment to develop a better knowledge on the concepts related to research. As the circular economy is seen as a means for sustainable development, the link between the circularity indicators and the dimension of sustainability is presented first. Later the literature focuses on the CE concept and the indicators required for the assessment. Finally, the existing state-of-art for BIM-based integration for the assessment is reviewed. The chapter concludes by answering the first three sub-questions.

4-1 Sustainability in the built environment

The concept of sustainability was introduced in 1972 during the United Nations (UN) conference. In the construction industry, the concept is seen as a 'triple-bottom-line' to balance the three-dimension: environment, economy, and society. The American Society of Civil Engineers (ASCE) defines sustainability as a set of economic, environmental, and social conditions through which society can improve and maintain the quality of life indefinitely, without degrading the quality, quantity, or availability of natural, economic, and social resources. Sustainable development can be defined as: *"A development to meet the needs of the present generation without compromising on future generations to meet their own needs"* [40].

4-2 Sustainability and Circular Economy

The application of CE concept is seen as a movement to meet the goals of sustainability and hence, plays a significant role in relation to sustainable development [41, 42, 43, 12]. The relationship between CE and sustainability has been explored by various research, where Geissendoerfer et al. (2017) [44] and Suarez et al. (2019)[43] concluded that a close correlation exists between CE and sustainability and CE is beneficial to achieve sustainable development. Thus, sustainability and CE are interrelated concepts that are gaining attention to meet the current concerns on climate change and resource depletion. Several efforts have been made to interrelate CE and sustainability, and the researchers have established that the three dimensions of sustainability can be achieved by implementing the CE model [42]. This is emphasized by Kirchherr et al. (2017)[45] after analyzing 114 definitions on CE reported that 46% of the definitions emphasize economic prosperity as the goal of CE, around 38% on environmental quality, while 18-20% of the definitions emphasized social equity and around 13% out 114 definitions considered all the three dimensions of sustainability.

4-3 The Circular Economy

4-3-1 The circular economy concept

The circular economy concept was first mentioned in the 1970s but has gained increasing attention from the government, academic and industry practitioners over the past few years on various aspects such as CE definitions, circular business models, origin and principle, policy, the link between CE and sustainability [16, 45, 30, 40, 2].

In 2013, the Ellen MacArthur Foundation (EMF) developed the conceptual model known as the butterfly model (figure 4-1), to explain that material cycles are closed in a circular economy model. According to the model, there is nothing called waste in a fully circular economy as all the residual flow can be used to make new products, thus closing the loop. The EMF defined the circular economy as "*an industrial economy that is restorative and regenerative by design and aims to retain the value and quality of products, components and materials at their highest level at all times, distinguishing between biological and technical cycles.*" The model consists of three parts: the middle part is the economic model; the left side forms the biological cycle while the right side is the technical cycle. The center of the model is the start point where renewable energy is first extracted from nature and then the products are manufactured and sold in the market. At the end of the product's life, instead of disposing it as a waste, the model tries to circle the product to the economic model through the biological or technical cycle. The technical materials are used while the biological materials are thought of as consumable. In the biological cycle, products at end-of-life with non-toxic materials regenerate into the biosphere whereas, in the technical cycle, the products, components or materials are restored into the market at their highest value and quality by repairing, refurbishing, remanufacturing, or recycling [7].

Similarly, various scholars have tried to define and explain the concept of the circular economy as per their understanding. However, until now there is no commonly accepted definition for the concept of circular economy [46]. Kirchherr et al. (2017) [45] analyzed 114 definitions on the circular economy and defined CE as "*an economic system that is based on business models which replace the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes, thus operating at the micro-level (products, companies, consumers), meso level (eco-industrial parks) and macro-level (city, region, nation and beyond), with the aim to accomplish sustainable development, which implies creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations*" [40, 45]. However, the author reported that the definition used for the studies should relate to the analysis of the study. Hence, for this research, the CE definition by Geissendoerfer et al., (2017) [44] is adopted: "*Circular Economy*

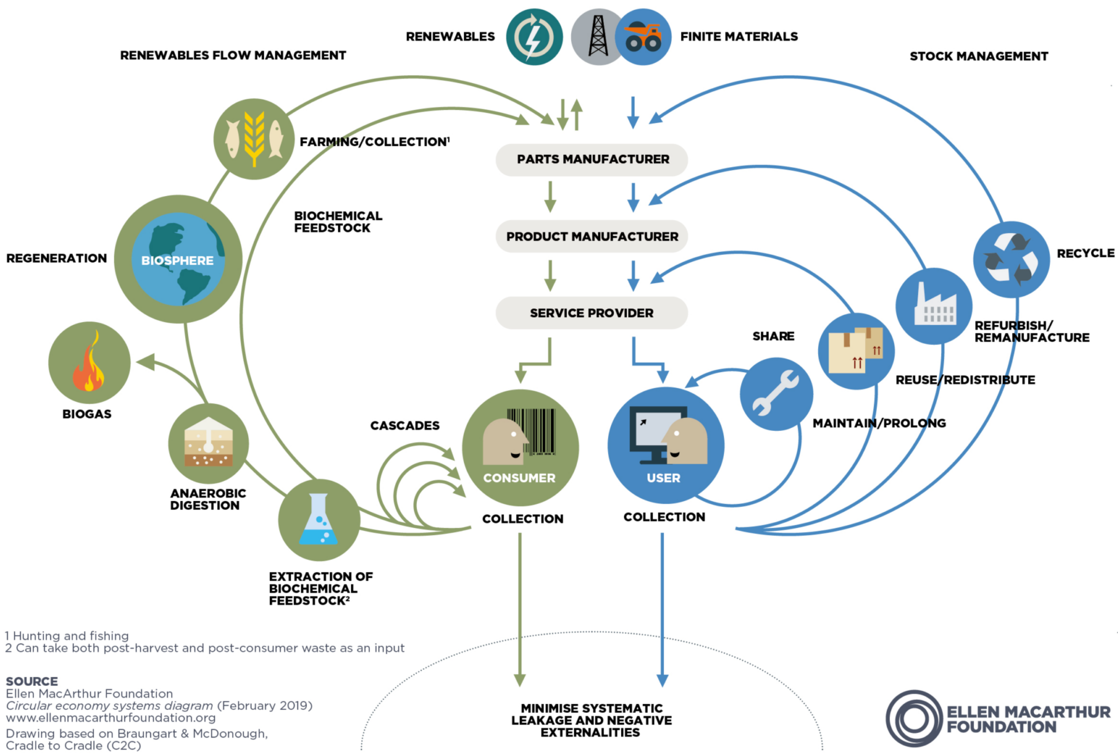


Figure 4-1: Butterfly model of CE [1]

is a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops". The definition used for the study focuses on the environmental parameters of sustainability, leaving economic and social aspects out of scope.

4-3-2 Design principles

The Ellen MacArthur Foundation (EMF) proposed that the CE rests on three core principles (EMF, 2015a). The first principle is to 'preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows.' The principle focuses on selecting resources wisely, such as choosing better-performing and renewable resources. The principle also emphasizes that CE increases the natural capital by encouraging nutrients flow within the system and creates conditions for regeneration. The second principle aims to '*optimize resource yields by circulating components, products, and materials at their highest utility at all times in both technical and biological cycles*'. This means that it is encouraged to design (e.g., remanufacture, refurbish, reuse etc.) components, products, and materials in such a way that they can be re-circulated to stay in the system for maximum time in the technical cycles. It is also said that the inner loops (e.g., reuse, rather than recycling) should be done wherever possible. In the biological cycles, the biological nutrients from the products, components, and materials are encouraged to re-enter the biosphere for decomposition so that they can be used as a feed-stock for a new cycle. The third principle aims at '*fostering a* *system's effectiveness by designing out negative externalities*'. The principle means to reduce the damage to the systems and managing externalities such as water, air, noise pollution and toxic emissions from substances.

4-3-3 Circular buildings

The CE in the built environment can operate at the macro-level, the meso-level, and the micro-level. The macro-level focuses on cities, and regions, the meso-level focuses on buildings whereas the micro-level focuses on products, components, and materials (figure 4-2). The application of CE at the building level is known as 'Circular Buildings' or 'Circularity in buildings. In order to achieve circular buildings, it is necessary to focus on the micro-level (products and components). Thus, the research focuses on circularity at meso-level by achieving circular products and components. Similar to the definition of the concept of CE, few researchers have attempted to define the circular economy in terms of the circular building. However, there is no commonly accepted definition for circular buildings. To arrive at a definition for the study, existing definitions for circular buildings have been gathered from literature and analyzed to formulate a definition for the study (Appendix A).

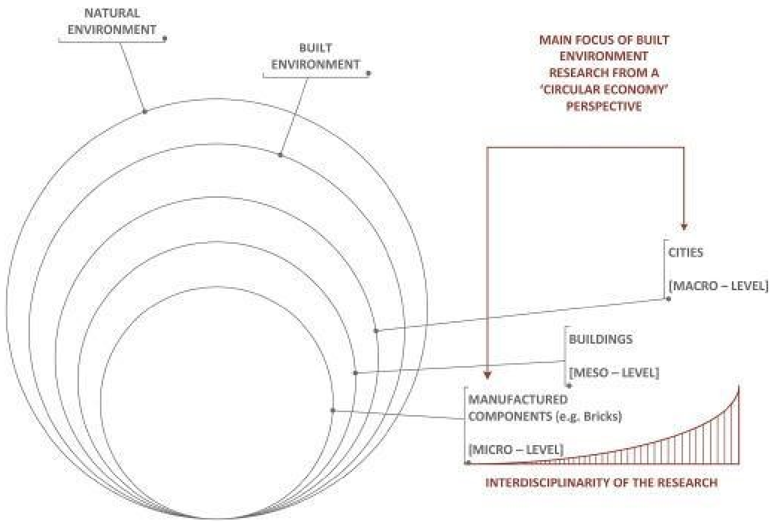


Figure 4-2: Framing of built environment research on CE [2]

After analyzing the commonly used definitions, the definition from Circle Economy is more appropriate for the study as the definition considered the whole life cycle performance of a building along with environmental impact. It is defined as "*A building that is developed, used and reused without unnecessary resource depletion, environmental pollution and ecosystem degradation*".

4-3-4 Circular building principles

The definitions on circular buildings mainly focus on building design and material usage characteristics. Various previous research recommends that a combination of circular design and circular material usage is necessary to achieve circularity [47]. Based on the literature, the design principles considered for the study are: Design principles that include 1) Design out waste, 2) Design for disassembly, 3) Design for adaptability and Material usage principle. Additionally, Cheshire (2016) included Building in layers as a design principle in addition to the above-mentioned principles.

1. Design Principle- The design principle is further divided into three principles. The design principle should consider the entire life-cycle phases of the building.
   (a) Design out waste- The principle focuses on reducing the waste during the building life cycle. The principle is based on five key design factors namely, reuse and recovery of materials, materials optimization, efficient procurement, deconstruction and flexibility. By using these design factors, it is possible to minimize waste.
   (b) Design for disassembly- The design principle refers to the design of products and components such that they can be disassembled at the end of their service life and used for the next life cycle. The principle aims to restore the products and components at their highest value through strategies such as reuse, remanufacture and recycle [47].
   (c) Design for adaptability- The design principle refers to the performance of the building or its components to be able to use it for a longer service life.
2. Material Usage Principle- The circular material usage principle mainly focuses on material selection and its processing method [47]. The aim is to maintain the material value by preventing material degradation and provide material regeneration [47]. Similar to the design principle, the material usage principle should consider the whole life-cycle phases.
3. Building in layers- The design principle is based on the shearing layers by Brand (1994). The design decision should be made based on the layers: site, structure, skin, services, space plan and stuff as each layer has different end of life scenarios.

The CE principles when applied to the buildings, several objectives can be achieved:

1. Material and energy efficiency through sustainable selection of materials.
2. Maximize reuse and recycling potential of products and materials, thereby reducing generation of waste.
3. Minimize waste disposal.
4. Reduce use of primary materials, thereby reducing the associated environmental impacts.

4-3-5 Assessment Methods

Similar to the CE concept, there is no standard assessment framework or tool to perform the assessment, however, several researchers have identified the key indicators for the assessment. The research identifies these indicators and utilizes the critical indicators for the study. Elia et al. (2017) [48] recommends using five indicators to assess CE strategies and its impact.

The indicators include: 1) reducing inputs and the use of natural resources, 2) increasing the share of renewable and recyclable resources, 3) reducing emissions levels, 4) reducing valuable materials losses, 5) increasing the value of products. Pomponi et al. (2017) [2] identified six dimensions of CE: technological, environmental, economic, governmental, societal, and behavioural as the indicators. Other recent researchers have considered recycling and reusing potential, adaptability, design complexity such as separability and accessibility, and ecological impacts as the key indicators for the assessment [49, 50]. Similarly, CB '23 platform has divided the circularity indicators into three categories: 1) protecting material stocks, 2) protecting the environment and 3) protecting existing value. Currently, the assessment methods and tools mainly focus on technical, economic, and environmental aspects [51]. However, based on literature study, it was seen that reducing the use of resources, limiting loss and their value retention should be the complementary indicators for protecting the environment (Platform CB '23). Based on the focus of the study, this research classifies the indicators into two type-

1. The indicators that measure the material or product circularity.
2. The indicators that measure the effects regarding the environmental concerns. The economic and social concerns are not in the scope of the research; hence, their indicators are not reviewed.

In previous research, it was recommended to use a life-cycle approach to evaluate the environmental impact and the benefits of implementing circular strategies in different life-cycle phases of a product [18, 19, 20, 21]. The research will use the life-cycle phases of a building to determine the indicators required for the assessment.

4-3-5-1 Circularity based indicators

The primary principle of circularity is to keep the flow of materials in a closed loop by improving material efficiency, reusing, and recycling materials without sending it to landfill at the end of life. To track the progress towards achieving these principles, the circularity indicators are classified based on the life cycle stages of a building: production and construction stage, use stage and end-of-life stage. The following sections describe the indicators in each stage.

1. Production and Construction stage
    (a) Quantity of Input material:
        i. Primary materials: The indicator refers to the degree of primary materials used.
        ii. Reused components or recycled materials: The indicator refers to the degree of components or materials that is obtained from the previous cycle.
    (b) Use of renewable energy: The indicator refers to the amount of renewable energy used for producing input materials or used as materials.
    (c) Use of non-renewable energy: The indicator refers to the amount of non-renewable energy used for producing input materials or used as materials.

2. Use stage
   (a) Utility of products: The indicator refers to the degree to which potential functional life of the product used in the building exceeds the average life of the same product type. The indicator is used to determine whether the product should be maintained, refurbished, or replaced.
3. End-of-life stage
   (a) Quantity of material output:
      i. Reusable products or components: The indicator refers to the degree of components that can be reused.
      ii. Recyclable products or components or materials: The indicator refers to the degree of materials that can be recycled.
      iii. Waste for landfill or incinerator: The indicator refers to the degree of waste materials that are sent to landfills or incineration for energy production.
   (b) Recycling efficiency: The indicator refers to the efficiency of the recycling process.
   (c) Disassembly potential: The indicator refers to the degree to which the 'Design for disassembly' principle is adopted. The reusability of components depends on the detachability aspect. Detachability can be defined as the degree to which products can be disassembled to retain their function so that high quality reuse can be achieved. The type of connection, accessibility, crossings, and geometry of products play a key role in determining reuse potential [50].
   (d) Adaptability potential: It is defined as the ability of the product to meet other functional needs apart from the function it is designed for or currently used. It has seven aspects, namely: versatile, convertible, adjustable, movable, scalable, and reusable. Previous research has recommended assessing adaptability potential separately on the building systems: site, structure, skin, services, space plan and stuff [52, 15].

4-3-5-2 Circularity indicator tools

There is no standardized assessment tool to measure circularity of products or materials. Previous tools have been explored to measure circularity of products and materials. The research reviews the most used tools found in the literature.

Material Circularity Indicator (MCI)

Material Circularity Indicator (MCI) developed by Ellen MacArthur Foundation and Granta Design is a web-based commercially available tool to measure circularity at the product level, thus being classified as a micro-level indicator [53]. The methodology assesses the extent to which linear flow of a product is minimized and restorative flow is maximized [53]. The tool focuses on the technical cycles, including non-renewable resources and can be applied across life-cycle phases, thus making it complementary to environmental impact assessment. The MCI is based on three parameters: a) mass of virgin materials (V), b) mass of unrecoverable waste (W), and c) utility factor (X) which represents the lifetime of products [8, 17].

A product that is produced using only virgin materials and at the end of its use phase, it ends up in landfill, is fully linear. On the other hand, a product that is manufactured with recycled materials or reused components and having 100% recycling efficiency is fully circular. Thus, the tool provides an MCI score that ranges between 0 (100% linear) to 1(100% circular). The calculation method for MCI is presented in Appendix B.

Building Circularity indicator (BCI)

Building Circularity Indicator (BCI) developed by Verberne (2016)[54] and van Vliet (2018)[55] are built upon Material Circularity Indicator and the transformation capacity model [56]. The BCI model consists of four calculation steps, namely, Material Circularity Indicator for a product (MCIp), Product Circularity Indicator (PCI), System Circularity Indicator (SCI) and Building Circularity Indicator (BCI). The calculation method for BCI is presented in Appendix B.

Madaster Circularity Indicators (CI)

The indicator developed by Madaster is also built upon the Material Circularity Indicator. These indicators measure the circularity level for the whole life cycle of a building, namely, construction stage, use stage and end of life stage. Similar to MCI, CI scores the building that ranges between 0% and 100%. In the model, CI score is given to each stage. For the construction stage, a CI of 100% is given when secondary materials are used completely (no virgin materials). In this stage, the recycling efficiency and waste generated during the recycling process is also considered. For the use phase, a CI score of 100% is given when the functional lifetime of a product is more than the industrial lifetime. In the last phase, a CI score of 100% is given when the output materials are fully recoverable. Finally, the scores of all the three stages are aggregated to provide a single CI score for the building.

CB'23 Platform

CB'23 Platform (2020) has developed a core measurement method for measuring circularity in the built environment. The method divides the indicator into three aspects that covers the objectives of construction: a) protect material stock, b) protect the environment, and c) protect the existing value. Each aspect consists of several sub-indicators. Currently, the second version of the guide focuses on the first two indicators and provides calculation rules for each sub-indicator. However, the guide does not give weights for indicators due to which it is difficult to arrive at a single score.

Transformation Capacity

Durmisevic (2006)[56] developed a model to assess the disassembly potential. The model consists of eight aspects with weighted determining factors ranging from 0 (worst impact) to 1 (best impact). APPENDIX C presents the details on the aspects and its scores.

Detachability Index

Recently, a research conducted by Alba concepts in collaboration with DGBC and other to develop a framework for circularity buildings to include detachability index (DI) in BREEAM assessment by normalizing the results with MPG score. The authors define detachability as the degree to which the connection between the products are broken or disassembled so that the products can retain its function, thereby, achieving high quality reuse [57]. The authors recognize that the quality of reuse depends on the degree of disassembly and complexity of configuration. The technical detachability factors proposed are based on Durmisevic transformation capacity model. APPENDIX C presents the calculations of the detachability index.

4-3-5-3 Evaluation

The research reviewed nine circularity indicators and eight assessment models. The circularity models cover most of the required indicators except the transformation model and detachability index which focuses only on the disassembly factors. The MCI model does not assess the disassembly and adaptability potential of products while the BCI, CI and CB '23 Platform considers these indicators. Whereas the recycling efficiency is considered by MCI and CI and not by BCI models.

The BCI model has certain disadvantages over MCI. The major reason is the interpretation of utility factor (X). In the MCI model, the utility factor (X) is the ratio of product's life in use phase (L) and the industry average length of the product in use phase (Lav) or the ratio of functional life of the product (U) and industry average functional life (Uav). Whereas, in the BCI model, the utility factor (X) is the ratio of lifetime of the product (Lp) and lifetime of the system (Brand's layer) the product belongs to (Lsys). As the circularity of a product depends on the system it belongs to, if the product changes its system, then the circularity value will be different. On the other hand, BCI has not been universally acknowledged as MCI. The CI indicator developed by Madaster is an online platform and available only for its clients, thus limiting its use for the research. Similarly, the core measurement method by CB '23 Platform is an exhaustive guide for measuring circularity and is the only method that considers qualitative assessment of adaptability potential indicators. However, the method does not give weighting for the indicators due to which it is difficult to evaluate the result. Considering the drawbacks of the models, MCI complemented with the Detachability Index on Design for Disassembly principles (DfD) was found to be suitable indicators for assessing the circularity of a building.

4-3-5-4 Environmental impact indicator

Life Cycle Assessment

The concept of LCA began in the period 1960-1970 when environmental issues such as waste accumulation, pollution control, resource depletion and energy efficiency were a public concern (Jensen et al., 2008). In 1997, the European standard ISO formalized and published different LCA methods and procedures, resulting in the ISO 14040 series.

There are two approaches to LCA namely, attributional LCA and consequential LCA. The consequential LCA is used when information on the environmental burden that occurs due to a change in demand for the functional unit of a product system is required. Whereas attributional LCA attempts to provide information on what portion of environmental burdens can be attributed to the product system's functional unit (UNEP, 2011). The study adopts consequential LCA. The ISO 14040 series provides four phases for LCA: goal and scope definition, inventory analysis, impact assessment and interpretation of results (ISO, 1997) as shown in figure 4-3. The description of each step is explained in APPENDIX D.

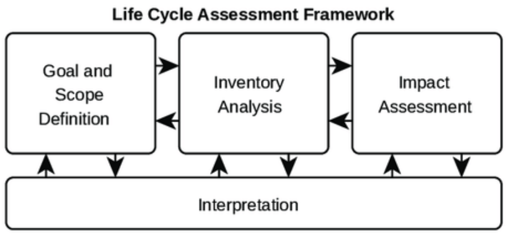


Figure 4-3: LCA methodology framework (ISO, 1997)

LCA in the construction industry

The life-cycle assessment in the built environment has been gaining attention since the beginning of the 21st century due to the high environmental impacts of the construction industry [58]. The general framework as mentioned in ISO 14040 can be applied to the building industry, however, it is more challenging compared to other industries due to various factor such as the uniqueness of every building, long lifespan of buildings (usually 50 to 100 years) but the lifespan of certain products will be shorter and the buildings undergo renovations over the lifetime [59]. The LCA application in the built environment is complex and time-consuming and hence it is not possible to complete the LCA methodology with the same level of detail as compared to other industries at all times. Recognizing this, Wittstock et al. (2015)[60] conducted the 'EeBGuide' project and established three types of LCA that differ in terms of data quality and completeness: 1) screening LCA, 2) simplified LCA and 3) complete LCA. A screening LCA is used for pre- and conceptual design stages to assess the environmental assessment of buildings and products. A simplified LCA is similar to the screening LCA however, performed when more data is available and yields an estimate on the environmental impact of buildings. This type of overview helps during the early design stages to identify 'hotspots' that require attention during the later stages of the project. Whereas complete LCA is conducted during the last stages of a project and conforms to the ISO 14040 framework. Similarly, a European research project called 'ACADEMY' proposed a fourth type of LCA that is based on streamlined LCA which was proposed by SETAC (Society of Environmental Toxicology and Chemistry) in 1999 [61]. This type of LCA is used when the LCA experts select the system boundaries and environmental categories that are relevant to their study. This type is mostly recommended to be applied during the early design stages. Hence, the streamlined LCA approach will be considered for the study.

All the types of LCA for a building, product or materials can be performed over the building whole life cycle phases to evaluate the environmental impacts. It is also possible to perform the assessment for an individual life cycle phase. As per EN standards, there are four main life cycle phases: A- Production phase, B- Construction phase, C- Use phase, and D- End-of-life phase. Each stage includes sub-phases as shown in figure 4-4. The product phase (A1-A3) includes raw materials extraction, transportation of these materials to the manufacturing units for manufacturing the products, thus covering the cradle-to-gate phase. The construction phase (A4-A5) includes transportation of the products and materials to the site, construction activities including installations to realize the building. During the use phase (B1-B7), the building products and services are used, maintained, repaired, and refurbished. In the end-of-life phase (C1-C4) the building is deconstructed or demolished, the waste materials and products are disposed of, however, few of them are reused, recovered, and recycled, thus covering the gate-to-grave phase. In addition to these life cycle stages, NEN-EN 15978 defined the final phase (D) as the phase that takes up the effect due to the potential of reuse, recovery, and recycling after the building's life cycle.

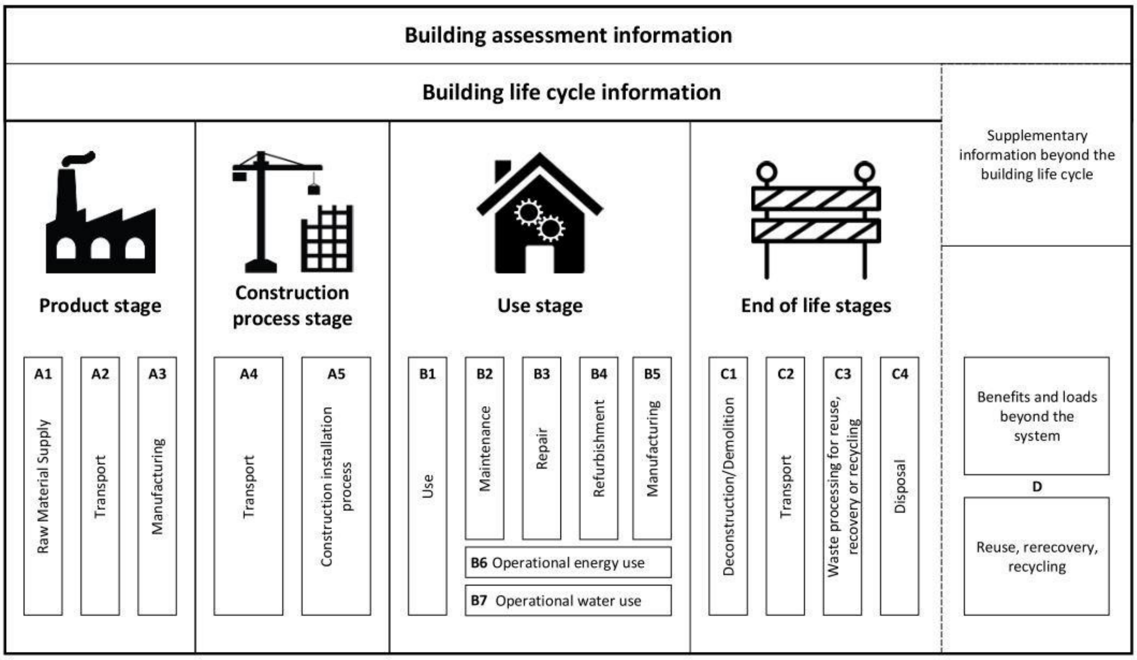


Figure 4-4: Life cycle modules according to EN15798 [3]

4-3-5-5 Environmental impact assessment methods

The study reviewed the most used environmental impact assessment methods. Allacker et al. (2014)[62] reviewed 11 allocation approaches and classified these methods into three approaches: Cut-off method (100:0), End-of-life (0:100) and Distributed (50:50). Apart from these approaches, Catherine De Wolf et al. (2020)[50] reviewed other recently developed allocation methods: European Commission Environmental Footprint (EC EF), Degressive, SIA 2032 and Energie plus Carbone monis (E+C-) along with the three main methods.

The 100:0 approach attributes the environmental impacts of virgin material production to the first life cycle of the product and the impact of recycling or reusing to the next life cycle and the impact of disposal to the last cycle. This method encourages the designers to utilize reused products in their design, however, does not allow the designers to obtain environmental benefit for designing the products that can be reused or recycled in future. In the 0:100 approach, the impact of production and end-of-life stages are attributed to the last life cycle. The 50:50 approach equally distributes the impact of production of virgin materials and impact of end-of-life cycle over the number of life cycles. The EC EF approach is built on 50:50 approach, where the environmental impact of production and end-of-life is distributed to the first and last life cycle of a product whereas the impact due to reuse and recycle is distributed over the life cycles. The degressive approach distributes the impact of production, end-of-life and recycle and reuse throughout the life cycle stages. The SIA 2032 methodology is adopted in Switzerland and uses the actual and expected life span of a product to distribute the impact of production and end-of-life stage. All these approaches except 100:0 are unreliable as the number of future life cycles of a product is unpredictable.

The environmental impact of a product in the Dutch construction industry is assessed on the basis of the European Standard EN 15804. The calculation for determining the environmental performance is performed according to the 'Bepalingsmethode Milieuprestatie gebouwen en GWW-werken' (MPG) published by the Nationale Milieu Database (NMD), also known as 'MP-system'. The methodology considers the impact of all the stages for the first cycle. The study uses this methodology as the research is being carried out in the Netherlands.

The results of the impact from the products or sub-products are assigned to the impact categories in the form of values which are then weighed. The process of weighing is to assign monetary values to each impact category. In the Netherlands, costs required to eliminate/-compensate for the environmental impact or bring the impact level to an acceptable level is used for monetization, known as 'shadow costs'. These costs, when included in the sale price of the product, are believed to compensate for the damage to the environment, thereby bringing the product to a sustainable level. Additionally, a 1-point score of the environmental performance is easy to compare with other buildings and communicate the impact. Thus, the professionals in the Dutch construction industry use instruments to calculate the environmental impact in terms of cost (MKI). Various tools have been developed to calculate the environmental performance of the buildings and GWW (civil engineering construction) sector and use environmental data from the NMD database.

The environmental performance of buildings (MPG) is expressed as an impact score in Euro/m2/year. The environment impact calculation is based on the problem-oriented approach consisting of eleven impact categories till 2021 and nineteen environmental impact categories from 2021 which are expressed in their equivalence units as shown in APPENDIX D. The environmental impacts of a product are calculated based on the impact categories from the calculation rules provided in the Nationale Milieu Database as per EN 15804. As per the calculation rules, the environmental impact per unit of product is determined per sub-phase (e.g., A1-A3, A4-A5) and later summed up to obtain the environmental impact per phase (A, B, C and D).

4-4 Building Information Modelling

4-4-1 BIM in the Construction Industry

Building Information Modelling (BIM) is a 3D digital model of a building's technical characteristics [63]. Due to the increase in complexity of projects in the construction industry, BIM is becoming more popular among the industry practitioners, academics, and policymakers in recent years. The implementation of BIM for various purposes such as 3D visualization of the model, cost estimation and control, and simulation, clash detection show promising potential in the construction industry. In addition, BIM implementation enables effective collaboration and communication among the project stakeholders from designers to managers, throughout the life cycle.

BIM has the ability to generate data of a building's life cycle, thus minimizing human errors in the design stage. BIM supports decision-making by optimal selection of materials, deciding on design alternatives, etc., during early design stages. Its integration with sustainability and circularity performance has a huge potential in achieving the goals in the construction industry [64]. Recently, the built environment is gaining interest in integrating BIM with sustainability and circularity principles during the design stage. Akanbi et al. (2018)[9] highlighted three BIM features to make it suitable for assessing the whole lifecycle performance of buildings in context to the CE process. These features include: 1) object parametric modelling that utilizes various parameters and certain rules to capture design and functionality of a building, 2) bi-directional associativity ensures that adequate support is provided for making changes in the design models, 3) intelligent modeling ensures that additional information is provided along with 3D geometric data for analytical purposes.

4-4-2 Integration of BIM with LCA and Circularity Assessment

Both LCA and circularity assessment approaches are based on life cycle thinking, hence it is found appropriate to combine these assessments with BIM. Circularity assessment and LCA have been widely used as individual assessment tools in the AEC industry. Several academic researchers and industry practitioners have tried to integrate these assessment tools individually with BIM which has resulted in prototype developments and commercial tools. As both the assessment can be applied across whole life cycle phases, it is possible to combine the assessment and ease the evaluation process. However, to integrate circularity and environmental assessment, both the assessment needs to be calculated individually.

The research reviews the current state-of-the-art BIM-based LCA and circularity assessment tools and methods and classifies these into three main approach categories. However, most of the literature reviewed was on BIM-based LCA assessment due to limited studies on BIM-based circularity assessment. In the first approach, the BIM model is used to obtain BoQ in various data formats such as Industry Class Foundation (IFC) or Construction Operations Building Information Exchange (CoBie) and process these in external assessment software tools. The approach is performed by experts. This approach is applied for both LCA and circularity assessment. The second approach in the literature is integration of BIM models comprising BoQ with external database containing properties required for the assessment and then performing the assessment. The main limitation of the approach is that it requires appropriate classification of data for linking the BIM model with external databases [61].

In the third approach, the LCA assessment is performed within the BIM-environment by including information required for the assessment within BIM models. This approach was attempted due to drawbacks of other approaches which is lack of information within BIM to conduct automatic assessment. The advantage in the third approach is that the BIM models are not only utilized for geometric and material data but also incorporate other properties such as environmental impact of the materials and products which can be used to perform an automatic assessment. The additional information is added to the BIM model by creating custom parameters. However, the current limitation is that the BIM IFC schema does not contain adequate properties for storing the information required for the assessment within BIM [61]. The following section describes the developed tools for each approach.

4-4-2-1 Approach 1: Processing an BoQ in external software tools

The approach is used by various consulting companies such as Madaster and Building as Material Banks (BAMB) for circularity assessment and oneClick LCA by Bionova Ltd for LCA and circularity assessment. Madaster Foundation offers an online platform for conducting circularity assessment. The users of the platform must follow certain steps to conduct the assessment. Firstly, the data from the BIM model should be extracted using an IFC/ Excel file. The data file should include the geometric information such as the quantity of materials, material data and NL-Sfb classification to link the materials from the BIM model to the Madaster material database. The NL-Sfb is a common naming language used in the Dutch construction industry to code elements in BIM. The classification system is obtained from Swedish classification, where SfB abbreviation stands for Samarbetskommitten för Byggnadsfrågor. This is necessary to facilitate automatic data exchange between the BIM model and database containing material information. The exchange file is then uploaded on their platform to obtain CI scores.

Similarly, BAMB developed the CBA prototype online platform for circularity assessment (figure 4-5). The prototype is similar to Madaster, as it allows the users to upload exchange files (only COBie) from BIM models. COBie contains the required building information in the form of a spreadsheet (BAMB, 2020). The LCA tool is developed by Bionova Ltd. Similar to Madaster and CBA prototype, the oneClick LCA extracts the data of BIM model in IFC, Excel CSV or gbXML format and upload the exchange file on the oneClick LCA platform.

4-4-2-2 Approach 2: Linking BIM model with external database containing the required information and performing assessment

The approach was attempted by few researchers and is considered to be effective for the assessment process. Tsikos et al. (2017)[65] developed an Integrated dynamic model (IDM) where Autodesk Revit is linked to an external LCI material database. A permanent link is developed between the Revit and the LCI database using the Dynamo script to extract material IDs and link to an external database to calculate the impact of the materials and export back to Revit and Excel sheet to visualize the results in the form of graphs and charts. Similar framework is adopted by Eldik et al. (2020) [66] where materials unique ID generated in Revit was linked permanently to an external database to perform the assessment and then imported back to Revit for visualization. Rock et al. (2018)[64] developed BIM based LCA assessment at early design stages to decide on the construction options based on their environmental impacts. The authors used Dynamo script to link BIM model with LCA database containing information on global warming potential impact category per m2 for all the available construction material options. The results are visualized in the BIM model for communicating the results and providing visual design guidance for the architects

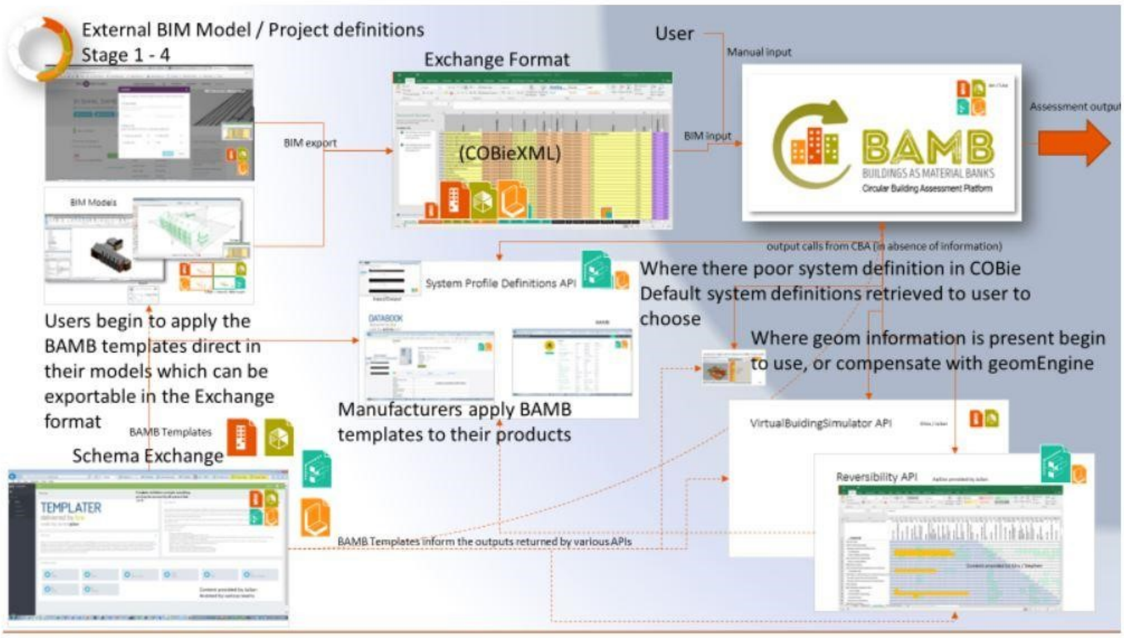


Figure 4-5: CBA Prototype (BAMB, 2020)

and structural designers. Van Gemert (2019)[67] developed 'MPG-ENVIE', a user application tool to support the designers in assessing the embodied impacts of the design (figure 4-6). The MPG-ENVIE links the IFC file containing the BoQ with an external database containing data on environmental impact of materials through NL-Sfb classification to calculate the embodied impact of the design. The obtained results are presented in tables and bar charts and color-overrides of the elements. Anita et al. (2020)[27] developed a dynamic tool for BIM based LCA calculation using parametric program Dynamo. The process of developing the tool consisted of three major steps: creating LCA parameters in BIM, calculating the LCA values and generating the report. The specific LCA parameters were created in the BIM software as as they are not contained in BIM libraries. The calculation is done in the parametric tool by extracting LCA values from the developed database and linking it with the elements' quantity imported from the BIM model. After calculation, the results are filled in the created LCA parameters. Thus, the LCA values can be viewed in the BIM model. Additionally, the obtained results are extracted to an Excel sheet to generate a report.

4-4-2-3 Approach 3: Creating parameters to store assessment information within BIM environment to perform the assessment

Most of the researchers have developed custom parameters containing the required information within the BIM environment to perform the assessment. Bueno et al. (2018)[68] used a combination of Microsoft Excel and Dynamo with Autodesk Revit to calculate the environmental impact of the design. The parameters required for the assessment were created in Revit and the data for the parameters were obtained using Dynamo scripts. Another script was used to perform the assessment. However, the research does not address the data collection and assumes it to be provided by the manufacturers in a spreadsheet. Akanbi et al.

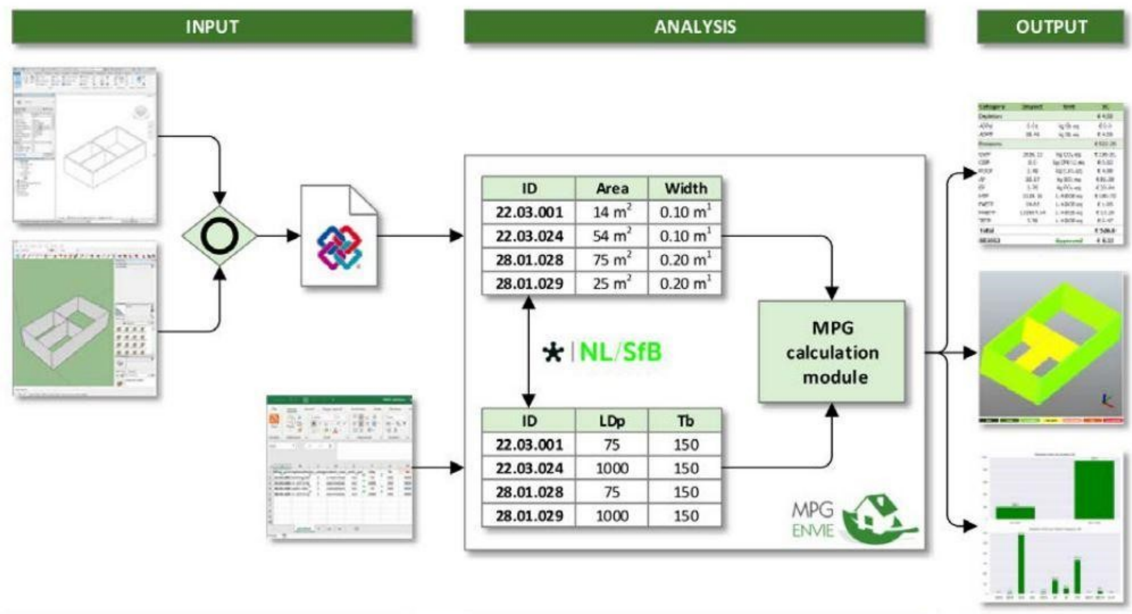
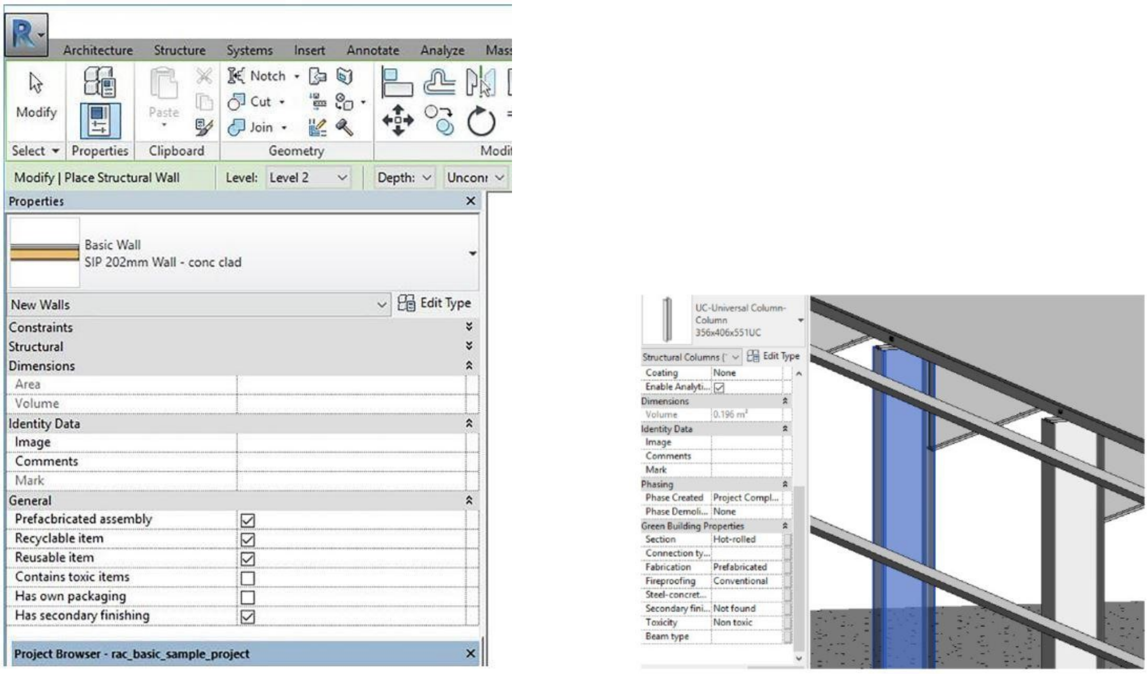


Figure 4-6: MPG-ENVIE (van Gemert, 2019)

(2018)[9] developed a decision support BWPE plug-in within Autodesk Revit to assess structural components based on its salvage performance. The developed tool reveals the quantity of recoverable materials from a building and whether it can be reused or recycled at the end of use phase. The same author along with a few other researchers developed the D-DAS tool for deconstruction and disassembly function along with building whole life performance analysis, thus making it an improvised version of BWPE (Akanbi et al., 2019)[9]. Similarly, Santos et al. (2020)[61] developed the BIMEELCA tool for Revit software for supporting the decision-making process during the design phases. The Revit API platform was used to develop the tool along with C language, windows presentation foundation (WPF). An automatic LCA and LCC analysis was performed for a high-rise building project by inserting the information from generic databases into the model. Recently, Basta et al. (2020)[69] based on D-DAS developed SS-DAS for scoring steel structure deconstructability (Figure 4-7). The proposed tool utilizes Autodesk Revit and Dynamo for visual scripting for automating the assessment process. The required parameters were inserted into the Revit model for an efficient calculation using the Dynamo tool.

4-4-3 Evaluation

The reviewed tools and methods to conduct assessment were evaluated. The first approach requires a certain amount of manual procedure to extract information exchange files from BIM and upload on online software tools, thus the approach does not fully automate the assessment process. Another challenge is that the online platforms are not public, and the user needs to pay and register to use the commercially available software. If such a platform needs to be developed it requires high programming ability. The third approach seems to be promising for automating the assessment, however it is time consuming as the user needs to create parameters for every required information and then input the data for the parameters. If it is



(a) **(b)**

Figure 4-7: (a)D-DAS (b)SS-DAS

required to perform assessment through the design process, then the model requires different types of input information such as generic data for lower LOD. It is not feasible to change the values of the parameters each time, making the approach ineffective. In previous research, it was seen that the IFC schema in the BIM software does not contain suitable properties to store the information required for the assessment. Thus, the second approach proves to be a more efficient integration approach. Few of the reviewed studies have encouraged the use of visual programming languages as it has the ability to manage data required for the assessment and conduct automatic assessment. In previous studies, it was seen that Autodesk Revit was the major BIM software tool used for the design and Dynamo scripting has been mainly used to support various assessments at different design stages (Rock et al., 2018).

4-4-4 Integration Challenges

It is evident that the integration of assessments with BIM has been gaining attention and various practitioners have tried to adopt different methodologies and calculations for implementing BIM based assessment. However, certain limitations were observed from the literature which limited the second type of integration approach. One of the overlapping challenges in the literature is the issue of interoperability. The main reason is the lack of appropriate data required for the integrated assessment [68]. Additionally, researchers have shown the lack of a user-friendly and reliable database for data input during assessment. Santos et al., 2019[61] added that currently there is no explicit data structure, thus limiting the interoperability of the developed integration method. Secondly, studies have shown that the assessments were carried out for higher LOD (usually LOD 300 and above) and required experts to perform such assessments and recommended to use simplified approaches so that the assessment can be performed by designers and continuously throughout the design phase. The last identified limitation of the approach was with regard to analysis of the results. The results were mostly presented with numerical values, thus making it difficult for the designers to understand and interpret the results and make design decisions. This research makes an attempt to overcome the above-mentioned challenges by combining approach 2 and 3.

Chapter 5

Building Circularity and Environmental impact assessment Framework

The chapter presents the proposed framework for the research which is based on the concept of integrating and automating the environmental impact and circularity performance in the BIM environment. The chapter starts by analyzing the current situation and a new workflow is proposed. Later, the proposed framework is described in detail. It answers sub-question 4 of the research.

5-1 Workflow

To understand the current workflow for the assessment process, semi-structured interviews were conducted with the LCA experts, architects, and BIM coordinators of the company. The details on the interviews are presented in APPENDIX E. The interviews were conducted to identify the actors involved in the process, the sequence of the activity, and how the information is exchanged during the process.

Based on the interview, certain observations were made: 1) the design and environmental assessment is carried out separately, 2) currently, circularity assessment is not been carried out for building sector unless required by clients, 3) most widely used design tool is Autodesk Revit for preliminary and detailed design and the conceptual design is usually carried out in Sketch up, 4) designers do not use the predefined materials from the database and use materials available in the software library, 5) sustainability experts' major issue is finding the products of the BIM model in the database to perform the assessment, and sometimes assume the values from a similar product, 6) designers are not very much familiar with assessments methods, however they are willing to conduct the assessment to their designs if it is easy and consumes less time and supports them in decision making, 7) designers wants to visualize the results in their BIM model so that they can do the necessary design changes accordingly, 8) sustainability experts wants the designers to perform preliminary assessment of their design to ease the final assessment. Based on the analysis this research makes an attempt to address these issues.

The first step is addressing the current workflow as shown in figure 5-1. As mentioned earlier, there was a clear separation between design phase and environmental impact assessment phase. At the end of the design phase, the designers export the quantity of materials from the BIM model and send it to the sustainability expert who later performs the LCA assessment. The sustainability experts after receiving the information, review the details and checks if all the information required for the assessment is available in the database. If not they either seek the information from the designers or supplier of the products or use the information from a similar product or use historical data. After performing the assessment, the sustainability expert analyses the results and communicates the results to the design team in the form of a report comprising graphs and tables. If the results are not within the allowable limits, the designer tries to make changes in the design to improve the environmental impact assessment scores of the design. However, the designers find it difficult to interpret these results and link it to the products used in the model due to lack of expertise. The complex process is currently consume a huge amount of time. The research tries to prevent this issue by proposing a new workflow for the design and assessment phase.

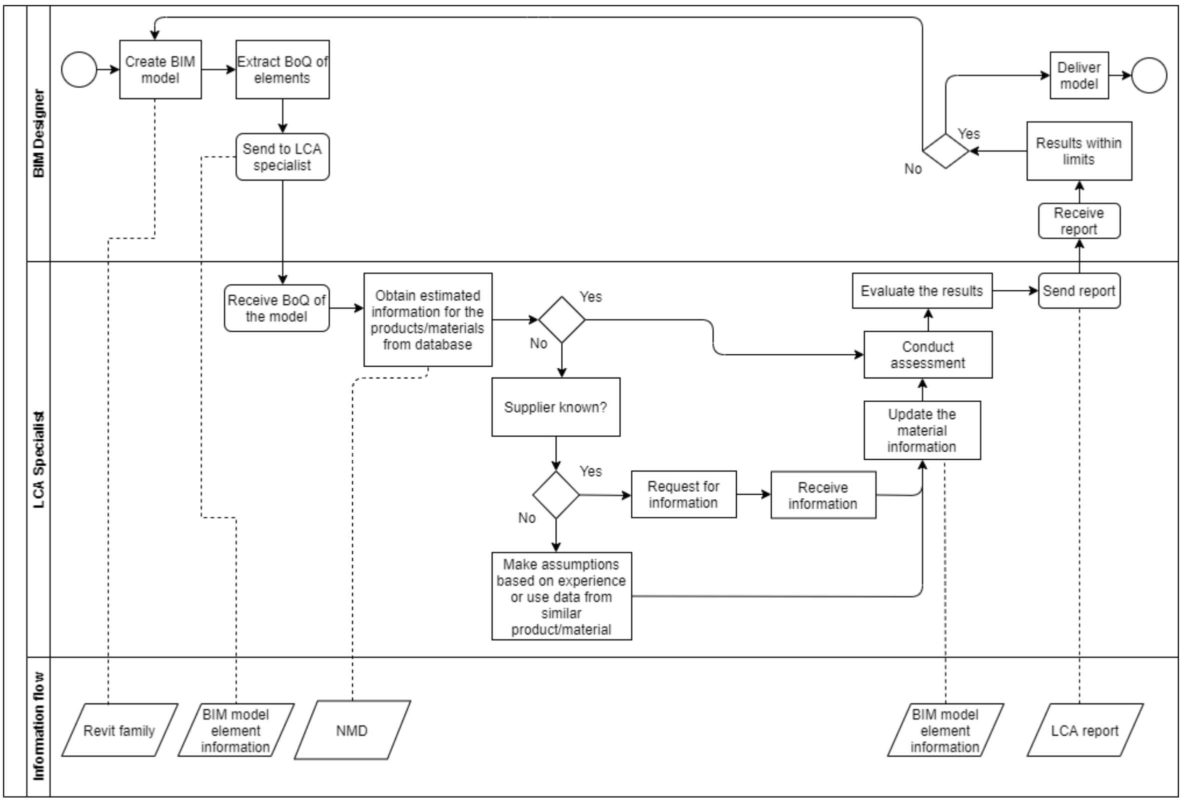


Figure 5-1: Current Assessment workflow (own illustration)

In the proposed workflow, the designers are made to perform circularity and environmental impact assessment during the design process as shown in figure 5-2. The proposed process starts when the designer creates the BIM model in Autodesk Revit. During the preliminary phase, the designers have various design options which can be decided based on the assessment results. For example, the designers must make a choice between different materials, type of structure or products. Each of them might have different circularity and environmental values which is necessary to consider preventing changes in the future. The designers can conduct the assessment by using the tool developed in the research. To perform an automated assessment, it is necessary to link the model with the database with the help of product classification codes. The developed tool helps the designers to visualize the results within the model which helps them in making the required design changes. It is hypothesized that over the period such assessment during the design phase will increase the designer's awareness on circularity and sustainability of materials and their designs. The next section describes the architecture of the developed tool and proposes the framework.

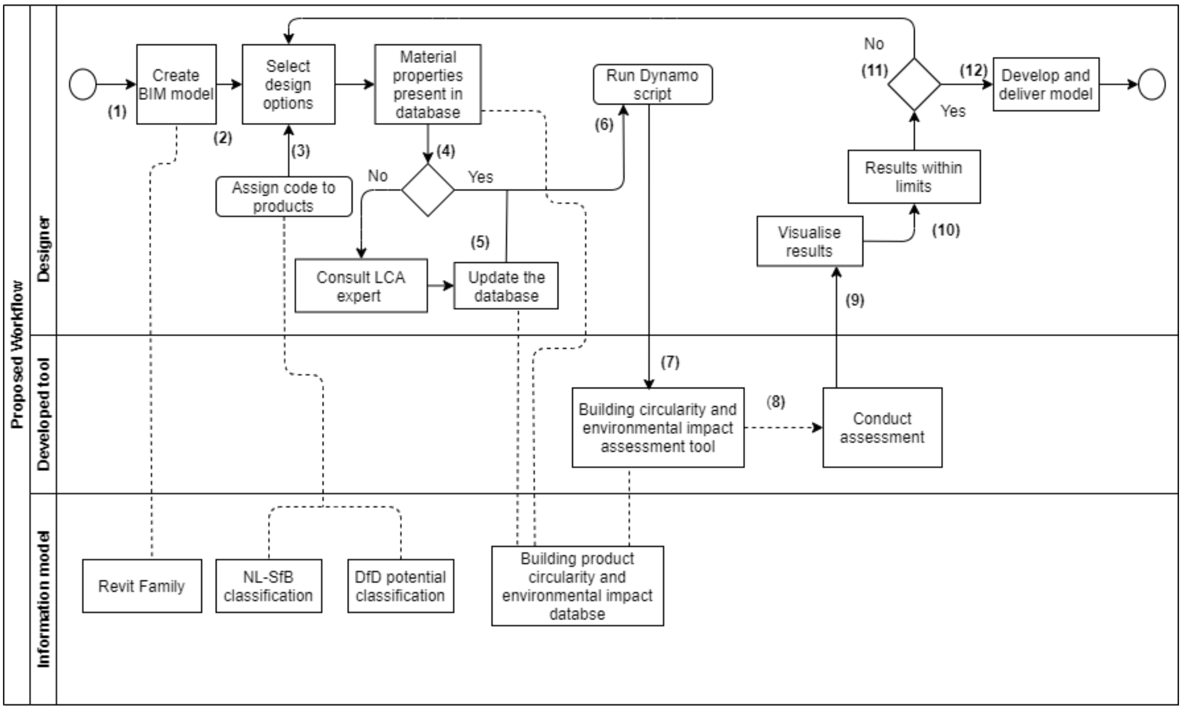


Figure 5-2: Proposed Assessment Workflow

5-2 Proposed framework

The proposed framework was developed according to the Input-Processing-Output (IPO) model proposed by Negele et al. (1999). In the IPO model, the three components are interlinked. In this research, the interlinked components are: 1) combination of input sources from BIM model and external database, 2) assessment module in which circularity and environmental impacts for the model is calculated based on the link between the two inputs using Dynamo, and 3) output form the results of the calculation visualized within BIM environment and the results from the multi-criteria decision analysis.

The proposed IPO model undergoes the following steps: 1) Identification and structuring of data 2) Data integration 3) Circularity and Environmental Impact Assessment 4) Visualization and analysis of the result 5) Multi-criteria Decision Analysis. The Input stage involves collection of data which is obtained by identifying the input data required for the assessment. Once the required data for the assessments are identified, the data is obtained and structured in an external database. The process stage comprises two sub-stages: data integration and assessment. The materials in the BIM model are linked to the database using a unique material ID in both the material library of Autodesk Revit and the developed database. Later, the circularity and environmental impact assessment is calculated using Dynamo visual scripts. The output stage encompasses the results of the assessment that are visualized in the BIM model and multi-criteria decision making to obtain the best alternative product based on circularity and environmental impact assessment results. The following section describes each stage of the framework.

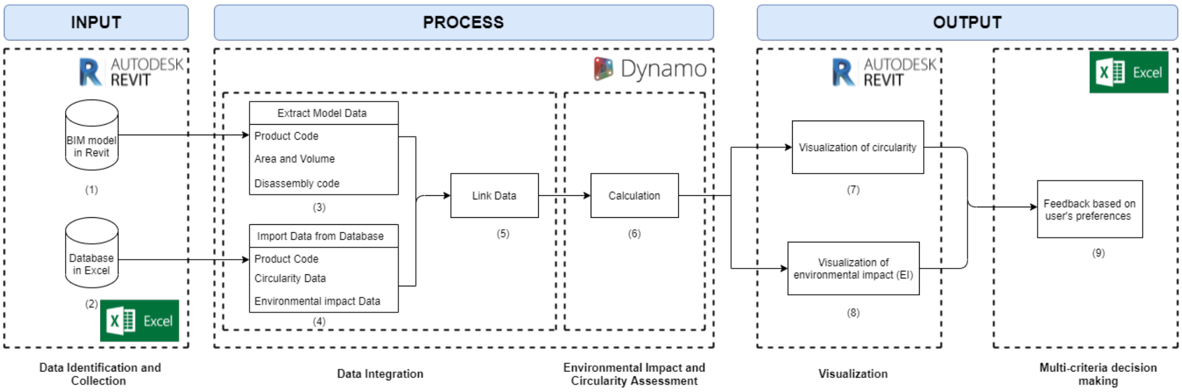


Figure 5-3: Proposed Framework

5-2-1 Data identification

The main objective of this phase was to identify and obtain the data required for BIM based circularity and environmental impact assessment. A significant amount of data is required for integrated assessment in BIM [70]. To identify the required data, a process breakdown structure was utilized for the life cycle of a building as shown in figure 5-4. The process map was derived and modified from Cavalliere et al (2018) [70]. It is important to note that the life cycle adopted in the study is based on the EN 15978 module and does not include operational energy and water use. Table 5-1 presents the identified variables from figure 5-4 and their related parameters.

5-2-2 Data structuring

Figure 5-5 shows the structuring of the data to perform the circularity and environmental impact assessment.The data required for the assessment had to be obtained from two sources namely, BIM model and the Dutch National Environmental Database (NMD) database. Since the information contained in the NMD database is not structured to perform automatic assessment, an external database named as CEI (Circularity and Environmental Impact) database was developed in MS-Excel. The BIM model contains information about every element which is characterized by its type (e.g., roof, slab, wall etc.), products (e.g. reinforced concrete wall), materials (e.g., steel, concrete, etc.) and dimension (e.g., area, volume, and

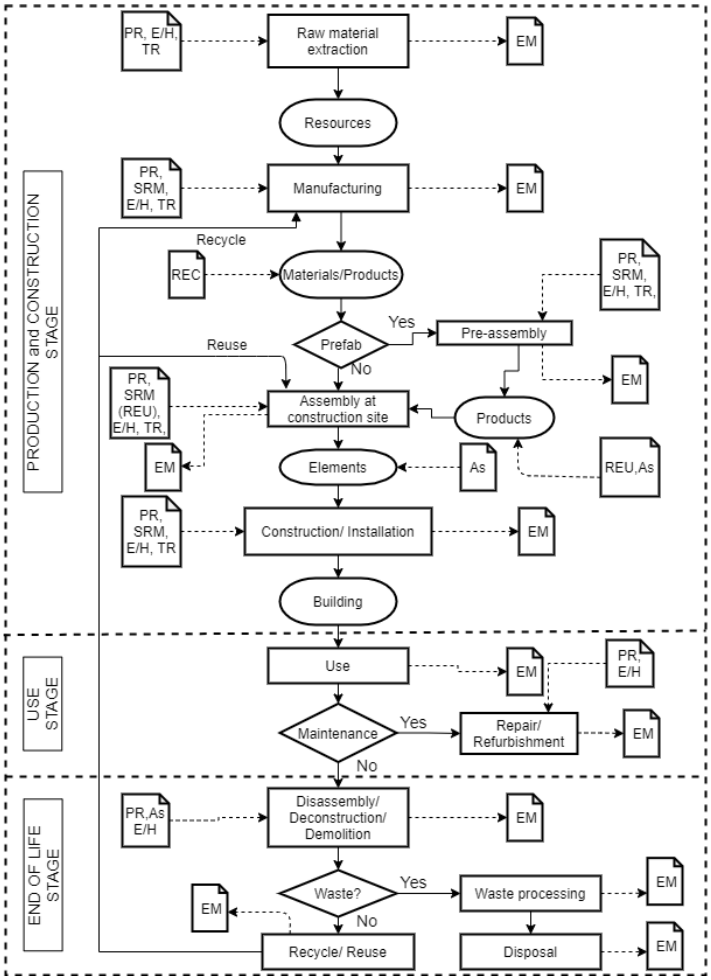


Figure 5-4: Input variables (own illustration)

quantity). Thus, the BIM model provides data on the type and quantity required to calculate the circularity and environmental impact, as well as classification codes and DfD codes to match the data in the CEI database. The CEI database comprises information regarding material characteristics such as nature of resources, and future scenario, products technical and service lifetime, environmental cost indicator (MKI) and environmental emission values etc. The extraction of these data from each source are discussed in the following sections.

5-2-2-1 Data Retrieval for MCI and MKI calculation

The calculation of material circularity and environmental impact assessment requires two types of data as input. Firstly, data on the nature of material including information on its end-of-life and lifespan of the products to determine MCI are obtained from the NMD database (old version) and verified with the designers. The environmental impact assessment is performed according to the 'Bepalingsmethode Milieuprestatie gebouwen enGWW-werken' (MPG) published by the Nationale Milieu Database (NMD). The research follows the new version of the MKI/MPG calculation (NMD 3.0) launched in July 2019. The environmental

Variables	Parameters
Primary resources (PR) and Secondary resources (SRM)	Dimensions (volume, area), Resource nature (reused/recycled, recyclable/reusable, incineration, landfill), service life
Transport (TR)	Mode of transport, Distance, Capacity
Emission (EM)	Type and Quantity of emission
Recyclability (REC)	Quantity of recyclable materials or products
Reusability (REU)	Quantity of reusable materials or products
Assembly/Disassembly potential (As)	Type of connection, Accessibility to connection, Crossing, Form Containment
Energy (E/H)	Source, Power, Time

Table 5-1: Variable and their parameters required for assessment

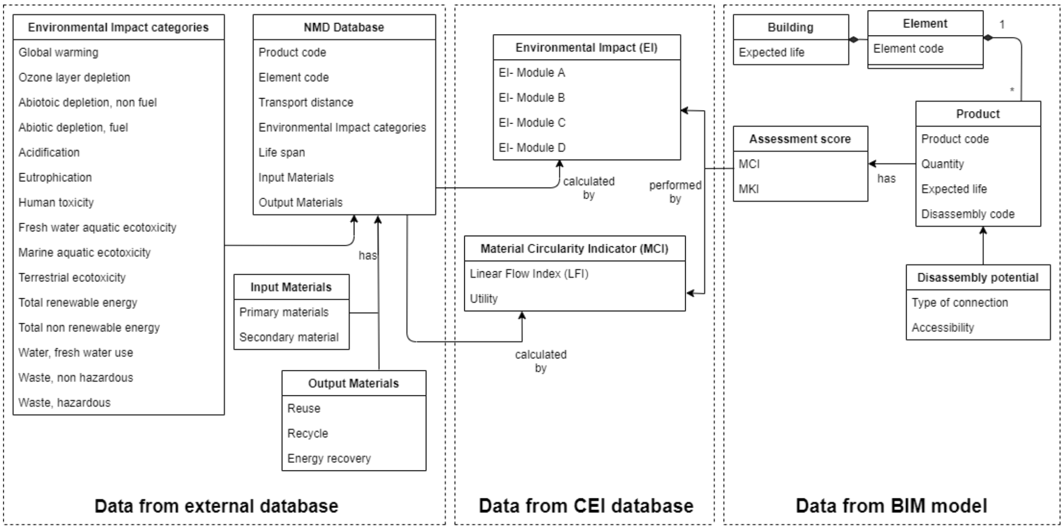


Figure 5-5: Data structure

cost indicator (MKI) is presented in the NMD database in terms of functional unit (FE) of the product (MKI/FE) and functional unit per year (MKI/FE/year). Thus, the MKI values in the developed tool is MKI/FE of products. It was observed that certain products have lower lifetime than the building design (usually considered 50 years or 75 years). To calculate the environmental impact of products according to the building design the environmental impact of the replaced products needs to be considered. For this reason, the calculation of environmental impact of products for the building design is as follows:

$$MKI_a = Q_a X f_a (MKI_{a,A} + MKI_B + MKI_{a_C} + MKI_{a_D}) \quad (5\text{-}1)$$

$$f_a = \frac{LT_b}{LT_a} \quad (5\text{-}2)$$

where:

MKI_a is the environmental cost indicator of product 'a'

Q_a is the quantity of product 'a'

f_a is the lifetime of products accounted for replacement

LT_b is the lifetime of the building

LT_a is the lifetime of the product 'a'

$MKI_{a,A,B,C,D}$ are the environmental cost indicator per module of product 'a'

At the moment, the new version of the NMD-database is made available through a web-based viewer which is still not very accurate in presenting accurate environmental impact data per module as the NMD viewer does not list the scaling information for products. For this reason, existing commercial tools which are being used to calculate the environmental impact of the products are evaluated and the most accurate tool was used for the application of the prototype. The evaluation of the commercial tool is shown in APPENDIX F. Based on the evaluation, results from BIMPACT was found to have exact total MKI as that in NMD viewer. There are several methods to retrieve and map the data from the NMD-database. The most widely used method is directly linking the database to an Application Programming Interface (API). With the help of an API, a computer program can communicate with another program. However, the process requires the data owner of the database to provide access to their API to extract the data. The other method is known as data crawling or web scraping where a programming code is written to navigate around a website and retrieve the required data. However, this method is determined as unethical and usually not preferred. The other option is obtaining the data manually in the form of machine-readable format such as Excel, CSV etc. The third option should be used when the API is not accessible. For the research, the third option was used as it was not possible to obtain permission to access the external party database. The NMD database consists of 3 categories of data and for the 3rd category was used as it is freely accessible.

5-2-2-2 CEI Database Setup

A classification system is used to identify the products in the product database. The classification codes for products are similar to the NMD database which is based on NL-Sfb classification codes. The detailed explanation on the classification codes is explained in the following section. The database was developed in MS-Excel consisting of five tabs as shown in APPENDIX F. The first tab is the 'Product Repository' which provides the different types of available products along with the classification codes and type of category data. The second tab is the 'CEI data' which contains MCI and MKI values for each product. The third tab is the 'Circularity data' containing information required for MCI calculation. The third tab 'LCA-MKI' contains MKI values of products per module along with their function unit and service life. The last tab is the 'LCA-Emission' containing emission values per impact category for all the modules.

5-2-3 Data integration

To assess the circularity and environmental impact of the products, the data from the BIM model and external database needs to be integrated. This was done using NL-Sfb and disassembly code classification in Dynamo. The following sections discuss the integration method in detail.

5-2-3-1 Product classification

To obtain automatic and bidirectional link between the building elements and the established database it is necessary to identify the products based on classification code. If these codes are not determined for an element, then it becomes a complex task to perform an automated assessment calculation for the element. The classification code used for the study is based on the NL-Sfb classification system. The dutch classification system divides the parts of the building based on different categories. The coding consists of five tables: Table 0 to Table 4. Table 0 indicates the type of building and spaces in the built environment. Table 1 represents the functional elements of a building and consists of two digits and then followed by a point number. Table 2 and 3 includes construction methods indicated by an upper-case alphabet and resources indicated by a lower-case alphabet respectively. Whereas Table 4 indicates the activities, characteristics, and properties of a building. However, the organizations are free to customize the NL-Sfb formats. The NMD represents a system wall consisting of an element made of steel frame and softwood plywood and drywall as 21.1 and the sub-products are given the fourth numerical value such as 21.1.1, and 21.1.2 etc. (Nationale Milieudatabase Stichting Bouwkwaliteit, 2020). The research considers the classification code used by NMD which is based on NL-Sfb format for the first three digits.

The classification codes are loaded into Revit software as 'Assembly Code'. The assembly code is a built-in parameter for Revit families with UniFormat classification developed by the US Construction Specification Institute (CSI). A list of classification codes was created and uploaded in Revit. The designers can select the products for the model based on these classification codes. Figure 5-6 shows the list of classification codes loaded in the 'Assembly Code' in Revit.

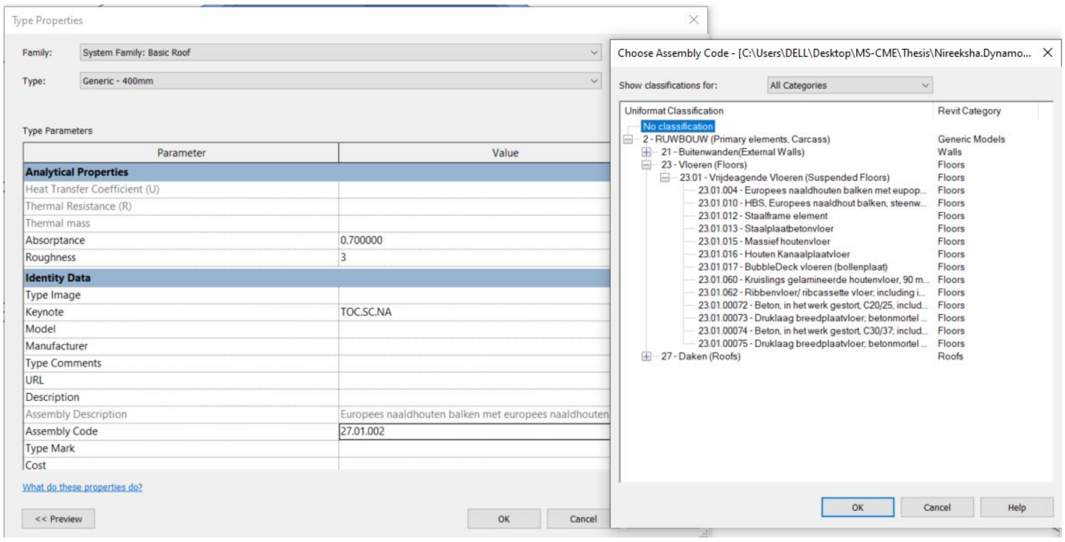


Figure 5-6: Classification codes uploaded as Assembly Code loaded in Revit

5-2-3-2 Design for Disassembly (DfD) Potential Classification

As mentioned in Chapter 4, the assessment of disassembly potential is necessary to determine the reuse potential of a product. In Detachability Index assessment model each factor in the categories is assigned with a certain score between 0.1 (lowest score) and 1 (highest score). The factors contain several types with different scores and unique codes as shown in table 5-2.

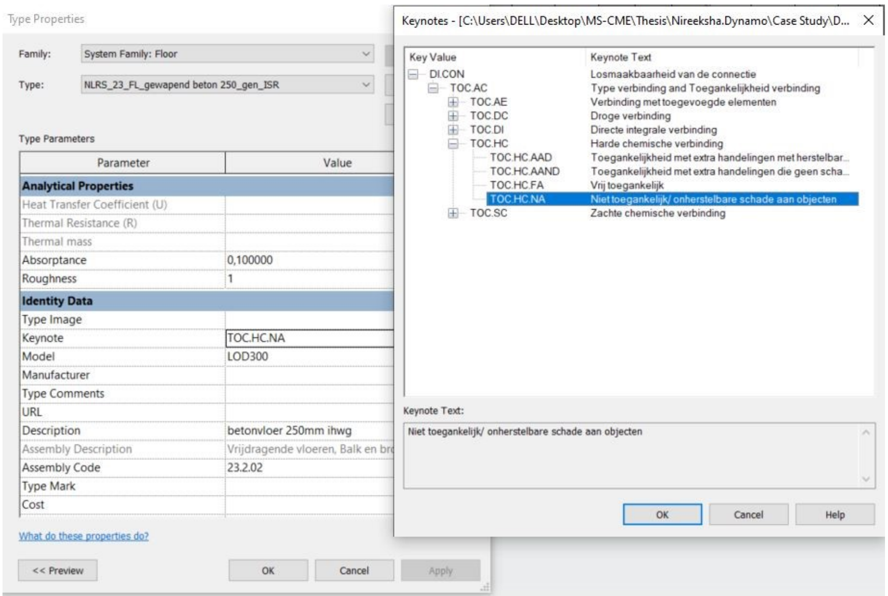


Figure 5-7: Disassembly codes uploaded as Keynote in Revit

DfD factor	Types	Score	Code
Type of connections	Dry connection	1	TOC.DC
	Connection with added elements	0.8	TOC.AE
	Direct integral connection	0.6	TOC.DI
	Soft chemical compound	0.2	TOC.SC
	Hard chemical compound	0.1	TOC.HC
Accessible connection	Free accessible	1	AC.FA
	Accessibility with additional actions with no damage	0.8	AC.AAND
	Accessibility with additional actions with repairable damage	0.4	AC.AAD
	Not accessible- irreparable damage	0.1	AC.NA
Form closure	Open linear	1	FC.OL
	Overlapping	0.8	FC.OV
	Closed on one side	0.2	FC.COS
	Closed on several sides	0.1	FC.CSS
Crossing	Modular zoning	1	CR.MZ
	Intersection between objects	0.4	CR.INT
	Full integration of objects	0.1	CR.FINT

Table 5-2: Disassembly factors, types, scores, and codes

The disassembly potential codes are loaded into Revit as 'Keynote'. Similar to 'Assembly Code', 'Keynote' is a built-in parameter in Revit. The designer can choose the disassembly potential of a product based on these codes. Figure 5-7 shows the disassembly codes uploaded in the Revit. For simplification, the disassembly potential is divided into 'Detachability Index - DI' and 'Detachability Index for Construction - DI CON'. The 'Detachability Index - DI' considers all the four factors (type of connection, accessibility, form closure and crossing) and can be used when the designers can determine all the four factors. Whereas, 'Detachability Index for Construction' considers two factors, mainly, type of connection and accessibility and can be used during the initial stages of design when all the factors are difficult to determine. The combined scores are calculated by the average score of each factor as shown in APPENDX F.

5-2-4 Circularity and environmental impact assessment

The data from the CEI database was used to calculate the circularity and environmental impact of the materials in the model. For the circularity assessment, the MCI value of the products are obtained and imported into Dynamo. Similarly, the environmental impact (EI) of production and construction (Module A), EI of use phase (Module B) and EI of end-of-life (Module C) and EI of beyond end-of-life (Module D) are considered for the impact assessment which is obtained from the CEI database and then imported into Dynamo. Dynamo is a python based visual programming language and a plugin for Revit. It is used to perform the automatic assessment. The MKI (Environmental cost indicator per lifetime of the product) values from the database are multiplied with the quantities obtained from the BIM model to obtain the MKI for the model.

5-2-5 Visualization and Analysis of the result

To assist the designers in designing a sustainable and circular building, it is necessary to provide them with the information which they can interpret easily. In the proposed method, it is possible to visualize the circularity and environmental impact score within the 3D model by color-coding the model elements, as shared parameters in project properties and graphical representation such as pie chart and graph chart.

5-2-6 Multi-criteria Decision Analysis

Multi-criteria decision making (MCDM) method is used for selecting the best alternative product from a list of potential alternative products when its is necessary to make a trade-off between circularity performance and environmental impact. A detailed description on MCDM and type of MCDM method used for the research are explained in APPENDIX F. For the research, TOPSIS (Technique for Order by Similarity to Ideal Solution) method in MS-Excel is used as the MCDM tool as it was found to be the most suitable method to address the identified problem. The TOPSIS method compares the alternatives namely, MCI, DfD, MKI-A, MKI-B, MKI-C and MKI-D based on the weights assigned to the criteria. The product that scores the best based on the given criteria is chosen as the best alternative product.

5-3 Dynamo Script for Circularity Performance

The following sections describe the structure of the dynamo script to determine MCI, Disassembly factor and analyse the circularity performance of the design. The developed scripts consist of the three steps, namely, data extraction from BIM model and CEI database, linking the obtained data and performing circularity calculation, and visualizing the results. Figure 5-8 represents the Dynamo script for assessing circularity, the green color in the scripts represents the data extraction, orange color represents the assessment and purple represents the data visualization. Each sub-script is explained in the following sub-section.

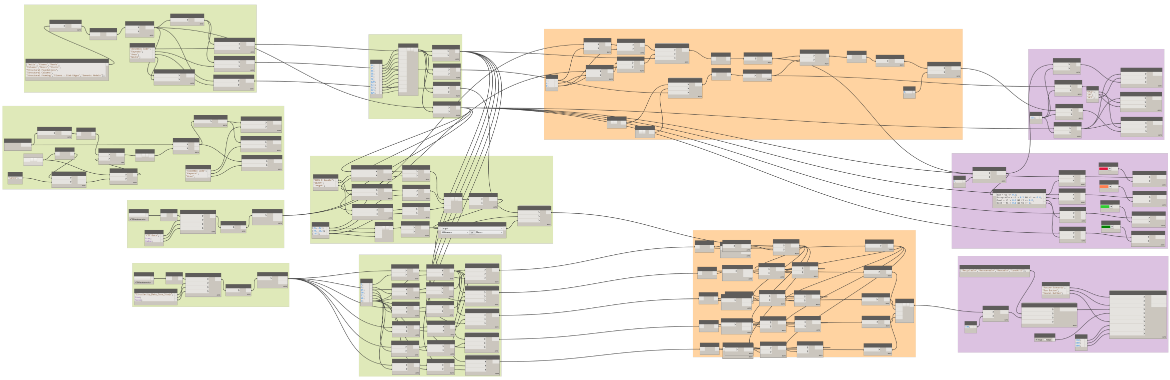


Figure 5-8: Dynamo script for measuring circularity performance (Green color- Data extraction, Orange color- Data linking and assessment, Purple- Visualization of assessment results)

5-3-1 Dynamo script for Extracting data from BIM model and CEI Database

The data required from the BIM model are product classification code, disassembly code and area. Certain number of nodes and python scripts were used to import the data into Dynamo from the BIM model (Figure 5-9). Similarly, product circularity data such as percentage of recyclable, reusable, recoverable contents, and product's mass etc. were imported into the Dynamo environment from the CEI database using a set of nodes (Figure 5-10).

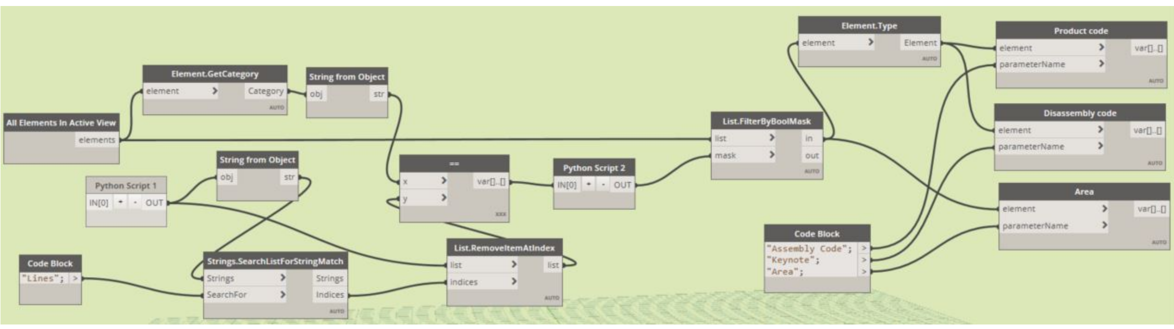
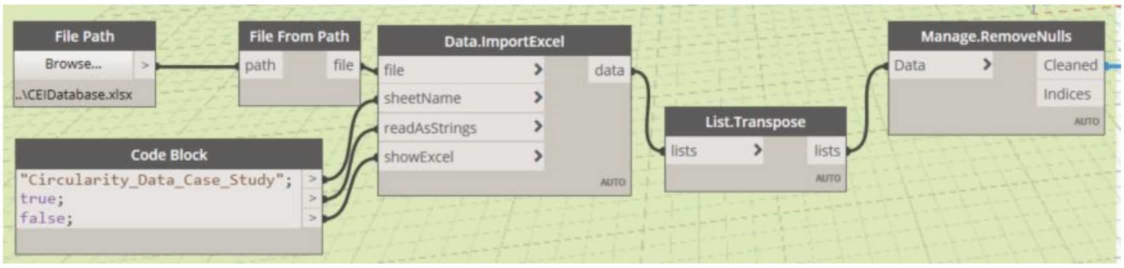
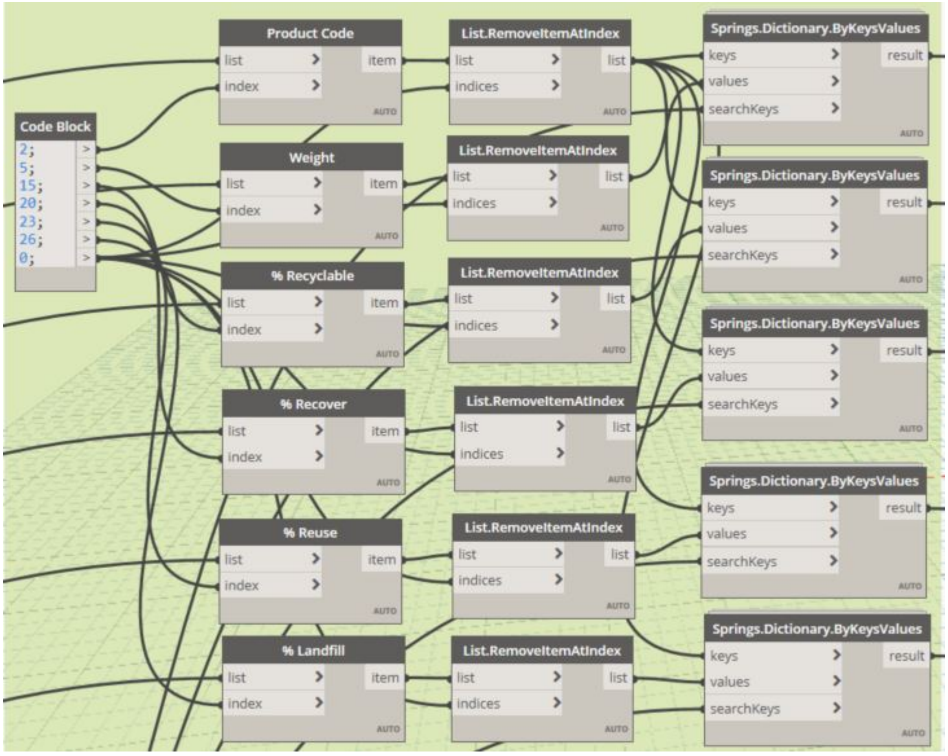


Figure 5-9: Dynamo script for Data Extraction from BIM model



(a)

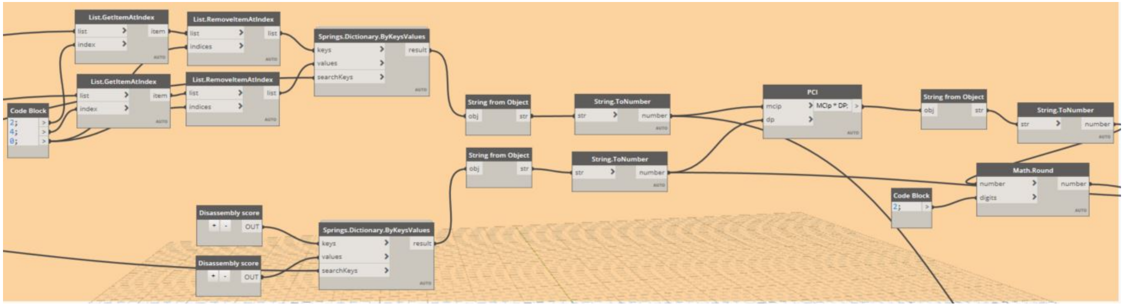


(b)

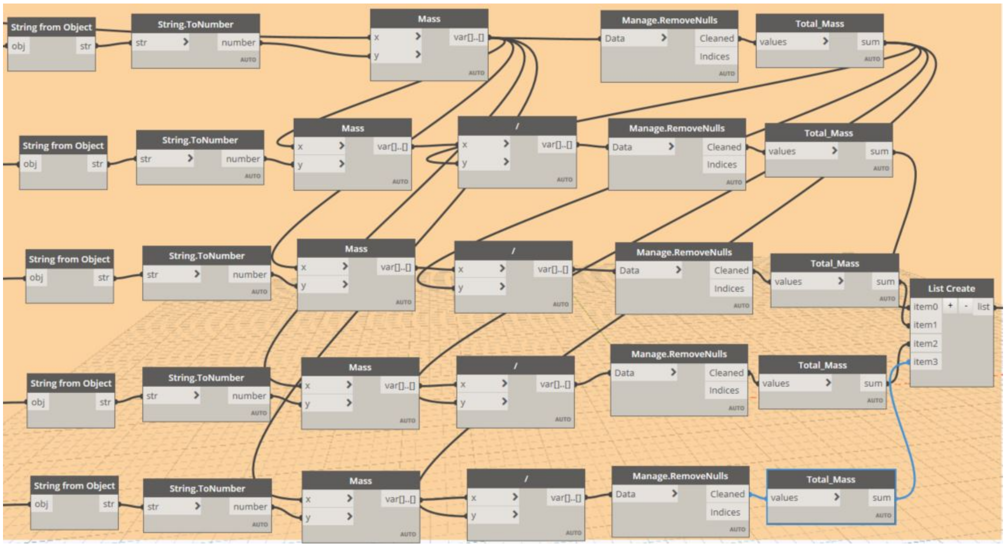
Figure 5-10: Dynamo script for (a) Import of Excel file (b) Data Extraction from CEI Database

5-3-2 Dynamo script for Linking data and performing calculation

After exporting the data from the BIM model and database, the two data were linked to obtained circularity information on the products in the BIM model. Figure 5-11 (a) represents the script used to link the model and the product circularity data from the imported Excel file (i.e. CEI database) by product classification code and disassembly code to obtain MCI and DfD scores of the products in the model. An additional step has been performed to calculate the product circularity score of each product by multiplying the obtained MCI score for products with DfD scores. Figure 5-11(b) represents the script to calculate the total mass of recyclable, reusable, recoverable and disposable contents in the products which were used to determine the future scenario of the products in the model.



(a)

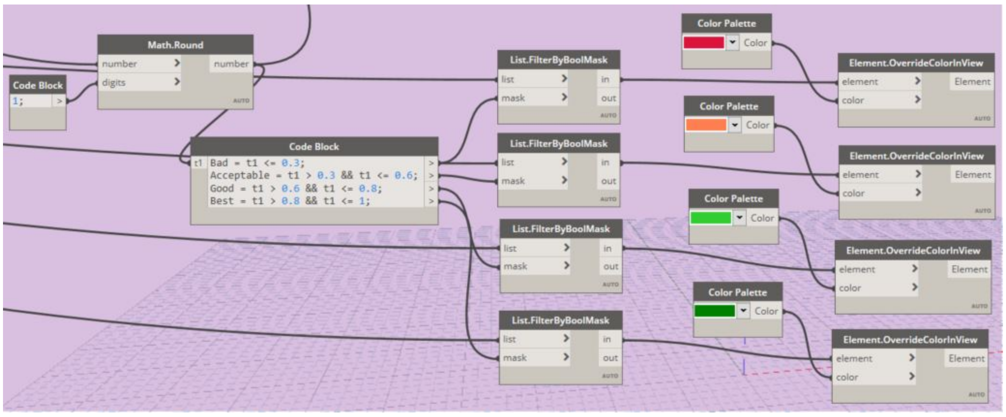


(b)

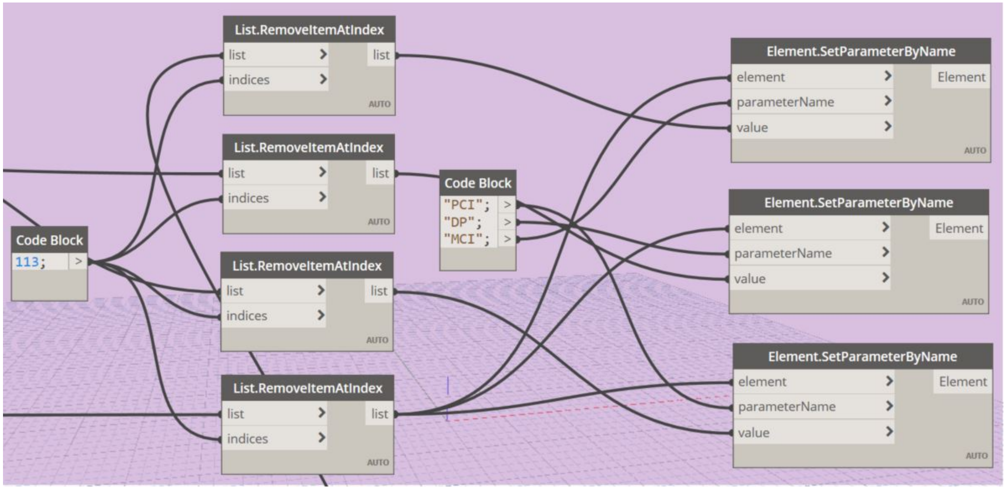
Figure 5-11: Dynamo script for (a) Linking Data and obtaining MCI and DfD scores for the products (b) Calculation of total mass

5-3-3 Dynamo script for Visualization of Results

The results from the assessment were visualized in three forms, namely color override of the elements in the BIM model (i.e. Revit), parameters in the project properties and a graphical user interface window. A script as shown in figure 5-12 was written to visualize the results based on color scheme. A set of color palettes were used to color the elements in the BIM model according to a range of values as shown in table 5-3. Another script was written to view the results of MCI, DP per product in the custom parameter created for each element under Identity Data in Revit as shown in figure 5-12. To analyse the future scenario of the products in the buildings a GUI was created in the form of pie chart. A pie chart presents the percentage by mass of materials that is sent to landfill, energy recovery, recycled or reused for the next cycle. This will help to conduct an analysis of the future scenario and select products for the design with lesser percentage of materials going to landfill and incineration and increase the percentage of reusability and recyclability. To visualize the GUI, a script is written in Dynamo as shown figure 5-13.



(a)



(b)

Figure 5-12: Dynamo script for Result visualization(a) Color override to BIM elements (b) Parameters in project properties

5-4 Dynamo Script for Environmental Impact Assessment

The following sections describe the structure of the dynamo script to perform environmental impact assessment and obtain environmental cost indicator value (MKI) per product and per module (A, B, C and D) as shown in figure G-1. Similar to circularity assessment, the environmental impact assessment script consists of three steps, namely, data extraction, data integration and calculation and visualization of the result. The green color in the scripts represents the data extraction, orange color represents the assessment and purple represents the data visualization

5-4-1 Dynamo script for Extracting data from BIM model and CEI Databse

The data from the BIM model and CEI database were extracted in the same manner as circularity performance. However, instead of circularity data from CEI database, the LCA data was extracted as shown in figure G-2 in APPENDIX G.

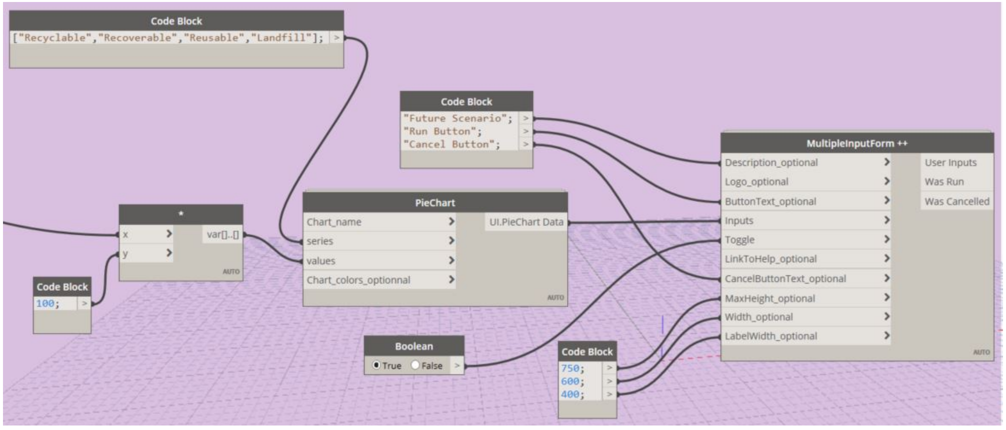


Figure 5-13: Dynamo script for visualization of future scenario

Sl.No.	Description	MCI	Color
1	Unacceptable	0 - 0.3	
2	Acceptable	0 - 0.3	
3	Good	0.6 - 0.8	
4	Best	0.8 - 1	

Table 5-3: Range and Color code for MCI scores

5-4-2 Dynamo script for Linking data and performing calculation

After exporting the data from the BIM model and CEI database, the data were linked to obtain MKI per square meter for each product in the BIM model. The obtained MKI values are then multiplied with the quantity of the products to determine the MKI values of products for the design. The calculation is done for total MKI of products as well as MKI per module. Figure G-3 in APPENDIX G shows the dynamo script for performing the calculation.

5-4-3 Dynamo script for Visualization of Results

The results of the assessment were visualized in four forms. The first type is the color override of the elements in the BIM model (i.e. Revit) as shown in figure5-14 where the MKI values of the product per square meter is visualized. This helps in comparing the products contribution towards the environmental impact as the products in the model belong to different category of components (floor, roof, wall, door etc.) and have different quantities. To analyse the products contribution towards environmental impact based on the design, a script was written to perform relative environmental impact assessment which forms the second type of visualization. The relative assessment helps in identifying the highest contributing product of the design. The third type is visualizing the values in the parameter in the project properties (figure 5-15). The fourth type is the graphical representation of the assessment in form of bar graphs. The bar graphs show the MKI values of elements (wall, floor, roof, door, etc.) per module (figure 5-15).

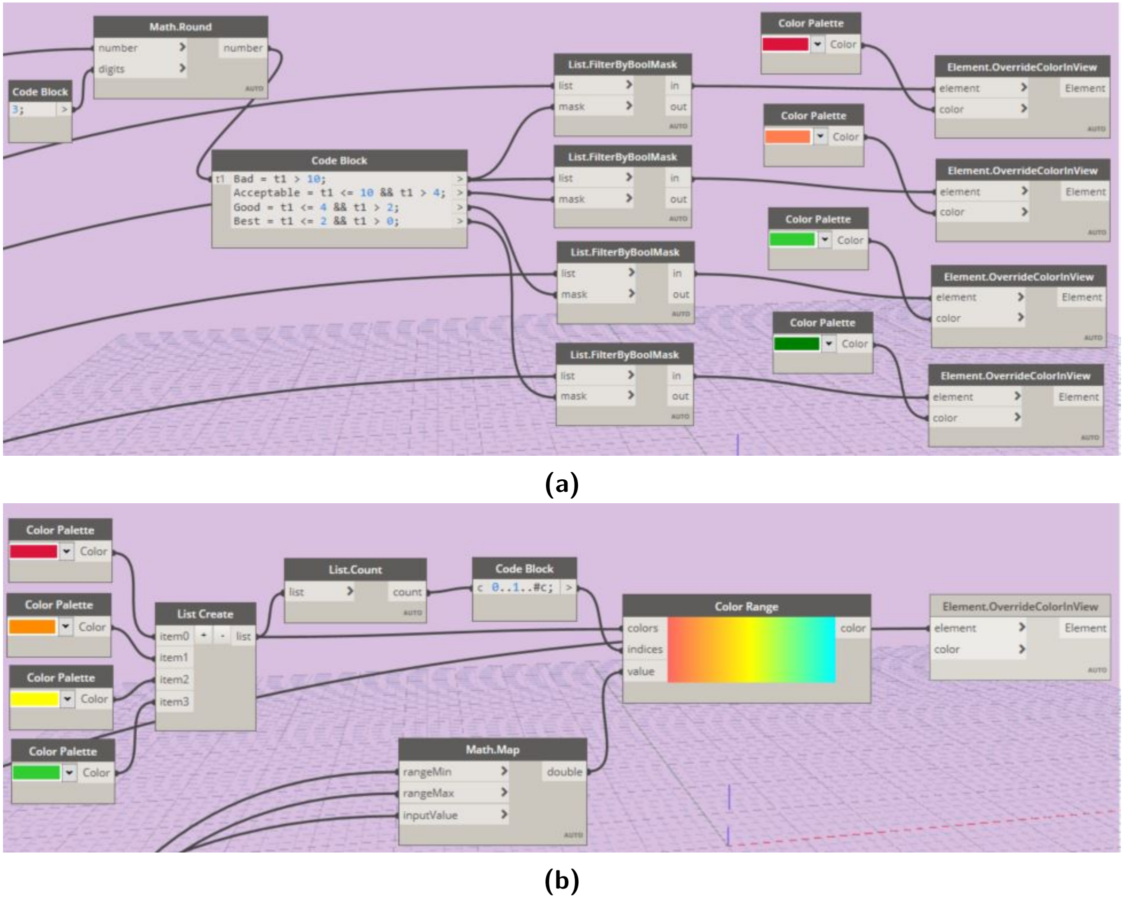
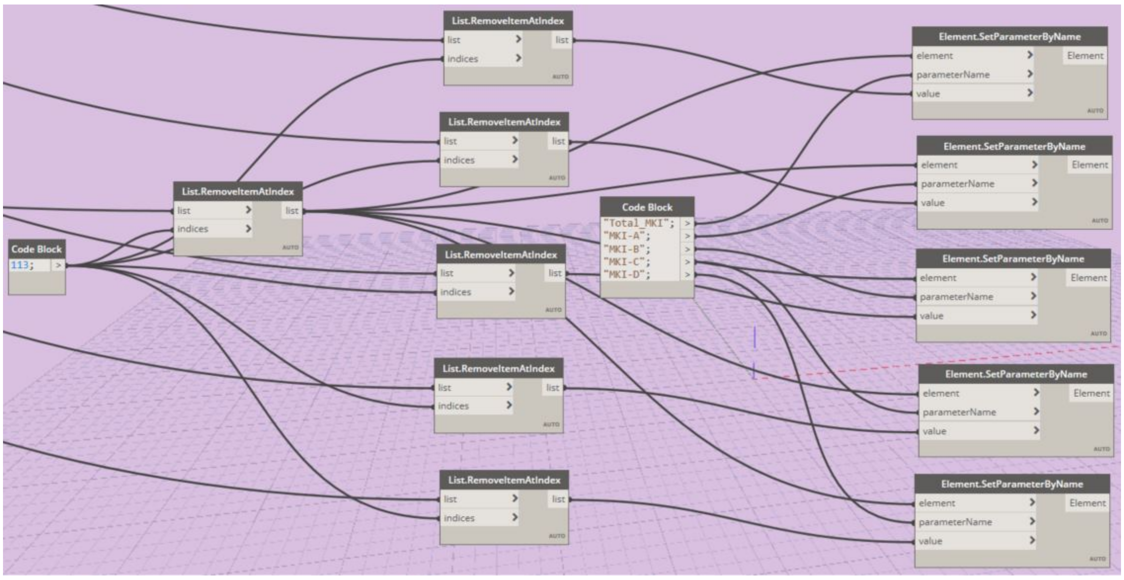


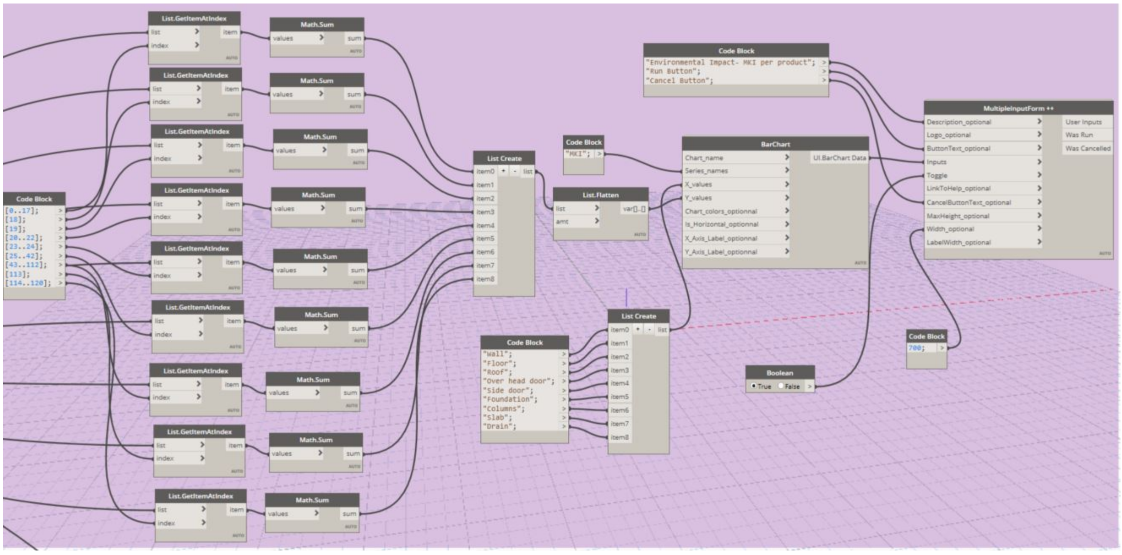
Figure 5-14: Dynamo script for Result visualization(Color override to BIM elements) (a) MKI per square meter (b) Relative MKI

Sl.No.	Description	Shadow Price	Color
1	Unacceptable	above 10	
2	Acceptable	10 - 4	
3	Good	2 - 4	
4	Best	less than 2	

Table 5-4: Range and Color code for MKI scores



(a)



(b)

Figure 5-15: Dynamo script for Result visualization (a) MKI values in project parameters (b) MKI per component as bar graph

Chapter 6

Validation

The previous chapter proposed a framework to perform the assessment for making design decisions. To evaluate the framework a tool was developed using Dynamo and MS-Excel. In this chapter, the framework and the tool will be validated based on four factors: 1) Applicability 2) Accuracy 3) Usability and 4) Effectiveness for decision making and Sustainability and Circularity consciousness. The first two factors are validated by implementing the framework for a case study and third and fourth factors are validated by conducting a workshop.

6-1 Introduction to the Case

A plot on Kustweg in Lauwersoog owned by Rijkswaterstaat is being realized with a new storage space (figure 6-1) for storing oil-fighting trailers and rigid inflatable boats (RHIB). The client wants to meet sustainable ambitions for all the wet support designs and this project is one among them. To meet the sustainability requirement, Witteveen+Bos along with the client considered possible sustainable principles while designing the storage space. Circularity and sustainability aspects are identified in the project as the designers have attempted to design demountable structure, reuse existing materials as far as possible, procure virgin materials from local construction marketplaces, use climbing plants on side walls and install solar panels on the roof in future. Presence of sustainable and circular ambitions during the design phase makes the project suitable to be used as a case study for validating the proposed framework. The other advantage of using the particular case study for validation is that the project is in the design stage (LOD 300) and the developed tool can be used to determine the level of sustainability and circularity in the design and make necessary design changes based on the obtained results to achieve client's objectives.

6-2 Applicability

The developed framework is applied to the Lauwersoog project to investigate the application of the framework on a real-time project and make design decision based on the circularity and

(a) **(b)**

Figure 6-1: Storage space(a)Front view (b)Back view

environmental scores. The arrows and numbering in figure 6-2 represents the process of the application of the developed framework. Firstly, the project was modeled in Revit and the

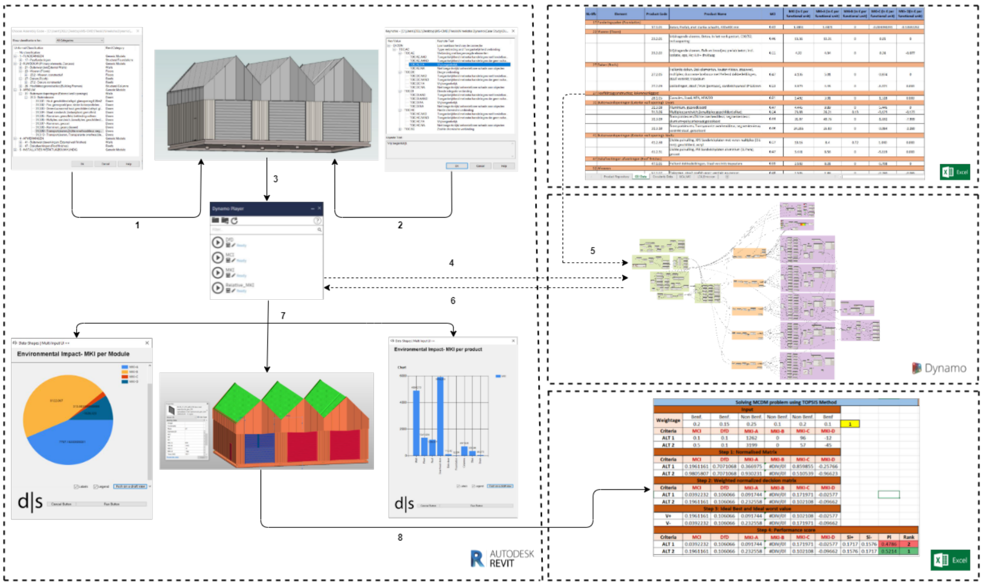


Figure 6-2: System architecture of the proposed framework for the case study

product code (1) and disassembly code (2) were applied to the elements of the model through 'Assembly Code' and 'Keynote' parameters. The products were selected based on designer's choice. The Dynamo player (3) was then used to the run the Dynamo scripts (MCI, DfD, MKI per functional unit and Relative MKI).The Dynamo script extracted the data from the BIM model (4) (Product Code, Disassembly Code and Quantity) and the CEI Database (5) (Product Code, Circularity Data and Environmental Data) depending on the type of script. For assessing circularity performance, the scripts extracts data relating to material circularity indicator, disassembly principles and future scenario of the products. The obtained data are then linked to calculate circularity performance or environmental impact of the products in the design. The assessment is then visualized in the Revit environment (6 and 7) through color overrides on the elements, added shared parameters in the project browser and statistical graphs (pie chart and bar chart). Lastly, multi-criteria decision making tool developed in MS-Excel (8) was used to select the best product alternative considering all the criteria based on user (designers and clients) preference.

6-2-1 Circularity and Environmental Impact Assessment of Products

The model elements considered in LOD 300 are Foundation piles, Floor, Exterior walls, Structural columns, External Doors, Rainwater drains and Roof. A set of products were selected for the elements in the design (design option 1) as shown in table 6-1. The design option 1 was first assessed on circularity performance and based on the results, products with lower circularity score were replaced by other products to improve the circularity performance of the design which formulated the alternative design option (design option 2) as shown in table 6-2. Both the design options are then assessed on environmental impact. A comparative analysis is done for certain products with conflicting circularity and environmental impact results using MCDM tool to decide on the best alternative based on the criteria weights.

Product Code	**Product Name**
17.1.01	Beton; Prefab, met slanke Schacht, 400 x 400mm
23.2.02	Vrijdragende vloeren, Balk en broodjes; prefab beton; incl. isolatie, eps, Rc; 4.0 + druklaag
27.2.09	Bekledingen, staal/ PUR (pentaan), sandwichpaneel d=100mm
28.1.05	Consoles, Staal; HEA, HEA200
31.3.06	Multiplex; sandwich;2xmultiplex; geschilderd: alkyd;
31.3.09	Transportdeuren, Dichte overheaddeur; segmentendeur; alumium + polycarbonaat, geisoleerd
41.2.30	Dichte puivulling, XPS Sandwichplaten met vuren multiplex (3.6mm); geschilderd, acryl
52.1.07	Dakgoten, staal; prefab goot; verzinkt en gecoate

Table 6-1: Products for Design option 1

Product Code	**Product Name**
17.1.01	Beton; Prefab, met slanke Schacht, 400 x 400mm
23.2.02	Vrijdragende vloeren, Beton, in het werk gestort, C30/37; incl. wapening
27.2.05	Hellende daken, Dak elementen, houten ribben steenwol, multiplex; duurzame bosbouw met Hellend dakbekkingen, staal verzinkt; trapezium
28.1.05	Consoles, Staal; HEA, HEA200
31.3.08	Aluminium, geanodiseerd
31.3.10	Transportdeuren, Transparante overheaddeur; segmentendeur; verzinkt staal, geisoleerd
41.2.30	Dichte puivulling, PIR Sandwichplaten aluminium (0.7mm); gecoat
52.1.07	Dakgoten, staal; prefab goot; verzinkt en gecoate

Table 6-2: Products for Design option 2

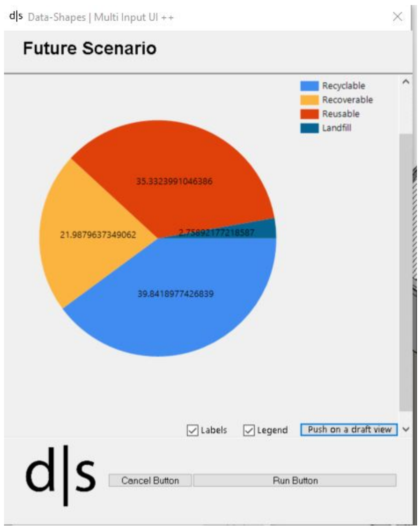
Circularity Performance: Design option 1

The products considered for the model elements are shown in Table 6-1. The results of the assessment are shown in figure 6-3. As shown in the figure 6-3 (a),the circularity score for all the elements except overhead doors, columns and foundation pile were in the unacceptable range. The MCI, DfD and PCI score of each product was visualized through the added shared parameter in the project properties. The MCI, DfD and PCI score for floor are shown in figure 6-3 (a). Furthermore, the future scenario of the design option was analysed through a pie chart (figure 6-3 (b)). The pie chart indicated that around 24.85% materials in the design will be waste (2.758% for landfill and 21.987% for energy incineration or recovery) and 35.33% will be reusable and 39.84% will be recyclable. The origin scenario of the products was not analysed as all the products were considered to be primary materials.

(a)

Sl.No.	Description	MCI	Color
1	Unacceptable	0 - 0.3	
2	Acceptable	0 - 0.3	
3	Good	0.6 - 0.8	
4	Best	0.8 - 1	

(b)

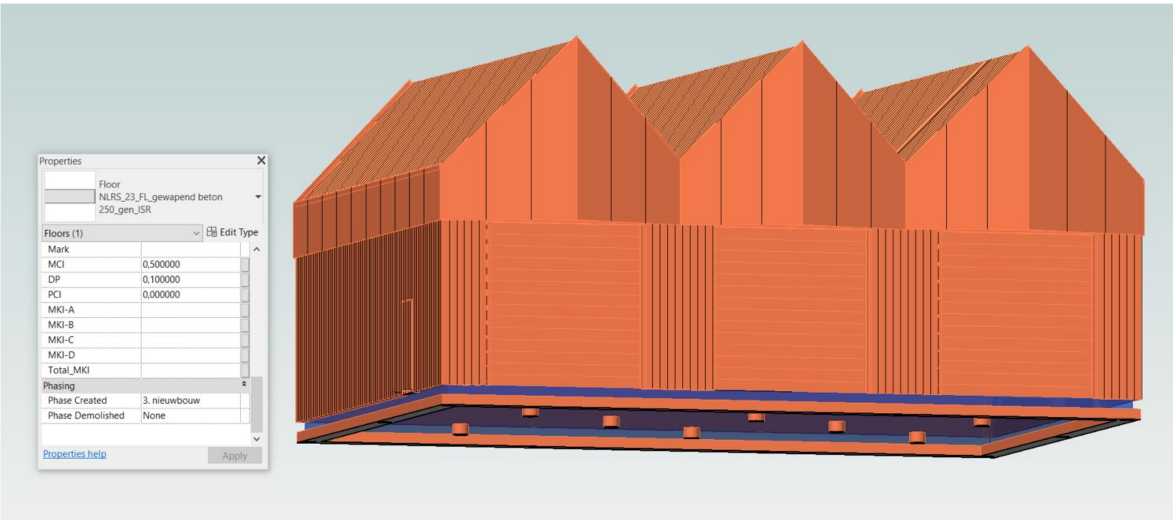


(c)

Figure 6-3: Visualization of Circularity Performance(a) Color override and Parameters in Project Properties (b) MCI range for interpretation of color override of elements (c) Future Scenario

Circularity Performance: Design option 2

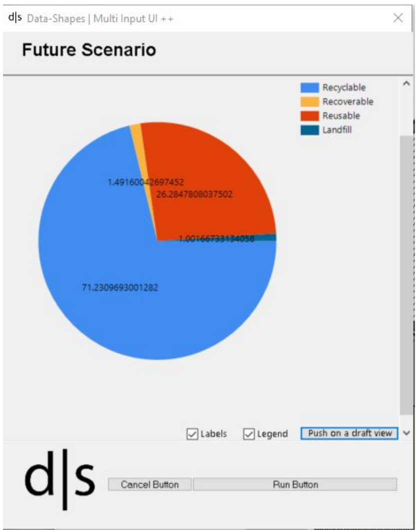
Based on lower circularity score for design option 1, products with low MCI were replaced by different products to obtain higher circularity score. The products considered for the new design option are as shown in the table 6-2. As shown in the figure 6-4, the circularity score for all the elements were in the acceptable range. The future scenario (figure 6-4 of the design option indicated 71.2% of materials were recyclable and 26.28% were reusable whereas only 1.49% were recoverable and 1% were to disposable. Based on this, design option 2 is preferred to design option 1.



(a)

Sl.No.	Description	MCI	Color
1	Unacceptable	0 - 0.3	
2	Acceptable	0 - 0.3	
3	Good	0.6 - 0.8	
4	Best	0.8 - 1	

(b)

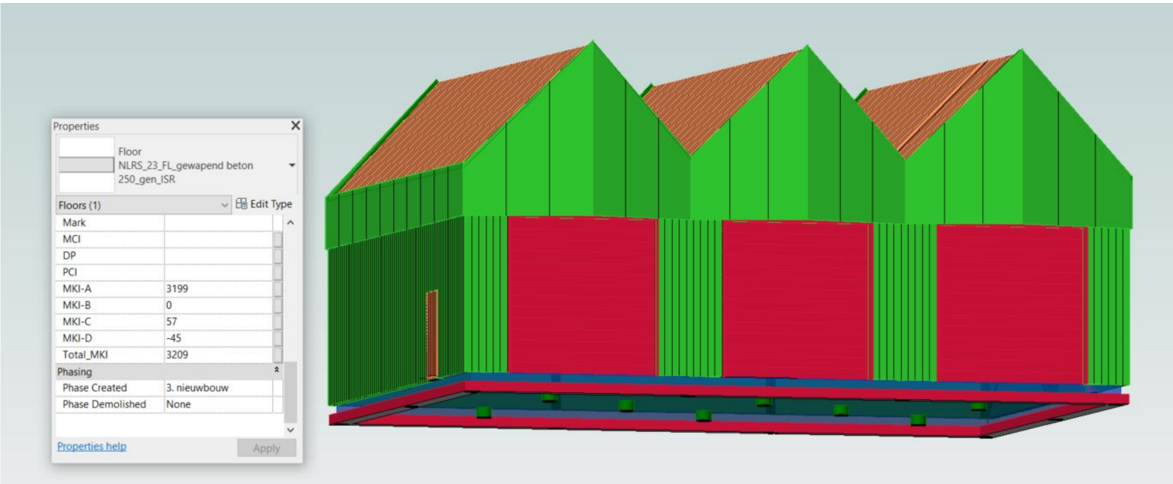


(c)

Figure 6-4: Visualization of Circularity Performance(a)Color override and Parameters in Project Properties (b) MCI range for interpretation of color overrides of elements (c) Future Scenario

Environmental Impact: Design option 2

The environmental impact of design option 2 was performed first as the design option 2 was more circular compared to design option 1. As mentioned earlier, the environmental impact was assessed in term of shadow price (MKI). Firstly, the impact is assessed based on the functional unit of products per sq.m which makes it easier to quickly visualize the environmental impact of the products and analyse the hotspots. The color overrides in the BIM model is shown in figure 6-6. From the analysis of figure, it was observed that the floor and overhead doors have higher impact followed by roof and side door. Further analysis was made by performing relative MKI assessment as shown in figure 6-6. The relative MKI assessment provides more realistic data regarding the products contribution towards environmental impact based on their design by comparing the environment impact of the products within the design.The color range adopted for the relative MKI is a heat map with red color indicating the product with the highest environmental impact and dark green color indicating the product with the lowest environmental impact and all the other products get a similar color based on its impact when compared to the highest and lowest impact.



(a)

Sl.No.	Description	Shadow Price	Color
1	Unacceptable	above 10	
2	Acceptable	10 - 4	
3	Good	2 - 4	
4	Best	less than 2	

(b)

Figure 6-5: (a) Environmental impact of products in Euro per square meter (b) MKI range for interpretation of color overrides of elements

The graphical representation of the assessment results are shown in figure 6-6 which helps in better interpretation of the obtained results. The pie chart shows the overall environmental cost per module (A, B, C, and D). This helps the designers to focus on improving overall MKI of the design. To support this, a graphical representation of environmental impact per component for each module was obtained and are shown in APPENDIX H. From the

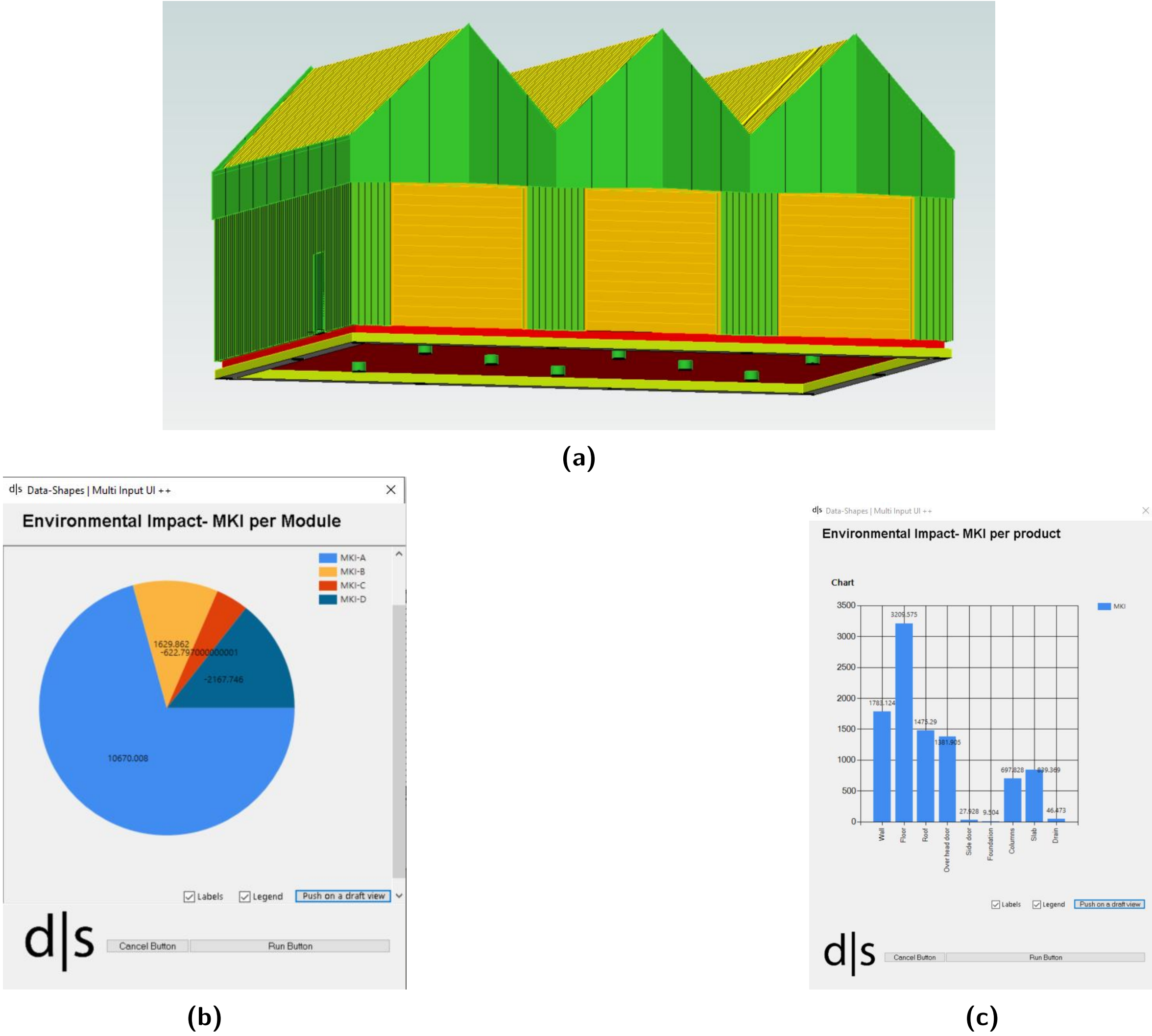
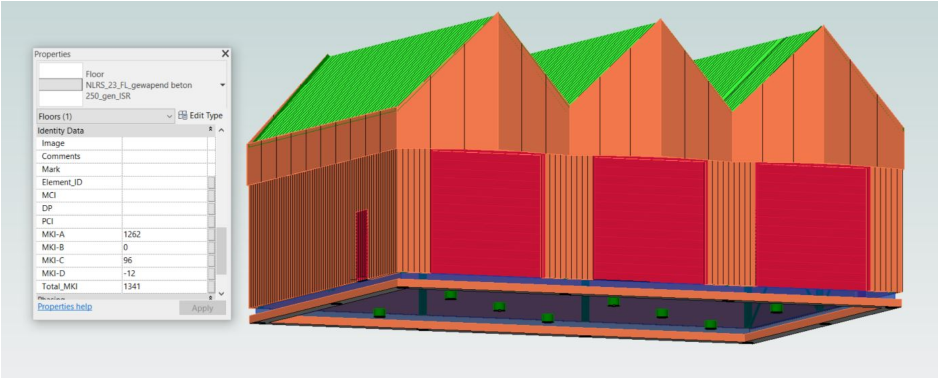


Figure 6-6: Environmental impact assessment (a) Relative Environmental impact of products (b) per module (c) per products

figure 6-6 (a) and (c) it was seen that the floor has a relatively high environmental impact contribution to the design when compared to other components in the design.

Environmental Impact: Design option 1

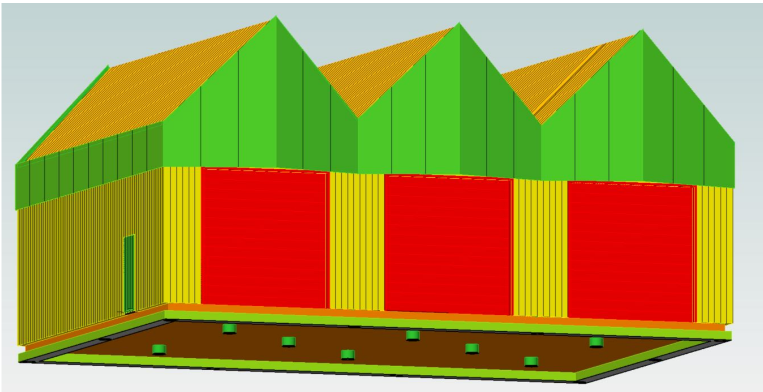
The environmental impact of design option 2 showed the need to improve on environmental impact of floor due to which environmental impact assessment was performed on design option 1. The environmental impact assessment is carried out in the same manner as design option 2. Figure 6-7 (a) shows the MKI of products per functional unit (b) shows the range for evaluation of MKI and figure 6-7 (c) shows the relative MKI. The graphical representation of assessments results per module and components are shown in APPENDIX H. Based on the assessment results, it was seen that the environmental impact of products of floor and roof were lower when compared to the design option 1.



(a)

Sl.No.	Description	Shadow Price	Color
1	Unacceptable	above 10	
2	Acceptable	10 - 4	
3	Good	2 - 4	
4	Best	less than 2	

(b)



(c)

Figure 6-7: (a) Environmental impact of products in Euro per sq.m (b) MKI range for interpretation of color overrides of elements (c) Relative Environmental impact of products

6-2-2 Multi-criteria decision making (MCDM)

Based on the circularity performance the design option 2 was a better choice. But the floor and roof in design option 1 performed better than design option 2 in terms of environmental impact performance. As mentioned earlier, when such a situation arises, it is necessary to make design choice based on project requirements. The weights for each criteria was decided in consultation with the sustainability expert and the designers based on clients requirement to meet sustainability. Figure 6-8 shows the multi-criteria decision for floor and roof. For obtaining the best alternative, it is necessary to fill in the results of the criteria (MCI, DfD, MKI- A,B,C,D) manually from Revit. Based on the analysis it was observed that the floor of design option 2 and roof of design option 1 were the best alternative.

Solving MCDM problem using TOPSIS Method										
Component:	Floor									
Input										
Weightage	Benf.	Benf.	Non Benf.	Non Benf.	Non Benf.	Non Benf				
	0.15	0.2	0.25	0.1	0.1	0.2	1			
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D				
Option 1	0.1	0.1	1262	0	96	-12				
Option 2	0.5	0.1	3199	0	57	-45				
Step 1: Normalised Matrix										
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D				
Option 1	0.196116	0.707107	0.366975	0	0.85985	-0.25766				
Option 2	0.980581	0.707107	0.930231	0	0.51054	-0.96623				
Step 2: Weighted normalized decision matrix										
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D				
Option 1	0.029417	0.141421	0.091744	0	0.08599	-0.05153				
Option 2	0.147087	0.141421	0.232558	0	0.05105	-0.19325				
Step 3: Ideal Best and Ideal worst value										
V+	0.147087	0.141421	0.091744	0	0.05105	-0.19325				
V-	0.029417	0.141421	0.232558	0	0.08599	-0.05153				
Step 4: Performance score										
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D	Si+	Si-	Pi	Rank
Option 1	0.029417	0.141421	0.091744	0	0.08599	-0.05153	0.187	0.141	0.4289	2
Option 2	0.147087	0.141421	0.232558	0	0.05105	-0.19325	0.141	0.187	0.5711	1

(a)

Solving MCDM problem using TOPSIS Method										
Component:	Roof									
Input										
Weightage	Benf.	Benf.	Non Benf.	Non Benf.	Non Benf.	Non Benf				
	0.15	0.2	0.25	0.1	0.1	0.2	1			
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D				
Option 1	0.2	0.25	1589	0	160	-538				
Option 2	0.5	0.25	1788	0	-310	0				
Step 1: Normalised Matrix										
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D				
Option 1	0.371391	0.707107	0.664286	0	0.45864	-1				
Option 2	0.928477	0.707107	0.747479	0	-0.88862	0				
Step 2: Weighted normalized decision matrix										
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D				
Option 1	0.055709	0.141421	0.166071	0	0.04586	-0.2				
Option 2	0.139272	0.141421	0.18687	0	-0.08886	0				
Step 3: Ideal Best and Ideal worst value										
V+	0.139272	0.141421	0.166071	0	-0.08886	-0.2				
V-	0.055709	0.141421	0.18687	0	0.04586	0				
Step 4: Performance score										
Criteria	MCI	DfD	MKI-A	MKI-B	MKI-C	MKI-D	Si+	Si-	Pi	Rank
Option 1	0.055709	0.141421	0.166071	0	0.04586	-0.2	0.159	0.201	0.5591	1
Option 2	0.139272	0.141421	0.18687	0	-0.08886	0	0.201	0.159	0.4409	2

(b)

Figure 6-8: Multi-criteria decision making (a) Floor (b) Roof

6-2-3 Conclusion

The assessment performed on the two design options reflects the design's level of circularity and environmental impact. The decision-making process demonstrate the importance of assessing the circularity performance and environmental impact of products to enhance the design and products choice for the building. Figure 6-9 shows the process of making product choices. The outcome of the decision-making process revealed that products from design option 2 except for the roof was a better choice for the design of the building. In comparison, the product for the roof in design option 1 proved to be a better choice when compared to design option 2. The decision-making process shows that the developed framework and the tool are applicable for real-time projects and can support making design decisions.

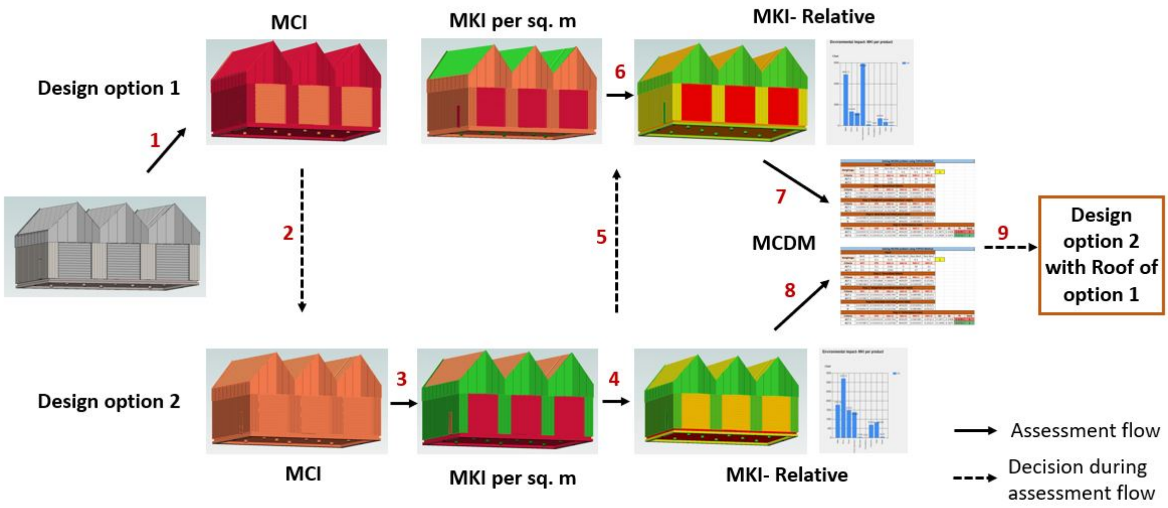


Figure 6-9: The decision-making process for product selection

6-3 Accuracy

The accuracy of the assessment is verified by comparing the assessment results from the developed tool with the results from existing commercial tools. The verification is performed to ensure that the circularity (MCI) and environmental cost indicator (MKI) of the products in the design obtained from the developed tool provide similar results as the existing commercial tools. For circularity performance assessment, the MCI score from the developed tool was compared with MCI Product-Level Dynamic Modelling Tool developed by Granta Design Ltd (co-founded by the EU's Life programme) and Ellen MacArthur Foundation. Based on the comparison, it was seen that 100% accuracy was obtained for MCI calculation for all the selected products of the design. For verifying the results of the environmental impact of the products from the developed tool, the BIMPACT tool which is verified and certified by the NMD was used by manually entering the quantities of the products in the BIM model. APPENDIX I shows the comparison of the MKI results between the developed tool and the BIMPACT tool for all the elements in the BIM model. The comparison results show that there is a difference (not more than 0- 5 %) between the two results, which can be due to rounding of the quantities of the elements during manual calculation. Overall, the developed tool provides similar results (95% - 100% accuracy) as that of the results from the commercial tool.

6-4 Workshop

A workshop was conducted with experts from Witteveen+Bos building team to validate the proposed framework. The workshop was conducted with experts namely, architect, BIM designer, BIM co-ordinator, and sustainability and circularity advisors from Witteveen+Bos. The focus of the workshop was to determine the usability of the developed tool from a user perspective and investigate the implications of the tool for making design decisions and sustainability and circularity consciousness. The session started with a presentation on the developed framework and application of the tool for the Lauwersoog project. The presentation was followed by a discussion round where the experts were allowed to ask questions regarding the framework or the tool. After the discussion round, a set of questionnaires (16 questions), as shown in APPENDIX J, were sent to the experts to fill in. The questions were based on the applicability of the framework in practice, usability and sustainability and circularity consciousness, including questions related to added value, recommendations for improvement and barriers/challenge and changes required for implementation.

6-5 Usability

During the workshop, the application of the developed tool on the Lauwersoog project was demonstrated to discuss the user perspective for performing the assessment and making decisions. The experts think that the proposed framework has the ability to fasten the current workflow. During the discussion session, it was identified that more time should be invested initially to build the database, and when the database contains all the products data, the assessment becomes easy and will save time especially in the later stages of the design. Also, the experts agreed on the possibility to assign product and disassembly codes to the BIM elements. The multi-criteria decision-making tool was found useful by the experts as the decision on the alternative depends on the different aspects and the importance of each aspect depends on the objective of each project.

6-6 Effectiveness for decision-making and Sustainability and Circularity consciousness

Based on response from the experts to the questionnaires, the tool developed on the proposed framework was acknowledged to significantly improve the decision-making process for making design choices (wood, steel or concrete construction) during the preliminary design stage (i.e. LOD 200) and for selecting products for the design during detailed design stage (i.e. LOD 300 and above). Majority of the experts, especially the sustainability and circularity advisors agreed that the proposed method of assessment will improve efficiency of building design by incorporating sustainability and circularity aspects in a better manner when compared to current method. They also see that the visualized results from the assessment are easier to interpret, present and discuss with clients to make design decisions on design alternatives. The architect and BIM modeler believe that the tool will eventually foster their circularity and sustainability consciousness which is comparatively less in the current workflow.

Chapter 7

Discussion

In this chapter the results and main findings of the research are discussed followed by the limitations of the research.

7-1 Discussion on the Research Objective

In Chapter 1 the problem identified was stated. It was found that there is a need to achieve a sustainable circular economy by assessing the implementation of circular strategies based on its environmental impact. Currently, the assessments are performed towards the end of the design stage when all the design decisions are made. Thus, the objective of the research was to propose a framework that can support the decision-making process during design phase to facilitate a sustainable and circular design. To meet the objective of the research two goals were set:

1. Define the indicators that assess the circular design principles and environmental impact of design and the appropriate BIM integration approach.
2. Develop a framework and a tool based on the framework to perform an automated assessment during the design stage and support the designers in decision making.

The outcome was a set of sixteen indicators and a tool developed using BIM tool (Autodesk Revit and Dynamo) and MS Excel. The designer needs to determine the product classification code and disassembly code to perform the assessment. Based on previous literature and the research, it was seen that it is not necessary that the circular products are sustainable and a trade-off between circularity and sustainability must be made [17]. Every project has different objectives and using multi-criteria decision-making tool, it is possible to make decisions in conflicting situations based on the project objectives [20]. Thus, the designer can make use of the multi-criteria decision making tool to select the best alternative in conflicting situations. The results from the tool is the design choice for a project based on circularity performance and environmental impact.

7-2 Discussion on Circularity Assessment

For the research, MCI and Detachability Index (DI) models were used for assessing the circularity performance. The data of the products were based on expert judgement as there is lack of circularity database. However, to perform the circularity performance the details on the source, lifetime and future scenario (demountability, reusability, and recyclability) of the sub-product or the product as a whole is necessary. Currently the circularity details of products are not available and these details needs to be provided in EPDs or should be provided by the suppliers and a database of the products needs to be created in future for accurate assessment.

7-3 Discussion on the Environmental Impact Assessment

Based on the research it was observed that the environmental impact assessment of products are influenced by building design, reliability of the database and the calculation rules adopted for the assessment. Each factor is discussed below:

1. *Calculation rules for the assessment:* During the literature study, several environmental impact allocation methods were reviewed and it was identified that the results from the allocation methods differ significantly, making the assessment results incomparable [50]. The other observation made was on the use of impact categories for environmental impact assessment. The results of the environmental impact assessment depend on the selection of impact categories and their weighting during the inventory analysis. Also, the existing allocation methods cannot effectively consider circularity principles such as demountability/reuse practice in their calculation steps, thereby making the assessment method limited for adopting for CE assessment. Thus, there is a need to realize a single calculation rule with standardized impact categories for obtaining reliable and precise environmental impact results [50]. The selection of impact categories could be based on its importance and emission values. For instance, impact categories such as Global Warming (GWP) and Ozone layer depletion are important and have higher emission contributions than impact category such as fine particulate emissions. Reducing the impact categories will help in analyzing the environmental impact of products based on product phases (Module A, B, C, and D) as well as impact categories (Climate change, Ozone depletion etc.) by designers. For instance, ecotoxicity can be considered as a single impact category instead of dividing it into three sub-categories: fresh, marine and terrestrial ecotoxicity.

2. *Building design:* The lifetime of a building design has a significant impact on the assessment results. For instance, a building with shorter lifespan will have higher environmental impact unless it possess principles such as design for adaptability and design for disassembly. Thus, there is a need to focus on the technical service life of products and the building lifetime and determine the products future scenario. Also, during the environmental impact calculation of products, it was seen that most of the products were not assessed on the environmental impact of the use phase. The reason could be that it is difficult to interpret as the use phase of a product depends on the location of the product used and maintenance frequency. Hence, it is incorrect to use the generalized

values of use phase (Module-B) from the database/EPDs. However, the information (such as maintenance frequency and future scenarios) in the EPDs regarding Module B and C will be beneficial while performing the assessment.

3. *Database:* The environmental impact assessment currently depends on the data in the database. The NMD database is used in the Netherlands for environmental impact assessment which has limited number of products data and the calculation rules especially the scaling factors are not explicit. It was also noted that the database is updated every 5 years, thus making few product data outdated. Thus, the limited products data and non transparency of the database make the assessments results unreliable. Thus, there is a need to have right information in the database to obtain accurate results.

7-4 Discussion on the Database

As mentioned earlier, the NMD datbase is used for performing the assessment. However, the current NMD viewer does not allow users to access full data making it incomplete for the research. Due to which a commercial tool that is certified by NMD was used to obtain MKI/ FE of products. If the NMD is complete then it is recommended to link the developed CEI database with the NMD database. It is important to note that the developed tool is applicable for building products within the Netherlands. The issue with the database is the limited variety of products making it difficult to perform environmental impact assessment. From the literature it was seen that most of the databases consist of traditional products and fail to consider sustainable/ bio-based materials and secondary products, thereby limiting the accuracy of the assessment [27]. The other challenge identified is that the LCA databases lack a standard structure and differ in the information. For instance, few products are assessed on Module B(use phase) and few or not assessed. For reliable assessment, the databases should contain EPDs with all the information required for circularity and environmental impact assessment in a standard structured format.

7-5 Discussion on the Developed tool

From the research objective, it was known that a tool a needs to be developed to support the designers whose expertise do not lie in circularity and environmental impact assessment. Hence, it was necessary to mainly test the tool based on its effectiveness to support the designers in the decision-making process. For this purpose, the tool was applied to a real-time project to demonstrate to the designers to get feedback on the usability and its effectiveness in supporting the design decisions. The design of the case study used in the research was in LOD 300, therefore the framework was applied in the initial stage of detailed design stage by selecting the products for the determined elements. However, it was observed that the tool can be used in the early design stage (LOD 200) for selecting the design variant such as concrete, steel or timber construction. Based on the demonstration, a positive feedback was received on the usability and benefits of using the tool to assist in decision-making. An example discussed during the workshop was the requirement of overhead doors in the design of Lauwersoog. Based on the assessment, it was observed that the overhead doors had a high environmental impact, which can make the designers re-think to use of the element and check the possibility to alternate the product or minimize the number of elements. Thus, the assessment results can be used to optimize the design by alternating the product for the elements or changing the design itself.

A few limitations of the tool were identified and discussed during the workshop. The majority of the experts think that the most challenging issue for using the tool is the database development as there is a lack of a standardized method to obtain information on products. The other challenge that was foreseen was organizational and managerial acceptance. The BIM coordinator anticipates the lack of support from the project leaders/managers and management team to accept the new workflow and invest time setting up the database and making design decisions by performing the assessment. However, this can be eliminated by implementing the tool for few projects and showing the benefit of the proposed workflow and assessment method and how the new method saves time and helps optimize the design. One of the BIM coordinator's recommendations was to create separate parameters and standardize them for assigning the classification and disassembly codes instead of using the built-in parameters because the parameters used in the tool are already being used for other purposes.

7-6 Limitations of the research

Some limitations of the research are as follow:

1. The research does not consider economic and social aspects of sustainability, adaptability potential and is specific to Dutch construction industry.
2. The assessment results visualized in the BIM environment is reliable as long as the information in the database are reliable.
3. The framework aims in automating the assessment, however, there is a need for a sustainability and circularity expert to develop the database and update it when new products are used for the design.
4. For the development of prototype the MKI values per product is obtained from a commercial tool instead of the NMD database.
5. The developed tool considers only eleven impact categories for MKI calculation, however, from 2021 the Netherlands has proposed nineteen impact categories that should be considered for MKI calculation for Dutch construction industry.
6. The tool is developed only for Revit users.
7. Due to time constraints, a simple model is used as a case study. Hence, the assessment is performed for limited elements (Walls, Floor, Foundation piles, Columns, Roofs, Rainwater drains and Doors).
8. The developed tool is validated from limited user's point of view and the benefits and drawbacks are drawn based on limited responses.

However, most of the limitation of the research can be considered as opportunities for future research and hence, addressed in the future scope for research and recommendation for implementation in practice in the next chapter.

Chapter 8

Conclusion

In this chapter, a conclusion is drawn by answering the research-questions. The thesis report is concluded by providing few recommendations for practice and future research.

8-1 Conclusion

The objective of the research as mentioned in Chapter 2 is as follows:

"Propose a BIM-based framework to enable assessment of environmental impact and circularity performance of products in building to support the designers for making design decisions based on the assessment during the design phase."

To meet the objective of the research, a research question was framed and to answer the research question five sub-research questions were formed. Hence, a conclusion is drawn by answering each sub-research question individually followed by main research question.

8-1-1 Sub-Research Questions

SQ1: What is the link between circular economy and sustainability? How can we apply the Circular Economy principles in the Built environment?

The sustainability and circular economy concepts are interrelated concepts to meet current concerns such as climate change, and resource depletion etc. Based on previous literature, the application of CE concept is seen as a movement to meet the goals of sustainability and hence, plays a significant role in relation to sustainable development. The application of circular principles in the built environment helps in transition from a Linear Economy to Circular Economy. The main design principles include: 1) design out waste by keeping the materials and products in use) 2) design for disassembly by closing the loop through reuse, remanufacture, refurbish or recycle of materials or products. 3) design for adaptability by extending the life of the products or materials. These principle can be used to determine the indicators necessary for CE assessment.

SQ2: What are the necessary indicators for assessing circularity and environmental impact in the built environment? What are the existing methods to perform the assessment?

Based on the literature review, it was observed that no consensus has been made on the circularity metrics for built environment. Measuring circularity is a new topic and is developing gradually. However, several existing methods to measure CE in the built environment were reviewed. The most recent study (i.e. CB'23 platform) classifies the CE indicators into three categories: 1) *protecting material stocks*, 2) *protecting the environment* and 3) *protecting existing valu*e. Based on the scope of the research the indicators in category *protecting material stocks* and *protecting the environment* are considered. The indicators within these categories are shown in table 8-1.

Circularity Indicators	Environmental Impact Indicators	Environmental Impact Indicators
Quantity of input materials: virgin, recycled, reused materials	Climate change -Global Warming (GWP)	Human toxicity (HTP)
Quantity of output materials: recyclable, reusable, recoverable, landfill	Ozone layer depletion (ODP)	Freshwater aquatic ecotoxicity (FAETP)
Disassemby potential	Acidification (AP)	Marine aquatic ecotoxicity (MAETP)
Recycling efficiency	Eutrophication (EP)	Terrestrial ecotoxicity (TETP)
Utility	Photochemical oxidation (POCP)	Depletion of fossil fuels and abiotic raw materials (ADP)

Table 8-1: Indicators for measuring CE

The research reviewed existing circularity and environmental impact assessment models. Upon evaluation of the circularity model, the research proposes to integrate MCI and Detachability index model for circularity assessment. For environmental impact assessment, the the 'Bepalingsmethode Milieuprestatie gebouwen en GWW-werken' allocation method is considered as the research is being carried out in Netherlands. The indicators (impact categories) considered in the method are mentioned in table 8-1.

SQ3: How can BIM support the design making process? What are the current integration approaches and challenges between BIM and assessment methods?

The decision-making process during the design stage is complex as the design decisions depend on several factors. BIM can reduce the complexity during the design stage by generating and managing building life cycle data required during the design stage and selecting design alternatives and products. Based on the literature, the features of BIM that make it suitable for making design decisions by considering the whole life cycle performance of buildings include 1) *object parametric modelling* that utilizes various parameters and specific rules to capture the design and functionality of a building,2) *bi-directional associativity* ensures that adequate support is provided for making changes in the design models, 3) *intelligent modelling* ensures that additional information is provided along with 3D geometric data for analytical purposes.

Three main integration approaches were identified from the previous literature. In the first approach, BIM is used to extract BoQ and other applications are used to perform the assessment. The approach requires experts to conduct the assessment and is time-consuming. Therefore, it is not recommended to use the approach. The second approach is linking the BIM model with an external database and performing the assessment. The BIM model is used to extract BoQ, and an external database is used to obtain information required to perform the assessment. The main limitation of the approach is the interoperability issue due to the lack of appropriate data in the external database. The third approach is the inclusion of information required for conducting an assessment by creating parameters with the BIM software tool. The limitation of this approach is that the BIM IFC schema does not contain adequate properties for storing the information required for the assessment within BIM.

SQ4: How to design a framework that integrates BIM and the circular economy assessment to facilitate circularity and environmental impact of building designs?

A set of interviews were conducted first to determine the current assessment workflow. Based on the interview responses, it was identified that the assessments are performed at the end of the design stage by sustainability and circularity advisor and designers used Autodesk Revit for designing the model and are not familiar with the assessment methods. Hence, a new workflow is proposed to integrate the assessment within the design process to be used for decision-making. By considering the integration approach and the new workflow, a framework is proposed to perform the assessment and design decisions. Since Autodesk Revit was the primary design tool, Dynamo is used to automate the process. The framework is based on the IPO model and uses BIM's competence for performing the assessment. The parametric modelling in BIM helps in obtaining the parametric attributes (i.e. dimension) from the model. The second feature (i.e. classifying data) allows linking the BIM model with the external database with the help of classification codes. The third feature of BIM that is utilized for visualization which helps in interpreting the results. In addition, a separate MCDM tool in MS-Excel has been proposed to support the designers to make design decisions based on multiple criteria and user preference.

SQ5: What are the implications for providing a BIM-based assessment framework for the designers in decision-making during the design phase?

A tool is developed based on the proposed framework for validation. The validation of the framework is carried out by implementing the developed tool on a case study and conducting a workshop. The implementation of the case study shows the applicability of the developed tool for making design decisions. The experts during the workshop acknowledged that the proposed framework would significantly improve the decision-making process for making preliminary design choices (concrete or steel, or wood construction) and selection of products during the detailed design stage. The perceived advantage of the proposed framework over the existing assessment method was that it was possible to compare products based on circularity and environmental impact aspects and make product selection based on projects objectives. The experts, especially the architects and the BIM designer, believe that the tool will eventually foster their circularity and sustainability consciousness and help them design more circular and sustainable buildings.

8-1-2 Main-Research Questions

"How can a BIM-based framework enable designers in the built environment to assess the material circularity and environmental impact of their design and make design decisions throughout the design stage?"

To answer the main research question, a decision support tool is developed based on the framework. The tool consists of two sub-tools namely, Dynamo and MS-Excel. Dynamo visual programming software is used to write scripts for performing circularity and environmental impact assessment. Whereas, MS-Excel is used to develop a MCDM tool to assist designers in selecting the best alternative products based on the circularity and environmental impact indicators. The developed tool make it possible to make design decision during the preliminary design and detailed design stage. During preliminary design, the tool helps in selecting the design variant (concrete or steel, or wood construction) and during design stage the tool helps in selecting the type of product to each element or change in design. The assessment process is made automated by selecting the product classification code and disassembly code for the elements and clicking the play button in the Dynamo player to conduct the assessment. The output of the assessment is the results visualized by color overrides on the elements and through graphical representations such as pie and bar chart. The elements with products of highest circularity performance and least environmental impact will be colored in dark green. Whereas, the elements with products of lowest circularity performance and highest environmental impact will be colored in red. The color coding helps the designers in interpreting the assessment results in a effective manner. In case of conflicting situation, the designers can use the MCDM tool to select the best alternative based on the weights of given each criteria by the users. The weights for the criteria can be based on the project requirement and stakeholder preference. Thus, decision on design choice or type of products or design can be made based on several parameters that are necessary to be considered during design stage.

The circular strategies and the service lifetime of products play a significant role in the final assessment results. Thus, the designers should have the information on the adopted circular strategies and products lifetime to obtain accurate results.

8-2 Recommendations for practice

Some of the recommendations for practice for implementation of the developed tool includes the following:

1. The database for the research was developed in Excel. However, SQL database is recommended as it is comparatively better for handling structured data. It can be made a centralized data for the design stage within the company.

2. There is a lack of standardization on information about the products in the NMD database. There are limited product environmental data provided by manufacturers/-suppliers or tested and verified by a third party. In most cases, the untested product data are used, making the assessment results inaccurate or unreliable in many situations. It is recommended to develop an open-source database within the company and determine a method to obtain information (mainly the EPD of products) from the suppliers. This will help in developing a reliable database and accurate environmental impact assessment results. Nevertheless, for the current application of the developed tool, the tool can be linked with the NMD database by seeking the API and extracting the data of the products.

3. During the research, it was realized that there is no database for circularity assessment and the MCI assessment is performed through expert judgment. It is possible to develop a circularity database within the company for different products they usually procure.

4. The developed tool should be applied to multiple complex projects to conclude its usability, effectiveness and efficiency for making design decisions. This will also help recognize the benefits of the proposed workflow over the traditional method and identify the challenges and areas for improvement. When the proposed tool is applied for

projects, the benefits obtained from the new method can be used to show the project leaders and management to get approval for changing the traditional workflow.

5. There is an opportunity to enrich the developed tool by performing MPG calculation and generating a report in MS-Excel. For MPG calculation, it is necessary to consider nineteen impact categories which are mentioned as mandatory in the Netherlands.

6. The loading of product classification codes and disassembly codes can be improvised using the BIM interoperability tool. Also, new parameters can be created to store this information instead of built-in parameters (Assembly code and Keynote) as they are already being used for other purposes.

7. AHP is a type of MCDM method recommended to use in practice to determine weights to criteria based on stakeholder preference (Policymakers/ Government, Clients and Designers).

8-3 Recommendation for future research

Some of the recommendations for future work include the following:

1. To limit the scope of the research, the focus was on the environmental aspect of sustainability. However, two pillars of sustainability, namely, economic and social aspects, should be considered along with environmental and circularity aspects. Thus, the future recommendation is to extend the scope of the research by including Life cycle costing (LCC) and Social Life cycle assessment (S-LCA).

2. It is recommended to perform future research to determine how the database needs to be developed and updated and how can it be standardized to obtain reliable assessment results. It is also recommended to identify the significance of a common database across countries.

3. Currently, for the environmental impact assessment, the visualization of MKI per unit (functional unit) has been given same range of shadow price for all the elements. For future research, the range can be based on element category (wall, door, floor etc.) to provide more precise metrics for decision-making. This can then be compared with the proposed method to check on the change in results.

4. In the research, TOPSIS was selected as the method for making multi-criteria decision making. However, it is encouraged to explore MCDM methods further and apply the method for selecting the best alternative products for the given criteria.

5. Based on previous literature, it was seen that MCDM has a significant role in the construction industry, and there are possibilities to integrate it with BIM. However, due to time constraints and a lack of programming skills, it was not possible to integrate the MCDM method with BIM in the research, thus leaving scope for future research. It is recommended to explore and develop strategies/techniques to integrate MCDM and BIM.

6. The developed framework was validated based on effectiveness for application to projects and its contribution for making design decisions. However, it was not assessed based on its efficiency on the process. It is still unknown whether the developed workflow saves considerable amount of time or increases the total time during the design process. Thus, leaving an opportunity for future study the efficiency of the proposed workflow.

7. The proposed framework is developed for the Revit software tool. Therefore, it is recommended to consider other design tools such as SketchUp and Rhino and determine techniques to perform automated assessments.

Chapter 9

Personal Reflection

In this chapter, personal opinion on the research process, collaboration with the company and research impact and applicability in practice are described.

9-1 Research Process

Before starting my master's journey at TU Delft I worked for around two years on building construction projects in India. Even though my main responsibility was planning and monitoring the progress of construction, I actively participated in understanding the techniques used for constructing sustainable buildings to reduce the impact on the environment. It is during my master's at TU Delft, I amplified my knowledge on the concept of Circular Economy, focusing on circular design strategies, circular procurement, and key performance indicators (KPIs) for sustainability. All these factors cultivated an interest in carrying out my graduation thesis in the field of Circular Economy. While looking for a research topic, 'Circularity Indicators/ Metrics' grabbed my focus. Circularity indicators are crucial as they are beneficial for benchmarking and monitoring the progress, create awareness on the opportunities for adopting circular principles and identify solutions and implement it. Thus, to support construction companies to become sustainable and circular, a set of metrics is required for quantifying the benefits and impacts of adopting certain strategies which are still lacking. Thus, I decided to pursue my graduation thesis on circularity assessment in the built environment. The thesis bridges the technology and environmental aspects. The technological contribution is the development of a BIM-based framework to assist designers in the built environment to perform automated assessments. While the contribution towards the environmental aspect is by using circularity indicators to make design decisions during the design stage to achieve sustainable circular buildings.

The research commenced by discovering the 'why' behind the need for Circular Economy in the built environment and the role of circularity indicators and its assessment during the design stage. Getting an overview of Circular Economy and Sustainability concepts was essential to identify the circularity design principles that can be adopted in the built environment along with the circularity indicators. Furthermore, the literature review on the current circularity assessment methods and tools in the Netherlands led to conclude the important indicators for the design stage thus, progressing towards defining the 'what' question in the research. The process then directed towards answering the 'how' question by exploring the BIM integration approaches, evaluating the existing approaches and determining an approach for the research, developing a framework for automating the assessment and implementing the framework to a real-time case by developing a tool.

The entire research process was in synergy with the planned timeline for the graduation thesis. The 'discover' and 'define' phase to answer the 'why' and 'what' questions were carried out before Mid-term Phase 1 and the 'develop' phase to answer 'how' question was performed in the time between Mid-term Phase 1 and Phase 2. The implementation of the developed framework to a real-time case study was executed in the time between Mid-term Phase 2 and Green Light.

9-2 Company Collaboration

While finalizing the research on BIM based circularity and environmental impact assessment during design stage, I realized that to meet my research objective I need to conduct my research in the real-world setting i.e. the construction industry. I find myself extremely fortunate to have got the opportunity to collaborate with Witteveen+Bos, an engineering and consultancy firm in the Netherlands to conduct my research. My journey at Witteveen+Bos was very smooth despite the pandemic and change in supervisor in the mid-way of my thesis. The conversations with project lead, BIM modellers and co-ordinations, architects, sustainability and circularity consultants were very insightful and played a crucial role in progressing my research. I believe that my project management skills helped me systematically conduct my research and meet the deadlines and complete my thesis as per the planned schedule. Coming from different cultural background with more power distance in the professional environment, I was initially hesitant to directly address higher position colleagues in the company, set up meetings and conduct interviews and receive feedback. But working with Witteveen+Bos made me overcome this and taught me that the professional environment in the Netherlands is open to anyone with innovative ideas. The seven months of work experience has made me gain more confidence in myself and I have improved my communication skills profoundly.

9-3 Research impact and applicability

This research contributes towards the exploration of indicators and assessing them during the design stage for transitioning towards a Circular Economy within the built environment. Since the Netherlands has set a target to become fully circular by 2050, it is the responsibility of every organization to achieve this target. Organizations in the construction sector should bring in changes that include technical, organizational and managerial aspects to successfully move towards a sustainable circular economy. The most important and challenging aspects are the organizational and managerial changes. The organizations should recognize the importance of the assessment of these indicators to meet the target and make these assessments mandatory for all the construction projects within the organization. This was evident in Witteveen+Bos, as circularity assessment (MCI) was not carried out for projects unless specified by the client. Thus, I recommend that the company should make circularity assessment mandatory along with environmental impact assessment for all the construction projects. In addition, the organization should offer basic training programs for the designers and architects on the concept of Circular Economy, the assessment methods and interpretation of the assessment results to create awareness. The second challenging aspect is the managerial changes. The directors and project leads should accept the proposed workflow and support the team members to adopt the proposed framework for making design decisions for pilot projects to recognise the benefits and impact. If significant benefits are identified then the framework should be accepted and implemented for all future projects by adopting the new workflow. From the research, it was identified that the development of the database is the most critical step for conducting an automated assessment. Hence, adequate time and necessary support such as assistance from an external company should be provided for developing a database. Concerning the technical aspect, from the interviews, I observed that the infrastructure department within Witteveen+Bos has already initiated the process of developing the database for the environmental impact assessment of infrastructure projects. Thus, there is a possibility for the building sector to discuss with the infrastructure department internally and adapt their method for developing the database. I recommend developing own EPDs for products using SimaPro or obtain product EPDs from manufacturers/suppliers for accurate assessment results. This might be complex and time-consuming initially but once all the commonly used products are fed into the database the process becomes very easy. Apart from this, there is a possibility that architects may not comprehend the new workflow to make design decisions based on the assessment results because it is not always necessary that secondary products or products with lower emissions values are aesthetically pleasing. A cultural change is necessary for the architects to change their viewpoint and practice of selecting products based on their appearance and texture to reduce the current environmental crisis. The developed tool when adopted can create social awareness during the design process and drive the designers and architects to balance between aesthetics and sustainability. Thus, by adopting the proposed framework the architects can use their expertise to propose a sustainable aesthetically pleasing design. The thesis can be used as a proof of concept and further developed by the company to assess circularity and environmental impact of products for obtaining a sustainable and circular design. If these measures are considered then I believe that the world will have a healthier built environment.

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Appendix A

Circular Building Definitions

Author	Focus	Definitions
Pomponi and Moncaster (2017)	CE principles	A building that is designed, planned, built, operated, maintained, and deconstructed in a manner consistent with CE principles.
Transitie team Circulaire Bouw Economie (2018)	Environment, economic and natural resources	Circular building means the development, use and reuse of buildings, areas, and infrastructure, without unnecessarily exhausting natural resources, polluting the environment and affecting ecosystems. Building in a way that is economically sound and contributes to the welfare of humans and animals. Here and there, now, and later.
Rijksdienst Voor Ondernemend Nederland (2018)	Environment, ecosystem, and natural resources	The circular building represents all related activities such as construction, use and reuse, avoid incurring unnecessary depletion of natural resources, negative influence on the living environment and ecosystems.
Circle Economy (2018)	Environment, ecosystem, social and natural resources	A building that is developed, used, and reused without unnecessary resource depletion, environmental pollution, and ecosystem degradation. It is constructed in an economically responsible way and contributes to the wellbeing of people and the biosphere. Here and there, now, and later. Technical elements are demountable and reusable, and biological elements can also be brought back into the biological cycle.

Figure A-1: Circular Building Definitions from literature

Appendix B

Circularity Assessment

B-1 Abbreviations for Material Circularity Indicator

Symbol	Definition
M	Mass of product
F_R	Fraction of mass of a product's feedstock from recycled sources.
F_U	Fraction of a product's feedstock from reused sources.
F_S	Fraction of a product's biological feedstock from Sustained Production. Biological material that is recycled or reused is captured as recycled or reused material, not biological feedstock.
V	Material that is not from reuse, recycling or, for the purposes of this methodology, biological materials from Sustained Production.
C_C	Fraction of mass of a product being collected to go into a composting process.
C_E	Fraction of mass of a product being collected for energy material satisfies the requirements for inclusion.
C_R	Fraction of mass of a product being collected to go into a recycling process.
C_U	Fraction of mass of a product going into component reuse.
E_C	Efficiency of the recycling process used for the portion of a product collected for recycling.
E_E	Efficiency of the energy recovery process for biological materials satisfying the requirements for inclusion.
E_F	Efficiency of the recycling process used to produce recycled feedstock for a product.
B_C	The carbon content of a biological material, by default a value of 45% is used unless supported by evidence to the contrary.
W	Mass of unrecoverable waste associated with a product.
W_O	Mass of unrecoverable waste through a product's material going into landfill, waste to energy and any other type of process where the materials are no longer recoverable.
W_C	Mass of unrecoverable waste generated in the process of recycling parts of a product.
W_F	Mass of unrecoverable waste generated when producing recycled feedstock for a product.
LFI	Linear Flow Index
F(X)	Utility factor built as a function of the utility X of a product
X	Utility of a product
L	Actual average lifetime of a product Average
L_{av}	Average lifetime of an industry-average product of the same type.
U	Actual average number of functional units achieved during the use phase of a product.
U_{av}	Average number of functional units achieved during the use phase of an industry-average product of the same type.
MCI_p	Material Circularity Indicator of a product

Table B-1: Abbreviation of MCI [1]

B-2 Steps to calculate MCI

The information required for calculating MCI include:

1. Production phase: amount of virgin content, recycled content, recycling efficiency and reused content
2. Use phase: lifetime of the product and average industry life of a similar product
3. End-of life phase: amount of recyclable content, recycling efficiency reusable content and amount of materials that goes to energy incineration and landfill

Calculating Virgin Feedstock

$$V = M(1 - F_R - F_U) \tag{B-1}$$

where:

V is virgin mass M is the total mass of the product

F_R is fraction of recycled content

F_U is fraction of reused content

Calculating Unrecoverable waste

$$W_O = M(1 - C_R - C_U - C_C - C_E) \tag{B-2}$$

where:

W_O is amount of waste (landfill and energy incineration)

C_R is fraction of mass going to recycling process

C_U is fraction of mass in the reuse component

C_E is fraction of mass collected during energy recovery

$$W_C = M(1 - E_C)C_R \tag{B-3}$$

where:

W_C is amount of waste generated from recycling process

E_C is efficiency of recycling process of the product collected for recycling

$$W_F = M\frac{(1 - E_F)F_R}{EF} \tag{B-4}$$

where:

W_F is amount of waste generated due to recycled content

E_F is amount of waste from recycling process

$$W = W_O + \frac{(W_F + W_C)}{2} \tag{B-5}$$

where:

W is amount of unrecoverable waste

Calculating Linear Flow Index (LFI)

$$LFI = \frac{(V + W)}{2M + \frac{W_F - W_C}{2}} \tag{B-6}$$

where:

LFI measures amount of the materials in linear fashion

Calculating Utility

$$X = \frac{L}{L_{av}} X \frac{U}{U_{av}} \tag{B-7}$$

where:

X is utility factor accounting the products lifetime or functional units

L is actual lifetime of a product

L_{av} is average lifetime of a similar product

U is actual functional unit of a product achieved during lifetime

U_{av} is average functional unit of a product achieved during lifetime

Calculating Material Circularity Indicator

$$MCI_p = 1 - LFIXF(X) \tag{B-8}$$

$$F(X) = \frac{0.9}{X} \tag{B-9}$$

where:

MCI_p is Material circularity indicator of a product

F(X) is a function of utility (X) to determine the influence of the utility of the product on MCI

B-3 Steps to calculate BCI

The calculation of MCI_p is same as described above.

Calculating Product Circularity Indicator

$$PCI_p = \frac{1}{F_d} \sum_{i=1}^{n} MCI_p X F_i \tag{B-10}$$

where:

PCI_p is the product circularity indicator of a product

F_d is the sum of all DfD aspects

F_i is the sum of one DfD aspect

Calculating System Circularity Indicator

$$SCI_{s(p)} = \frac{1}{W_s} \sum_{j=1}^{n} PCI_j X W_j \tag{B-11}$$

where:

$SCI_{s(p)}$ is the system circularity indicator of a product

W_j is the mass of the product

W_j is the summation mass of all products

Calculating Building Circularity Indicator

$$BCI_p = \frac{1}{LK} \sum_{k=1}^{n} SCI_{s(p)} X LK_k \tag{B-12}$$

where:

BCI_p is the building circularity indicator

LK is the factor of system dependency (Stuff = 1.0, Space plan = 0.9, Services = 0.8, Skin = 0.7, Structure = 0.2 and Site = 0.1)

LK_k is the summation of system dependency

Appendix C

Design for Disassembly aspects

C-1 Detachability Index

Calculation of detachability index of the connection of element n

$$LI_c n = \frac{TV_n + TOV_n}{2} \tag{C-1}$$

where:

$LI_c n$ is the detachability index of connection of element n

TV_n is connectivity type of elements n

TOV_n is accessibility connection of elements n

Calculation of detachability index of the composition of element n

$$LI_s n = \frac{DK_n + VI_n}{2} \tag{C-2}$$

where:

$LI_s n$ is the detachability index of composition of element n

TV_n is cintersection elements n

TOV_n is form closure of elements n

Calculation of detachability index of element n

$$LI_s n = \frac{LI_c n + LI_s n}{2} \tag{C-3}$$

C-2 Transformation Capacity

C				grading
CONNECTIONS	type of connection	tc 01	accessory external connection or connection system	1
		tc 02	direct connection with additional fixing devices	0,8
		tc 03	direct integral connection with inserts (pin)	0,6
		tc 04	direct integral connection	0,5
		tc 05	accessory internal connection	0,4
		tc 06	filled soft chemical connection	0,2
		tc 07	filled hard chemical connection	0,1
		tc 08	direct chemical connection	0,1
			tc= [tc1+ tc2 + ...tc(n)] / n	
	accessibility to fixings and intermediary	af 01	accessible	1
		af 02	accessible with additional operation which causes no damage	0,8
		af 03	accessible with additional operation / causes reparable damage	0,6
		af 04	accessible with additional operation/causes partly reparable damage	0,4
		af 05	not accessible - total damage of bought elements	0,1
			af= [af1+ af2 + ...af(n)] / n	
	tolerance	t 01	high tolerance	1
		t 02	minimum tolerance	0,5
		t 03	no tolerance	0,1
			t= [t1+ t2 + ...t(n)] / n	
	morphology of joint	mc 01	knot (3D connections)	1
		mc 02	point	0,8
		mc 03	linear (1D connections)	0,6
		mc 04	service (2D connection)	0,1

Figure C-1: Disassembly aspects

Aspect	Description	Code	Criterion	grading
LCC LIFECYCLE CO-ORDINATION	lifecycle of components and alelents in relation to the size (1)- assembled first	s 01	small element (1) / short LC or medium component (1) / short LC	1
		s 02	big component (1) / long L.C.	1
		s 03	big (small) element (1) / long LC	0,8
		s 04	big component (1) / short LC	0,4
		s 05	material (1) / short L.C.	0,2
		s 06	big element / short L.C. or material / short life cycle	0,1
			s = [s1+ s2 + ...s(n)] / n	
			LCC = fuzzy calculation based on "ulc","tlc" and "s" and their weighting factors	
RP RELATIONAL PATTERN	position of relations in relational diagram	r 01	vertical	1
		r 02	horizontal in lower zone of the diagram	0,6
		r 03	horizontal between upper and lower zone of the diagram	0,4
		r 04	horizontal in upper zone	0,1
			r = [r1+ r2 + ...r(n)] / n	
			RP = fuzzy calculation based on "r" and its weighting factor	
A ASSEMBLY	assembly direction based on assembly type	ad 01	parallel - open assembly	1
		ad 02	stuck assembly	0,6
		ad 03	base el.in stuck assembly	0,4
		ad 04	sequential seq.base el	0,1
			ad= [ad1+ ad2 + ...ad(n)] / n	
	assembly sequences regarding material levels (1)- assembled first (2)- second	as 01	component (1) / component (2)	1
		as 02	component (1) / element (2)	0,8
		as 03	element (1) / component (2)	0,6
		as 04	element (1) / element (2)	0,5
		as 05	material (1) / component (2)	0,3
		as 06	component (1)/material (2)	0,2
		as 07	material (1) / material (2)	0,1
			as= [as1+ as2 + ...as(n)] / n	
			A = fuzzy calculation based on "ad" and "as" and their weighting factors	
G GEOMETRY	geometry of product edge	gp 01	open linear	1
		gp 02	symmetrical overlapping	0,8
		gp 03	overlapping on one side	0,7
		gp 04	unsymmetrical overlapping	0,4
		gp 05	insert on one sides	0,2
		gp 06	insert on two sides	0,1
			gp= [gp1+ gp2 + ...gp(n)] / n	
	standardisation of product edge	spe 01	pre-made geometry	1
		spe 02	half standardised geometry	0,5
		spe 03	geometry made on the construction site	0,1

Figure C-2: Disassembly aspects

Aspect	Sub-aspect	Code	Description	grading
FD FUNCTIONAL DECOMPOSITION	functional separation	fs 01	separation of functions	1
		fs 02	integration of functions with same lc* into one element	0,6
		fs 03	integration of functions with different lc* into one element	0,1
			fs = [fs1+ fs2 + ...fs(n)] / n	
	functional dependence	fdp 01	modular zoning	1
		fdp 02	Planed interpenetrating for different solutions (overcapacity)	0,8
		fdp 03	Planed interpenetrating for one solution	0,4
		fdp 04	Unplanned interpenetrating	0,2
		fdp 05	total dependence	0,1
			fdp = [fdp1+ fdp2 + ...fdp(n)] / n	
			FD = fuzzy calculation based on "fs" and "fdp" and their weighting factors	
SY SYSTEMATISATION	structure and material levels	st 01	components	1
		st 02	elements / components	0,8
		st 03	elements	0,6
		st 04	material / element / component	0,4
		st 05	material / element	0,2
		st 06	material	0,1
			st = [st1+ st2 + ...st(n)] / n	
	clustering	c 01	clustering according to the functionality	1
		c 02	clustering according to the material life cycle	0,6
		c 03	clustering for fast assembly	0,3
		c 04	no clustering	0,1
			c = [st1+ st2 + ...st(n)] / n	
			SY: = fuzzy calculation based on "st" and "c" and their weighting factors	
BE BASE ELEMENT	base element specification	b 01	base element- intermediary between systems /components	1
		b 02	base element- on two levels	0,6
		b 03	element with two functions (be. and one building function)	0,4
		b 04	no base element	0,1
			b = [b1+ b2 + ...b(n)] / n	
			BE = fuzzy calculation based on "b" and its weighting factor	
LCC LIFE CYCLE CO-ORDINATION	use life cycle/ coordination (1)- assembled first (2)- second	ulc 01	long LC (1) / long LC (2) or short LC(1) / short LC(2)	1
		ulc 02	long LC(1) / short LC(2)	0,8
		ulc 03	medium LC (1) / long LC (2)	0,6
		ulc 04	short LC (1) / medium (2)	0,3
		ulc 05	short (1) / long LC (2)	0,1
			ulc = [ulc1+ulc2 + ...ulc(n)] / n	
	technical life cycle/ coordination	tlc 01	long LC (1) / long LC (2) or short (1) / short (2) or long (1) short (2)	1
		tlc 02	medium LC (1) / long LC (2)	0,5
		tlc 03	short LC (1) / medium LC (2)	0,3
		tlc 04	short LC (1) / long LC (2)	0,1

Figure C-3: Disassembly aspects

Appendix D

LCA steps

The steps involved in performing life-cycle assessment is as follows:

1. **Goal and Scope definition**

   This phase forms the first step of any LCA study. The goal is to describe the cause for undertaking the study, intended areas of application of the results, and the intended audience. The scope of the study is described to establish criteria for the functional unit, system boundaries, methodology and data quality. The functional unit is used to measure the performance of a product system that is being studied and compare it with other products with similar function (product performance criteria) (ISO, 1997). It mainly consists of the product's characteristics such as function, durability, quantity and quality. The system boundaries define which unit processes (extent of materials in a system) should be included in the LCA study. The system boundary describes the life cycle stages that will be considered for the study (figure **??**). The methodology established the impact categories that will be considered for the study and their weighting criteria. The data quality defines the characteristics of data required for the study. As defined in ISO: 14044:2006, the data quality criteria should consider then characteristics: 1) technology coverage, 2) time-related coverage, 3) geographical coverage, 4) completeness, 5) consistency, 6) representativeness, 7) sources of the data 8) reproducibility, 9) precision, and 10) uncertainty of the information (ISO, 2006).

2. **Inventory analysis**

   In the second phase, the input and output flow for the life cycle considered for the product system is quantified. The input flow is the ones that enter the system boundary from the environment (e.g., materials), whereas the output flows are the ones that leave the system boundary and goes back to the environment (e.g., waste and emissions). This phase consists of four sub-steps: 1) mapping input and output data of the system in a flow diagram, 2) preparing a data collection plan where the data types, sources and indicators are identified, 3) data collection of primary (e.g., real-time measurements and calculation) and secondary data (e.g., information from literature and database),

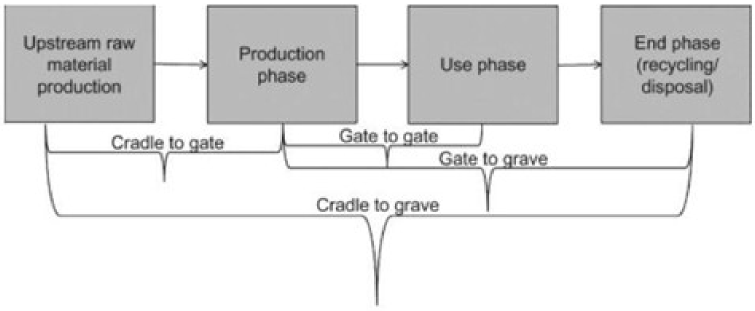

Figure D-1: System boundaries

4) evaluating the identified data and reporting the results along with the assumptions made.

3. **Impact assessment**

The third phase of an LCA study consists of evaluating the environmental and human health due to emissions from the resources that are identified in the previous phase [71]. This phase defines the link between the products in the system and their impacts on the environment. In practice, there are two types for carrying out impact assessment: problem-oriented or midpoints approach and damage-oriented or endpoint approach. Sometimes both methods are combined. The difference between the two methods is the way they look at the stages in the cause-effect model to calculate the potential environmental impact [67]. The midpoint approach relates to elementary flows and accounts for all parameters between inventory data and category endpoints in the cause-effect chain. The approach focuses on single environmental problems [72]. With the midpoint approach, it is possible to derive the characterization factors and express the consequence of emissions. The method involves calculation processes and is more reliable. Whereas, in the endpoint approach it is possible to provide information regarding the characterization flow to the intended audience. The indicators of the approach show impact on environmental aspects such as effect on human health, resource scarcity, and biodiversity [72]. However, the method requires certain assumptions and hence, the results are not reliable. There are various impact assessment approaches such as CML, ReCiPe, EDIP and Eco-indicator which have been explained by Acero et al. (2016) [73]. Explaining each method is beyond the scope of this research.

The phase is divided into three parts: 1) impact categories selection where the environmental impact categories will be chosen assigning the results from inventory analysis to the chosen impact categories also known as ‘classification’ 3) calculating the category indicators also referred to as ‘characterization’ [59]. A characterization factor is assigned to every classified output flow which shows the contribution of each flow towards a particular impact category (midpoint or endpoint). The results are presented as an impact score with a common unit for all inventory results within the impact category.

The optional steps in this phase as per ISO 14040 include 1) normalization, 2) clustering and 3) weighting. Normalization ensures that the characterized impact scores have a common reference value so that comparisons among the impact categories are possible. Clustering ensures that the environmental impact categories are assigned to defined groups for interpreting the results to a specific area of concern. Weighting is a process where certain weightage is given to the impact categories as per their relative importance.

In the Netherlands, the nineteen environmental impact categories are being used from January 2021 as shown in figure D-2.

Impact category	Indicator	Unit
Climate change – total	GWP-total	kg CO2-eq.
Climate change – fossil	GWP-fossil	kg CO2-eq.
Climate change – biogenic	GWP biogenic	kg CO2-eq.
Climate change – land use and change to land use	GWP-luluc	kg CO2-eq.
Ozone layer depletion	ODP	kg CFC11-eq.
Acidification	AP	mol H+-eq.
Freshwater eutrophication	EP freshwater	kg PO4-eq.
Seawater eutrophication	EP-seawater	kg N-eq.
Land eutrophication	EP-land	mol N-eq.
Photochemical ozone formation	POCP	kg NMVOC-eq.
Depletion of abiotic raw materials, minerals, and metals	ADP-minerals&metals	kg Sb-eq.
Depletion of abiotic raw materials Fossil fuels	ADP-fossil	MJ, net cal. val.
Water use	WDP	m3 world eq. deprived
Fine particulate emissions	Illness due to PM	Illness incidence
Ionizing radiation	Human exposure	kBq U235-eq.
Ecotoxicity (freshwater)	CTU ecosystem	CTUe
Human toxicity, carcinogenic	CTU human	CTUh
Human toxicity, non-carcinogenic	CTU human	CTUh
Land-use related impact/soil quality	Soil quality index	Dimensionless

Figure D-2: Impact categories

4. **Interpretation**

   The final stage of an LCA study consists of analyzing the results, reporting conclusions, limitations and recommendations for further studies based on the findings and finally communicating the results.

Appendix E

Interview

Selection of interviewees

A semi-structured interview was selected as it fits the requirement. A set of criteria was identified for the selection of interviewees. They are as follow:

1. They are involved in building sector projects.
2. They have a minimum of 3 years of experience in the same field.
3. They have expertise in any one of these topics': circularity, LCA, assessment method, and BIM.

Interview protocol

A set of questionnaires were prepared for the interview. The duration was around 30 mins per candidate. The main objective of the interview was to understand the current workflow of the assessment and designers' awareness on circularity and sustainability strategies and how they adopt these strategies in their designs.

In addition, an interview protocol was followed for all the interviews conducted to maintain consistency. The protocol is divided into three parts.

1. The interview started with a short introduction about the research topic addressing the objective and the interview process and its confidentiality.
2. After a short introduction, the set of questionnaires were asked to the candidates.
3. The interview was finished by closing remarks and asking if they are willing to help in future when necessary.

It should be noted that all the interviews were performed digitally through Microsoft teams and the interviewees were asked permission to record the session at the beginning. This helped in analyzing the interviews to propose the new workflow and framework.

Set of questionnaires

General:

1. What is your role in the company?
2. What is your field of expertise?

If he/ she is a design expert -

1. Which software tool do you use for designing?
2. Are you aware of circularity principles? Have you tried to consider these principles while designing?
3. In your opinion what will be the added value of using circularity and sustainability assessment from the early design stages?
4. Are you willing to perform the assessment for your designs while designing and use it for the decision-making process?
5. What features do you like to see in the integrated tool? Do you prefer a plug-in or a web-based application where an IFC file needs to be uploaded?
6. Any remarks or recommendations?

If he/ she is a LCA expert -

1. Which software tool do you use for assessment?
2. How do you obtain information from the designers and at what stage of the design? Please, elaborate the assessment process?
3. How long do you take to perform an assessment for a project? Do you face any difficulties?
4. From your perspective, do designers consider circularity and sustainability principles in their designs?
5. Do you think integrating the assessment in BIM software eases the assessment process? Are there any barriers you could think of?
6. Any remarks or recommendations?

Appendix F

CEI Database and Disassembly Factors

NL-Sfb	Element	Product Code	Product Name	Unit	Service life (years)	MKI-NMD	Tool	MKI (in € per functional unit)	MKI-A (in € per functional unit)	MKI-B (in € per functional unit)	MKI-C (in € per functional unit)	MKI- D(in € per functional unit)
17	Paalfunderingen											
		17.1.01	Beton; Prefab, met slanke schacht, 400x400 mm	m	75	1.32	oneClick	1.315	1.31	0	-0.001	0
							BIMPACT	1.32	1.33	0	-0.010	0
23	Vloeren (Floors)											
		23.2.01	Vrijdragende vloeren, Beton, in het werk gestort, C30/37; incl.wapening	m2	1000	13.36	oneClick	13.36	13.31	0	0.050	0
							BIMPACT	13.37	13.33	0	0.240	-0.19
		23.2.02	Vrijdragende vloeren, Balk en broodjes; prefab beton; incl. isolatie, eps, Rc; 4.0 + druklaag	m2	1000	5.59	oneClick	4.22	4.04	0	0.260	-0.076579079
							BIMPACT	5.59	5.26	0	0.400	-0.05
27	Daken (Roofs)											
		27.2.05	Hellende daken, Dak elementen, houten ribben, steenwol, multiplex; duurzame bosbouw met Hellend dakbedekkingen, staal verzinkt; trapezium	m2	75	4.14	oneClick	4.136	5.01	0	-0.874	0
							BIMPACT	4.14	5.02	0	-0.870	0
		27.2.09	Bekledingen, staal / PUR (pentaan), sandwichpaneel d=100mm	m2	100	3.38	oneClick	3.379	4.45	0	-1.071	0
							BIMPACT	3.39	4.46	0	0.450	-1.51
28	Hoofddraagconstructies; kolommenliggers											
		28.1.05	Consoles, Staal; HEA, HEA200	m	1000	1.5	oneClick	1.492	3.01	0	0.000	-1.518106516
							BIMPACT	1.5	3.02	0	0.010	-1.51
31	Buitenwandopeningen (Exterior wall opening)- Doors											
		31.3.08	Aluminium, geanodiseerd	m2	75	5.56	oneClick	5.557	14.71	0	-9.157	0
							BIMPACT	5.56	14.73	0	-2.050	-7.09
		31.3.06	Multiplex;sandwich;2xmultiplex;geschilderd:alkyd;	pieces(s)	20	23.07	oneClick	23.08	26.21	0.13	-3.129	-0.123368237
							BIMPACT	23.08	7	16.96	-0.670	-0.19
		31.3.09	Transportdeuren,Dichte overheaddeur; segmentendeur; alumium+polycarbonaat,geisoleerd	m2	20	32.7	oneClick	31.069	40.76	0	-1.692	-7.998993079
							BIMPACT	32.77	10.88	24.03	-0.080	-2.04
		31.3.10	Transportdeuren, Transparante overheaddeur; segmentendeur; verzinkt staal, geisoleerd	m2	20	26.74	oneClick	24.266	26.83	0	-0.084	-2.280214889
							BIMPACT	26.75	7.16	19.62	0.270	-0.28
41	Buitenwandopeningen (Exterior wall opening)- Walls											
		41.2.30	Dichte puivulling, XPS Sandwichplaten met vuren multiplex (3.6 mm); geschilderd, acryl	m2	20	9.44	oneClick	10.16	8.4	0.72	1.040	0
							BIMPACT	9.45	2.25	7.12	0.090	0
		41.2.31	Dichte puivulling, PIR Sandwichplaten aluminium (0,7mm); gecoat	m2	50	3.44	oneClick	3.441	8.56	0	-5.119	0
							BIMPACT	3.45	5.72	1.15	-0.760	-2.62
47	Dakafwerkingen afwerkingen (Roof finishes)											
		47.1.01	Hellend dakbedekkingen, Staal verzinkt; trapezium	m2	20	2.50	oneClick	2.502	8.21	0	-5.708	0
							BIMPACT	2.5	2.2	1.84	-0.100	-1.42
52	Afvoeren-Disposal											
		52.1.07	Dakgoten, staal; prefab goot; verzinkt en gecoat	m	40	1.59	oneClick	1.505	1.88	0	-0.290	-0.084748615
							BIMPACT	1.59	1.01	0.75	-0.030	-0.12

Figure F-1: LCA tools evaluation for data selection to CEI Database

NL-Sfb	NMD	Element name	Product code	Product (NL)
23		Vloeren (Floor)		
	23.2	Vrijdeagende Vloeren (Suspended Floor)	23.2.01	Beton, in het werk gestort, C30/37; including wapening
			23.2.02	Balk en broodjes; prefab beton; incl. isolatie,eps,Rc:4.0 + druklaag
			23.2.03	Beton, in het werk gestort, C20/25; including wapening
			23.2.04	Druklaag breedplaatvloer; betonmortel C20/25; including wapening
			23.2.05	Druklaag breedplaatvloer; betonmortel C30/37; including wapening
			23.2.06	Europees naaldhouten balken met eupopees naaldhouten multiplex; duurzame bosbouw
			23.2.07	HBS; Europees naaldhout balken, steenwol, multiplex, 2x gipsplaat; duurzame bosbouw
			23.2.08	Staalframe element
			23.2.09	Staalplaatbetonvloer
			23.2.10	Massief houtenvloer
			23.2.11	Houten Kanaalplaatvloer
			23.2.12	BubbleDeck vloeren (bollenplaat)
			23.2.13	Kruislings gelamineerde houtenvloer, 90 min WBDBO, ws; duurzame bosbouw
			23.2.14	Ribbenvloer/ ribcassette vloer; including isolatie
27		Daken (Roof)		
	27.2	Hellende daken (Sloping roofs)	27.2.01	Europees naaldhouten balken met eupopees naaldhouten multiplex; duurzame bosbouw
			27.2.02	Staalframe element
			27.2.03	Dak elementen, Houten ribben, PIR, spaanplaat; duurzame bosbouw
			27.2.04	Dak elementen, Houten ribben, steenwol, multiplex; duurzame bosbouw
			27.2.05	Dak elementen, Houten ribben, steenwol, spaanplaat; duurzame bosbouw
			27.2.06	Dak elementen, Houten ribben, massief PIR, multiplex; duurzame bosbouw
			27.2.07	Dak elementen, Houten ribben, massief PIR, spaanplaat en OSB; duurzame bosbouw
			27.2.08	Renovatie dakekement; Cellenbeton
			27.2.09	Bekledingen, staal / PUR (pentaan), sandwichpaneel d=100mm
28		Hoofdraagconstructies (Building frames)		
	28.1	Kolommen (Columns)	28.1.01	Beton, in het werk gestort, C20/25; including wapening
			28.1.02	Beton, in het werk gestort, C30/37; including wapening
			28.1.03	Baksteen, gewapend
			28.1.04	Gelamineerd europees naaldhout; duurzame bosbouw
			28.1.05	Consoles, Staal; HEA, HEA200
			28.1.06	Consoles, Staal; HEA, HEA400
	28.2	Massieve wanden dragend (Loard-bearing soild walls)	28.2.01	Beton, in het werk gestort, C20/25; including wapening
			28.2.02	Beton, in het werk gestort, C30/37; including wapening
			28.2.03	Baksteen geperforeerd
			28.2.04	Baksteen (gelijmd)
			28.2.05	Betonblokken (gelijmd)
			28.2.06	Cellenbetonblokken
			28.2.07	Grene logs, neit verduurzaamd, duurzame bosbouw
			28.2.08	Holle betonnenblokken (gemetseld)

Figure F-2: CEI Database: Product Repository

NL-Sfb	Element	Product Code	Product Name	MCI	MKI (in € per functional unit)	MKI-A (in € per functional unit)	MKI-B (in € per functional unit)	MKI-C (in € per functional unit)	MKI- D(in € per functional unit)
17	Funderingspalen (Foundation)								
		17.1.01	Beton; Prefab, met slanke schacht, 400x400 mm	0.43	1.3151	1.4871	0	-0.004090291	-0.13592253
23	Vloeren (Floors)								
		23.2.01	Vrijdragende vloeren, Beton, in het werk gestort, C30/37; incl.wapening	0.46	13.36	13.31	0	0.05	0
		23.2.02	Vrijdragende vloeren, Balk en broodjes; prefab beton; incl. isolatie, eps, Rc; 4.0 + druklaag	0.11	4.22	4.04	0	0.26	-0.077
27	Daken (Roofs)								
		27.2.05	Hellende daken, Dak elementen, houten ribben, steenwol, multiplex; duurzame bosbouw met Hellend dakbedekkingen, staal verzinkt; trapezium	0.47	4.136	5.01	0	-0.874	0
		27.2.09	Bekledingen, staal / PUR (pentaan), sandwichpaneel d=100mm	0.23	3.379	4.45	0	-1.071	0.000
27	Hoofddraagconstructies; kolommenliggers								
		28.1.05	Consoles, Staal; HEA, HEA200	0.51	1.492	3.01	0	-1.518	0.000
31	Buitenwandopeningen (Exterior wall opening)- Doors								
		31.3.08	Aluminium, geanodiseerd	0.47	4.446	9.89	0	-5.446	0
		31.3.06	Multiplex;sandwich;2xmultiplex;geschilderd:alkyd;	0.14	23.08	26.21	0.13	-3.129	-0.123
		31.3.09	Transportdeuren,Dichte overheaddeur; segmentendeur; alumium+polycarbonaat,geisoleerd	0.44	31.07	40.76	0	-1.692	-7.999
		31.3.10	Transportdeuren, Transparante overheaddeur; segmentendeur; verzinkt staal, geisoleerd	0.46	24.266	26.83	0	-0.084	-2.280
41	Buitenwandopeningen (Exterior wall opening)- Walls								
		41.2.30	Dichte puivulling, XPS Sandwichplaten met vuren multiplex (3.6 mm); geschilderd, acryl	0.17	10.16	8.4	0.72	1.040	0.000
		41.2.31	Dichte puivulling, PIR Sandwichplaten aluminium (0,7mm); gecoat	0.47	3.441	8.56	0	-5.119	0.000
47	Dakafwerkingen afwerkingen (Roof finishes)								
		47.1.01	Hellend dakbedekkingen, Staal verzinkt; trapezium	0.59	2.502	8.21	0	-5.708	0
52	Afvoeren								
		52.1.07	Dakgoten, staal; prefab goot; verzinkt en gecoat	0.48	1.505	1.88	0	-0.290	-0.085

Figure F-3: CEI Database: CEI Data

NL-Sfb	Element Description	Product Code	Product Name	Materials	Total Weight (kg/m2)	Product Weight (kg)	Virgin Material (%)	Weight of Virgin mass(kg)	Recyclable content (%)	Weight of recyclable content (kg)	Recycling efficiency	Waste of recyalable content (kg)	Recoverable content (%)	Weight of recoverable content (kg)	Reusable content (%)	Weight of re-usable content (kg)	Landfill (%)	Weight of unrecoverable waste (kg)	Functional service life (years)	Expected technical life (years)	MCI
17	Funderingspalen (Foundation)																				
		17.1.01	Prefab, met slanke schacht, 400x4	Betonmortel and Wapening	65.5594	65.5594	1	65.5594	0.99	64.903806	0.8	12.9807612	0	0	0	0	0.1	6.55594	75	75	0.43
23	Vloeren (Floors)																				
		23.2.01	Vrijdragende vloeren, Beton, in het werk gestort, C30/37;	Betonmortel and Wapening	669.2	669.2	1	669.2	0.93	622.356	0.8	124.4712	0.03	20.076	0.02	13.384	0.02	13.384	75	75	0.46
		23.2.02	Vrijdragende vloeren, Balk en broodjes; prefab beton; incl. isolatie, eps, Rc; 4.0 + druklaag	Druklaag, Wapening, Broodjes, Balken	252.99	252.99	1	252.99	0.02	5.0598	0.8	1.01196	0.88	222.6312	0	0	0.1	25.299	75	75	0.11
27	Daken (Roofs)																				
		27.2.05	Hellende daken, Dak elementen, houten ribben, steenwol, multiplex; duurzame bosbouw met Hellend dakbedekkingen, staal verzinkt; trapezium	Vuren, Schroten, FSC, Steenwol, Multiplex, Kit/ Lijm	52.60	52.6023	1	52.6023	0.75	39.451725	0.8	7.890345	0.03	1.578069	0.2	10.5205	0.02	1.052046	75	75	0.47
		27.2.09	Bekledingen, staal / PUR (pentaan), sandwichpaneel	Staalplaat, Sandwichpaneel, PUR	14	14	1	14	0.85	11.9	0.8	2.38	0	0	0	0	0.15	2.1	75	100	0.23
28	Hoofddraagconstructies; kolommenliggers																				
		28.1.05	Consoles, Staal; HEA, HEA200	Staal	494	494	1	494	0.51	251.94	0.8	50.388	0	0	0.49	242.06	0	0	75	75	0.51
31	Buitenwandopeningen (Exterior wall opening)- Doors																				
		31.3.08	Aluminium, geanodiseerd	Aluminium, ASA, Anodiseerlaag, EPDM,	13.436	13.436	1	13.436	0.97	13.03292	0.8	2.606584	0.03	0.40308	0	0	0	0	75	75	0.47
		31.3.06	Multiplex;sandwich;2xmultiplex; geschilderd:alkyd;	Hand/Sluitwerk, Schilderwerk nieuw, Frame, Bekleding, Isolatieplaat, Schilderwerk onderhoud	31.887	31.887	1	31.887	0.1	3.1887	0.8	0.63774	0.87	27.74169	0	0	0.03	0.95661	20	20	0.14
		31.3.09	Transportdeuren,Dichte overheaddeur; segmentendeur; alumium+polycarbonaat,geisoleerd	Beslag, Zinklaag, Beplating, Beglazing, Kokerprofiel, Kozijnprofiel, Isolatie	20.5	20.5	1	20.5	0.9	18.45	0.8	3.69	0.05	1.025	0	0	0.05	1.025	20	20	0.44
		31.3.10	Transportdeuren, Transparante overheaddeur; segmentendeur; verzinkt staal, geisoleerd	Beslag, Zinklaag, Deurblad, Kokerprofiel, Kozijnprofiel, Isolatie	20.88	20.88	1	20.88	0.94	19.6272	0.8	3.92544	0.03	0.6264	0	0	0.03	0.6264	20	20	0.46
41	Buitenwandopeningen (Exterior wall opening)- Walls																				
		41.2.30	Dichte puivulling, XPS Sandwichplaten met vuren multiplex (3.6 mm); geschilderd, acryl	Multiplex, XPS, Primer acryl, 1ste verflaag acryl, Onderhoud	5.66	5.6599	1	5.6599	0.05	0.282995	0.9	0.0282995	0.8	4.52792	0	0	0.05	0.282995	20	20	0.17
		41.2.31	Dichte puivulling, PIR Sandwichplaten aluminium	Aluminium, gecoat, PUR met pentaan	4.92	4.92	1	4.92	0.97	4.7724	0.8	0.95448	0.03	0.1476	0	0	0	0	50	50	0.47
47	Dakafwerkingen afwerkingen (Roof finishes)																				
		47.1.01	Hellend dakbedekkingen, Staal verzinkt; trapezium	Staal, Vuren, Schroten, FSC	11.6088	11.6088	1	11.6088	0.87	10.099656	0.8	2.0199312	0	0	0.12	1.39306	0.01	0.116088	25	20	0.59
52	Afvoeren-Disposal																				
		52.1.07	Dakgoten, staal; prefab goot;	Coating, Goot, Afwerking	2	2	1	2	0.87	1.74	0.8	0.348	0	0	0.1	0.2	0.01	0.02	40	40	0.48

Product Repository | CEI Data | Circularity Data. | LCA_MKI | LCA_Emission

Figure F-4: CEI Database: CEI Data

NL-Sfb	Element	Product Code	Product Name	Unit	Service life (years)	MKI (in € per functional unit)	MKI-A (in € per functional unit)	MKI-B (in € per functional unit)	MKI-C (in € per functional unit)	MKI- D(in € per functional unit)
17	Paalfunderingen									
		17.1.01	Beton; Prefab, met slanke schacht, 400x400 mm	m	75	1.32	1.33	0	-0.010	0
23	Vloeren (Floors)									
		23.2.01	Vrijdragende vloeren, Beton, in het werk gestort, C30/37; incl.wapening	m2	1000	13.37	13.33	0	0.24	-0.19
		23.2.02	Vrijdragende vloeren, Balk en broodjes; prefab beton; incl. isolatie, eps, Rc; 4.0 + druklaag	m2	1000	5.59	5.26	0	0.4	-0.050
27	Daken (Roofs)									
		27.2.05	Hellende daken, Dak elementen, houten ribben, steenwol, multiplex; duurzame bosbouw met Hellend dakbedekkingen, staal verzinkt; trapezium	m2	75	4.140	5.02	0	-0.870	0
		27.2.09	Bekledingen, staal / PUR (pentaan), sandwichpaneel d=100mm	m2	100	3.39	4.46	0	0.450	-1.510
28	Hoofddraagconstructies; kolommenliggers									
		28.1.05	Consoles, Staal; HEA, HEA200	m	1000	1.5	3.02	0	0.010	-1.510
31	Buitenwandopeningen (Exterior wall opening)- Doors									
		31.3.08	Aluminium, geanodiseerd	m2	75	5.56	14.73	0	-2.050	-7.09
		31.3.06	Multiplex;sandwich;2xmultiplex;geschilderd:alkyd;	pieces(s)	20	23.08	7	16.96	-0.670	-0.190
		31.3.09	Transportdeuren,Dichte overheaddeur; segmentendeur; alumium+polycarbonaat,geisoleerd	m2	20	32.77	10.88	24.03	-0.080	-2.040
		31.3.10	Transportdeuren, Transparante overheaddeur; segmentendeur; verzinkt staal, geisoleerd	m2	20	26.75	7.16	19.62	0.270	-0.280
41	Buitenwandopeningen (Exterior wall opening)- Walls									
		41.2.30	Dichte puivulling, XPS Sandwichplaten met vuren multiplex (3.6 mm); geschilderd, acryl	m2	20	9.45	2.25	7.12	0.090	0.000
		41.2.31	Dichte puivulling, PIR Sandwichplaten aluminium (0,7mm); gecoat	m2	50	3.45	5.72	1.15	-0.760	-2.620
47	Dakafwerkingen afwerkingen (Roof finishes)									
		47.1.01	Hellend dakbedekkingen, Staal verzinkt; trapezium	m2	20	2.5	2.2	1.84	-0.100	-1.42
52	Afvoeren-Disposal									

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Figure F-5: CEI Database: LCA-MKI Data

Product Code	Product	Module	Abiotic depletion, non fuel	Global warming (GWP 100)	Ozone layer depletion (ODP)	Human toxicity	Fresh water aquatic ecotoxicity	Marine aquatic ecotoxicity	Terrestrial ecotoxicity	Photochemical oxidation	Acidification	Eutrophication	Abiotic depletion, fossil fuel
23.2.01	Beton, in het werk gestort, C30/37; including wapening												
		A1-A3	3.08863E-04	1.62109E+02	6.995E-06	7.69E+01	7.324E-01	2.87E+03	2.05E+00	9.13E-02	5.127E-01	9.82E-02	6.57563E-01
		A4	8.39726E-06	2.948930E+00	5.44E-07	1.18E+00	3.46E-02	1.25E+02	4.18E-03	1.74E-03	1.28E-02	2.56E-03	2.17668E-02
		C2	4.58714E-07	1.61090E-01	2.97E-08	6.44E-02	1.89E-03	6.82E+00	2.28349E-04	9.50E-05	6.98E-04	1.40E-04	1.18905E-03
		C3	-6.97865E-06	2.15E+00	4.95E-07	9.96E-01	3.15E-02	1.58E+02	8.52E-03	2.14E-03	1.54E-02	3.63E-03	1.92886E-02
		C4	3.56824E-08	3.5660E-02	1.11E-08	3.33292E-02	4.13E-03	3.60E+00	5.04E-05	5.40E-05	3.57E-04	8.55E-05	3.07901E-04
		D	-4.71744E-05	-3.86E+00	-1.40E-07	-2.93E-01	-3.40E-02	-7.01E+01	-2.07E-03	-2.07E-03	-7.25E-03	-1.29E-03	-1.95652E-02
		Total	2.63602E-04	1.63551E+02	7.93475E-06	7.89107E+01	7.70412E-01	3.09337E+03	2.05912E+00	9.330E-02	5.347E-01	1.03E-01	6.81E-01
		Total Module A	3.17260E-04	1.65058E+02	7.53923E-06	7.81104E+01	7.66970E-01	2.99544E+03	2.05239E+00	9.30816E-02	5.25453E-01	1.00754E-01	6.79330E-01
		Total Module C	-6.48425E-06	2.34872E+00	5.35916E-07	1.09360E+00	3.74885E-02	1.68083E+02	8.80111E-03	2.28568E-03	1.64979E-02	3.85486E-03	2.07856E-02
		Total Module D	-4.71744E-05	-3.85599E+00	-1.40400E-07	-2.93261E-01	-3.40465E-02	-7.01478E+01	-2.06725E-03	-2.06725E-03	-7.25090E-03	-1.29449E-03	-1.95652E-02
23.2.06	Europees naaldhouten balken met eupopees naaldhouten multiplex; duurzame bosbouw												
		A1-A3	1.11E-04	3.33E+01	3.53E-06	1.34E+01	4.91E-01	1.21E+03	1.01E-01	3.73E-02	1.94E-01	4.98E-02	2.64E-01
		A4	3.30E-06	1.16E+00	2.14E-07	4.64E-01	1.36E-02	4.91E+01	1.65E-03	6.84713E-04	5.03E-03	1.01E-09	8.57E-03
		C3 (Waste processing)	-4.51E-07	-3.68E-02	-1.34E-09	-2.80E-03	-3.25E-04	-6.70E-01	-5.23E-05	-1.97E-05	-6.93E-05	-1.24E-05	-1.87E-04
		C4 (Waste Disposal)	-4.95E-06	-2.27E+01	-1.86E-06	-6.47E-01	-2.72E-02	-1.54E+02	-1.11E-02	-1.28E-03	-2.67E-02	-5.12E-03	-1.97E-01
		D	-1.35E-06	-1.10E-01	-4.02E-09	-8.40E-09	-9.76E-04	-2.01E+00	-1.57E-04	-5.92E-05	-2.08E-04	-3.71E-05	-5.61E-04
		Total	1.08E-04	1.16E+01	1.88E-06	1.33E+01	4.76E-01	1.10E+03	9.15E-02	3.67E-02	1.72E-01	4.46E-02	7.47E-02
		Total Module A	1.15E-04	3.45E+01	3.75E-06	1.39E+01	5.05E-01	1.26E+03	1.03E-01	3.80E-02	1.99E-01	4.98E-02	2.73E-01
		Total Module C	-5.41E-06	-2.28E+01	-1.86E-06	-6.50E-01	-2.75E-02	-1.55E+02	-1.11E-02	-1.30E-03	-2.67E-02	-5.13E-03	-1.97E-01
		Total Module D	-1.35E-06	-1.10E-01	-4.02E-09	-8.40E-09	-9.76E-04	-2.01E+00	-1.57E-04	-5.92E-05	-2.08E-04	-3.71E-05	-5.61E-04
27.2.01	Europees naaldhouten balken met eupopees naaldhouten multiplex; duurzame bosbouw												
		A1-A3	1.11E-04	3.33E+01	3.53E-06	1.34E+01	4.91E-01	1.21E+03	1.01E-01	3.73E-02	1.94E-01	4.98E-02	2.64E-01
		A4	3.30E-06	1.16E+00	2.14E-07	4.64E-01	1.36E-02	4.91E+01	1.65E-03	6.84713E-04	5.03E-03	1.01E-09	8.57E-03
		C3 (Waste processing)	-4.51E-07	-3.68E-02	-1.34E-09	-2.80E-03	-3.25E-04	-6.70E-01	-5.23E-05	-1.97E-05	-6.93E-05	-1.24E-05	-1.87E-04
		C4 (Waste Disposal)	-4.95E-06	-2.27E+01	-1.86E-06	-6.47E-01	-2.72E-02	-1.54E+02	-1.11E-02	-1.28E-03	-2.67E-02	-5.12E-03	-1.97E-01
		D	-1.35E-06	-1.10E-01	-4.02E-09	-8.40E-09	-9.76E-04	-2.01E+00	-1.57E-04	-5.92E-05	-2.08E-04	-3.71E-05	-5.61E-04

Product Repository | CEI Data | Circularity Data. | LCA_MKI | LCA_Emission

Figure F-6: CEI Database: LCA-Emission

Code	Description (NL)	Parent Group	Value
DI.CON	Losmaakbaarheid van de connectie		
TOC.AC	Type verbinding and Toegankelijkheid verbinding	DI.CON	
TOC.DC	Droge verbinding	TOC.AC	
TOC.DC.FA	Vrij toegankelijk	TOC.DC	1
TOC.DC.AAND	Toegankelijkheid met extra handelingen die geen schade veroorzak	TOC.DC	0.9
TOC.DC.AAD	Toegankelijkheid met extra handelingen met herstelbare schade	TOC.DC	0.7
TOC.DC.NA	Niet toegankelijk/ onherstelbare schade aan objecten	TOC.DC	0.55
TOC.AE	Verbinding met toegevoegde elementen	TOC.AC	
TOC.AE.FA	Vrij toegankelijk	TOC.AE	0.9
TOC.AE.AAND	Toegankelijkheid met extra handelingen die geen schade veroorzak	TOC.AE	0.8
TOC.AE.AAD	Toegankelijkheid met extra handelingen met herstelbare schade	TOC.AE	0.6
TOC.AE.NA	Niet toegankelijk/ onherstelbare schade aan objecten	TOC.AE	0.45
TOC.DI	Directe integrale verbinding	TOC.AC	
TOC.DI.FA	Vrij toegankelijk	TOC.DI	0.8
TOC.DI.AAND	Toegankelijkheid met extra handelingen die geen schade veroorzak	TOC.DI	0.7
TOC.DI.AAD	Toegankelijkheid met extra handelingen met herstelbare schade	TOC.DI	0.5
TOC.DI.NA	Niet toegankelijk/ onherstelbare schade aan objecten	TOC.DI	0.35
TOC.SC	Zachte chemische verbinding	TOC.AC	
TOC.SC.FA	Vrij toegankelijk	TOC.SC	0.6
TOC.SC.AAND	Toegankelijkheid met extra handelingen die geen schade veroorzak	TOC.SC	0.5
TOC.SC.AAD	Toegankelijkheid met extra handelingen met herstelbare schade	TOC.SC	0.3
TOC.SC.NA	Niet toegankelijk/ onherstelbare schade aan objecten	TOC.SC	0.15
TOC.HC	Harde chemische verbinding	TOC.AC	
TOC.HC.FA	Vrij toegankelijk	TOC.HC	0.55
TOC.HC.AAND	Toegankelijkheid met extra handelingen die geen schade veroorzak	TOC.HC	0.45
TOC.HC.AAD	Toegankelijkheid met extra handelingen met herstelbare schade	TOC.HC	0.25
TOC.HC.NA	Niet toegankelijk/ onherstelbare schade aan objecten	TOC.HC	0.1

Code	Description with types (NL)
TOC.DC	Droge verbinding
	Droge verbiding
	Klikverbinding
	Klittenbandverbinding
	Magnetische verbinding
TOC.AE	Verbinding met toegevoegde elementen
	Bout- en moerverbinding
	Veerverbinding
	Hoekverbindingen
	Schroefverbinding
	Verbindingen met toegevoegde verbindingselementen
TOC.DI	Directe integrale verbinding
	Pin-verbindingen
	Spijkerverbinding
TOC.SC	Zachte chemische verbinding
	Kitverbinding
	Schuimverbinding (PUR)
TOC.HC	Harde chemische verbinding
	Lijmverbinding
	Aanstortverbinding
	Lasverbinding
	Cementgebonden verbinding
	Chemische ankers
	Harde chemische verbinding

Figure F-7: Disassembly factors with average codes and score

Appendix G

Developed Tool

G-1 Multi-criteria Decision Analysis

The multi-criteria decision analysis (MCDA) is commonly used to make decision during conflicting objective [20]. The method has the ability to provide the most optimal alternative by analyzing multiple criteria (quantitative or qualitative or both) simultaneously. The advantage of using MCDM is that it considers stakeholders (user or decision-maker) preference in the decision making process. There are various types of MCDA which differ based on the approach namely, compensatory approach or non-compensatory approach. The trade-off between the indicators is allowed in compensatory approaches, whereas non-compensatory approaches are usually based on principles that use pairwise comparison of alternatives. The application of MCDA in AEC industry include sustainability assessment, supplier selection, redevelopment assessment, and constructability assessment, etc. The most common types used in the construction industry indude Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Technique for order of preference by similarity to ideal solution (TOPSIS), Preference ranking orhanization method for enrichment of evaluations (PROMETHEE) ans Multi-attribute utility theory (MAUT). Based on literature review, AHP and TOPSIS based models are widely applied MCDA methods in the most application domain. It was observed that AHP was used as a part of the approach to obtain weights to the identified criteria. Wheras, TOPSIS was used as the main method to determine the best alternative.

G-1-1 TOPSIS

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a type of multi-criteria decision analysis method that identifies and prioritizes the best alternative based on its geometric distance from the ideal solution. The method adopts Euclidean distance measure to define the Positive Ideal Solution (PIS) and the Negative Ideal Solution (NIS). The PIS is formed from the highest scores of all the beneficial criteria (i.e. MCI and DfD) and lowest score of non beneficial/cost criteria (i.e. MKI). For NIS it is formed from the opposite logic of PIS. The alternative that is nearer to PIS and farther to PIS gets the highest score. It is important to note that the weights given to each criteria has a significant influence on the selection of the best alternative and hence the decision on the weights must be made based on the scenarios or AHP method can be used to determine the weights. Thus using TOPSIS it is possible to assist decision-makers to evaluate the alternatives and select the best alternative. The calculation involved in the TOPSIS method include:

1. ***Calculation of Normalised Matrix***

$$\overline{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{n} X_{ij}^2}} \tag{G-1}$$

2. ***Calculation of Weighted Normalised Decision Matrix***

$$V_{ij} = \overline{X}_{ij} X W_j \tag{G-2}$$

3. ***Calculation of Ideal Best and Worst value***

$$V_j^+ = MAX(V_{ij}) \tag{G-3}$$

$$V_j^- = MIN(V_{ij}) \tag{G-4}$$

4. ***Calculation of the Euclidean distance from the ideal best***

$$S_i^+ = \left[\sum_{j=1}^{m} (V_{ij} - V_j^+)^2\right]^{0.5} \tag{G-5}$$

5. ***Calculation of the Euclidean distance from the ideal worst***

$$S_i^- = \left[\sum_{j=1}^{m} (V_{ij} - V_j^-)^2\right]^{0.5} \tag{G-6}$$

6. ***Calculation of Performance Score***

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{G-7}$$

G-2 Dynamo Script for Environmental Impact Assessment

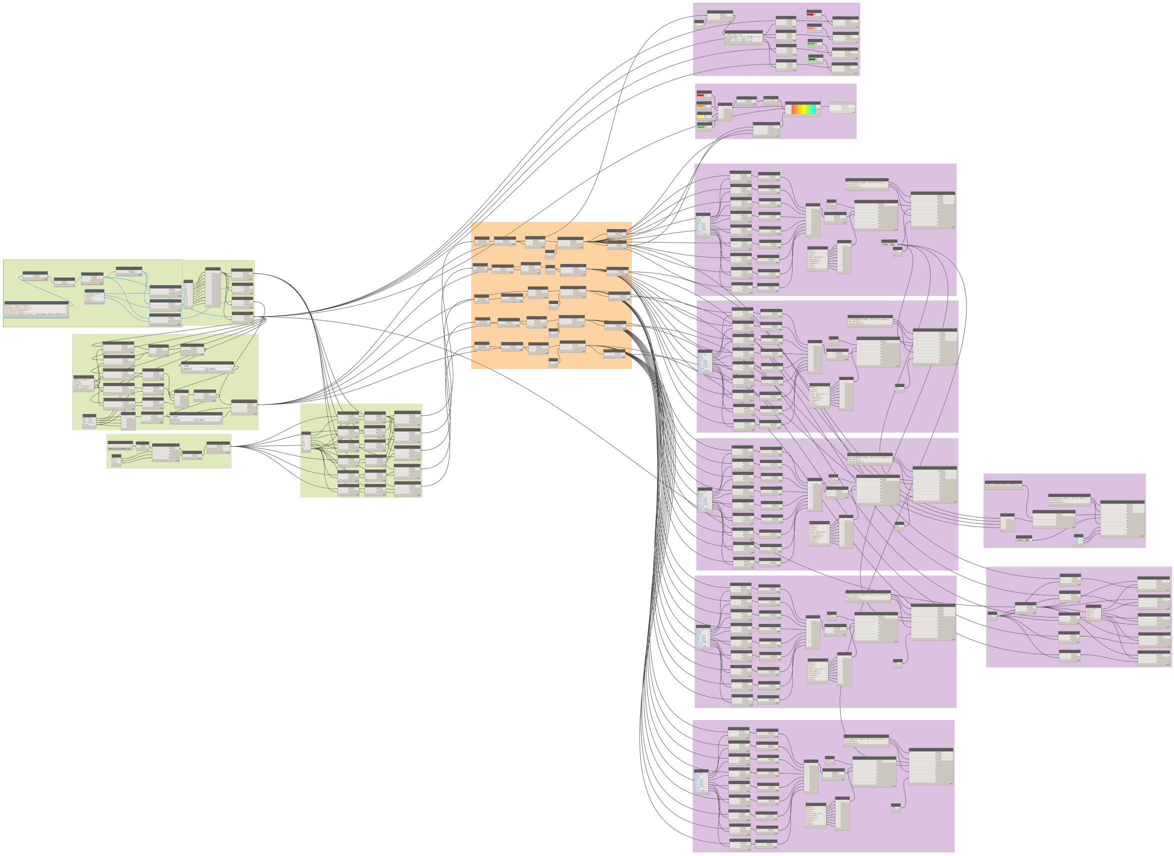


Figure G-1: Dynamo script for environmental impact assessment

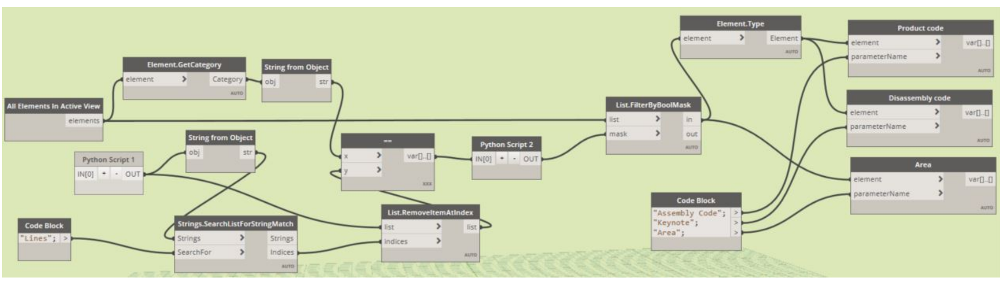


Figure G-2: Dynamo script for environmental impact assessment calculation

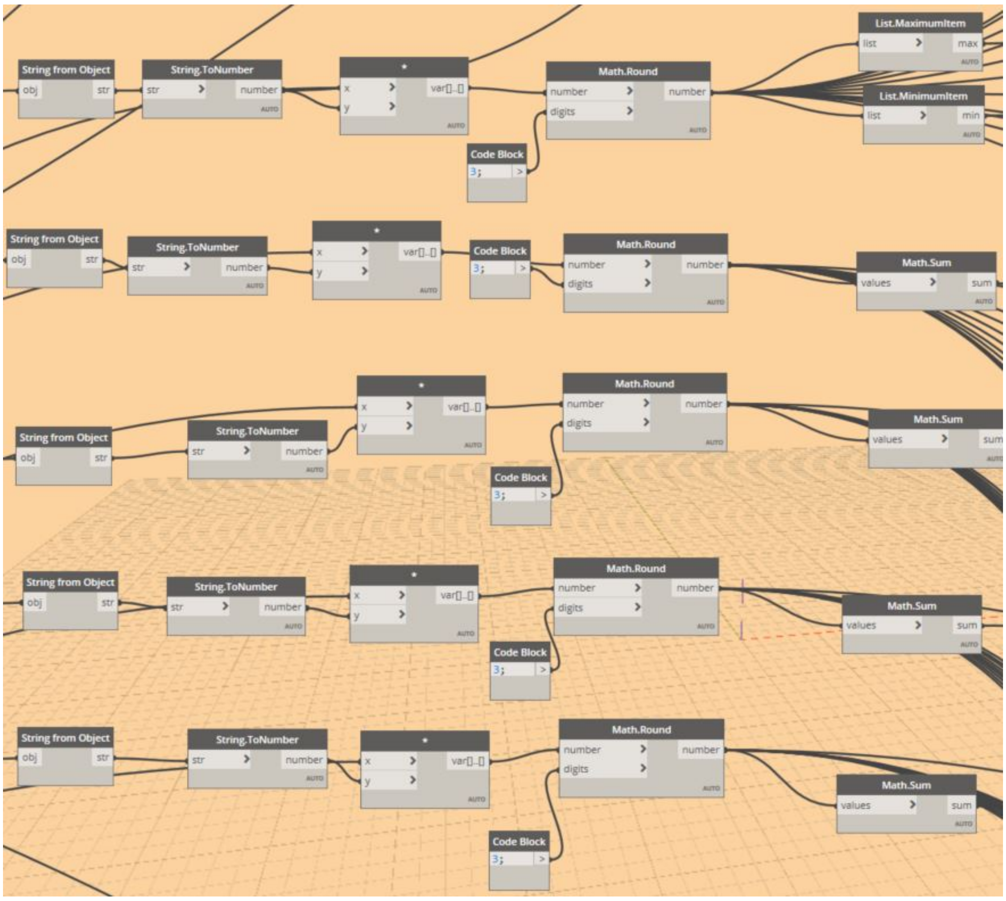
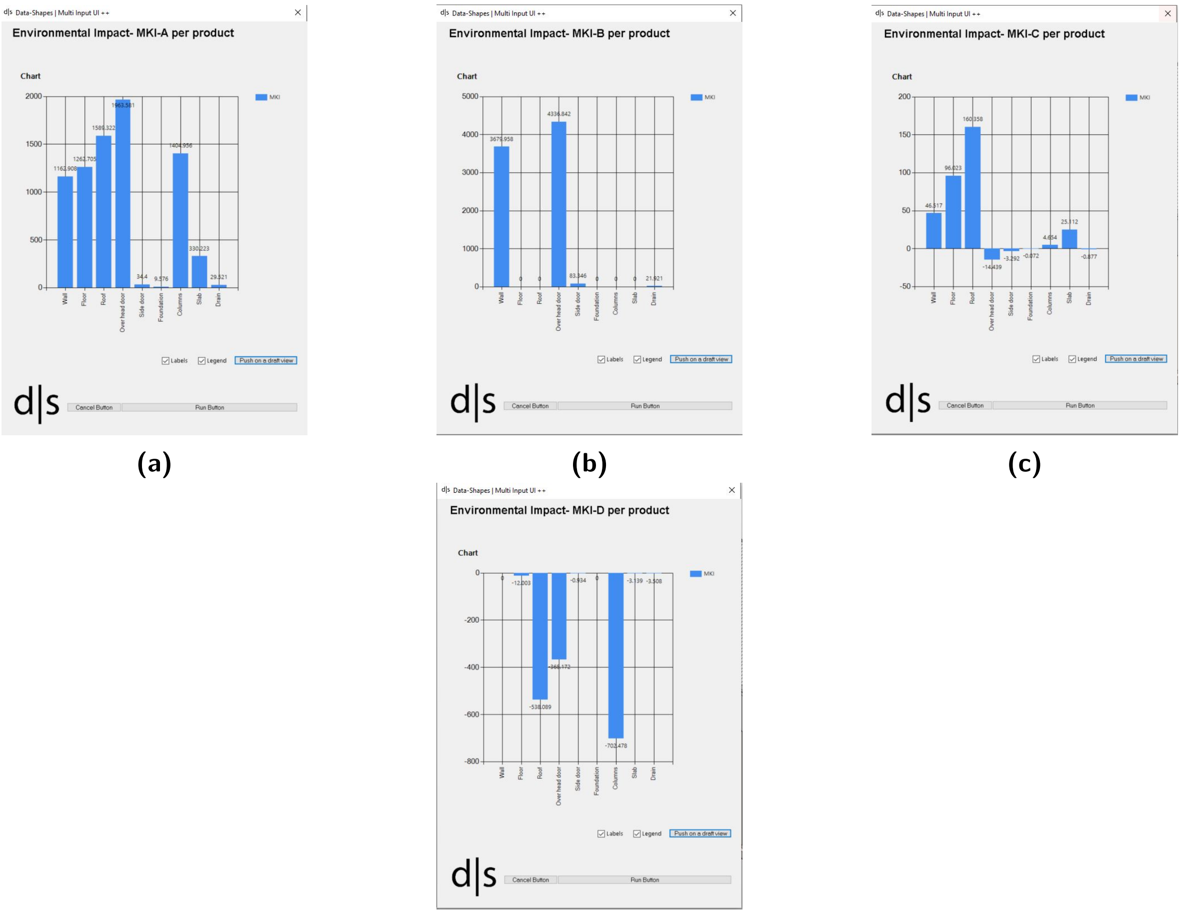


Figure G-3: Dynamo script for environmental impact assessment calculation

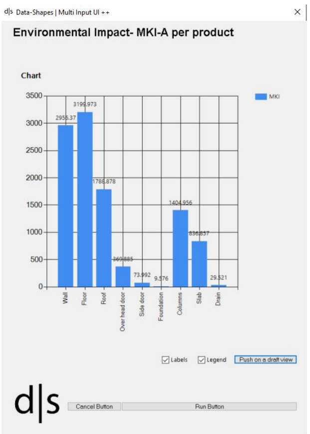
Appendix H

Environmental impact Assessment

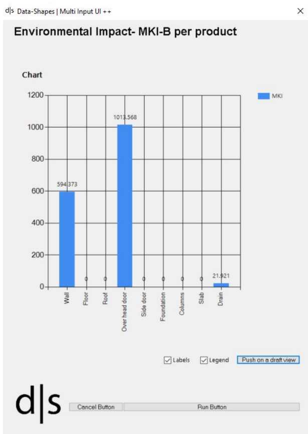


(a) (b) (c) (d)

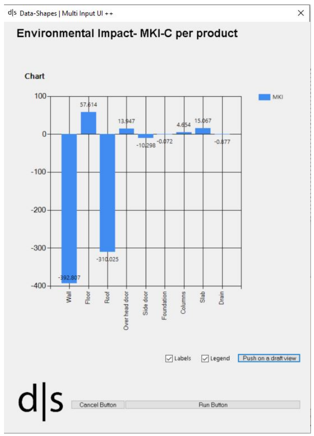
Figure H-1: Environmental cost indicator per component (MKI) (a) Module A (b) Module B (c) Module C (d) Module D



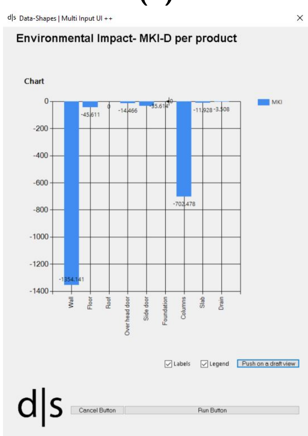
(a)



(b)



(c)



(d)

Figure H-2: Environmental cost indicator per component (MKI) (a) Module A (b) Module B (c) Module C (d) Module D

Appendix I

Accuracy

NL-Sfb	Element	Product Code	Product Name	Location	Tool	MKI (in € per functional unit)	MKI-A (in € per functional unit)	MKI-B (in € per functional unit)	MKI-C (in € per functional unit)	MKI- D(in € per functional unit)
17	Paalfunderingen									
		17.1.01	Beton; Prefab, met slanke schacht, 400x400 mm	Sub-structure	BIM	0.53	0.54	0	-0.010	0
					DYN	0.528	0.532	0	-0.004	0
					Difference	-0.377358491	-1.481481481	0	-60	0
					Accuracy	99.62%	98.52%	100.00%	160.00%	100.00%
23	Vloeren (Floors)									
		23.2.01	Vrijdragende vloeren, Beton, in het werk gestort, C30/37; incl.wapening	Super-structure	BIM	3207.85	3196.6	0	57.56	-46.29
					DYN	3209.575	3199.973	0	57.614	-45.611
					Difference	0.053774335	0.105518363	0	0.093815149	-1.46683949
					Accuracy	99.95%	99.89%	100.00%	99.91%	98.53%
		23.2.02	Vrijdragende vloeren, Balk en broodjes; prefab beton; incl. isolatie, eps, Rc; 4.0 + druklaag	Super-structure	BIM	1341.12	1259.43	0	95.35	-13.64
					DYN	1341.924	1262.705	0	96.023	-12.003
					Difference	0.059949893	0.260038271	0	0.705820661	0
					Accuracy	99.94%	99.74%	100.00%	99.29%	100.00%
27	Daken (Roofs)									
		27.2.05	Hellende daken, Dak elementen, houten ribben, steenwol, multiplex; duurzame bosbouw met Hellend dakbedekkingen, staal verzinkt; trapezium	Super-structure	BIM	1474.64	1740.26	0	-311.28	0
					DYN	1475.29	1788.878	0	-310.025	0
					Difference	0.044078555	2.793720479	0	-0.403173991	0
					Accuracy	99.96%	97.21%	100.00%	99.60%	100.00%
		27.2.09	Bekledingen, staal / PUR (pentaan), sandwichpaneel d=100mm	Super-structure	BIM	1205.28	1587.11	0	157.11	-538.92
					DYN	1208.027	1589.322	0	160.358	-538.089
					Difference	0.227913846	0.139372822	0	2.067341353	0
					Accuracy	99.77%	99.86%	100.00%	97.93%	100.00%
28	Hoofddraagconstructies; kolommenliggers									
		28.1.05	Consoles, Staal; HEA, HEA200	Main	BIM	7.63	15.394	0	0.04	-7.767
					DYN	7.71	15.523	0	0.042	-7.852
					Difference	1.048492792	0.837988827	0	5	1.094373632
					Accuracy	98.95%	99.16%	100.00%	95.00%	98.91%
				Support	BIM	11.59	23.37	0	0.012	-11.78
					DYN	11.54	23.442	0	0.0119	-11.72
					Difference	-0.431406385	0.308087291	0	-0.833333333	-0.509337861
					Accuracy	99.57%	99.69%	100.00%	99.17%	99.49%

Figure I-1: Accuracy of assessment

NL-Sfb	Element	Product Code	Product Name	Location	Tool	MKI (in € per functional unit)	MKI-A (in € per functional unit)	MKI-B (in € per functional unit)	MKI-C (in € per functional unit)	MKI- D(in € per functional unit)
31	Buitenwandopeningen (Exterior wall opening)- Doors									
		31.3.08	Aluminium, geanodiseerd	Super-structure	BIM	13.96	36.96	0	-5.16	-17.82
					DYN	13.964	36.996	0	-5.149	-17.807
					Difference	0.028653295	0.097402597	0	-0.213178295	-0.07295174
					Accuracy	**99.97%**	**99.90%**	**100.00%**	**99.79%**	**99.93%**
		31.3.09	Transportdeuren,Dichte overheaddeur; segmentendeur; alumium+polycarbonaat,geisoleerd	Super-structure	BIM	564.18	187.19	413.73	-1.44	-35.29
					DYN	564.299	187.354	413.797	-1.378	-35.129
					Difference	0.021092559	0.087611518	0.016194136	-4.305555556	-0.456219892
					Accuracy	**99.98%**	**99.91%**	**99.98%**	**95.69%**	**99.54%**
		31.3.10	Transportdeuren, Transparante overheaddeur; segmentendeur; verzinkt staal, geisoleerd	Super-structure	BIM	460.59	123.22	337.76	4.6	-4.98
					DYN	460.635	123.295	337.856	4.649	-4.822
					Difference	0.009770078	0.060866742	0.028422549	1.065217391	-3.172690763
					Accuracy	**99.99%**	**99.94%**	**99.97%**	**98.93%**	**96.83%**
41	Buitenwandopeningen (Exterior wall opening)- Walls									
		41.2.30	Dichte puivulling, XPS Sandwichplaten met vuren multiplex (3.6 mm); geschilderd, acryl	Backwall	BIM	1221.7	289.8	920.91	11.01	0
					DYN	1214.117	288.77	913.796	11.551	0
					Difference	-0.620692478	-0.355417529	-0.772496769	4.913714805	0
					Accuracy	**99.38%**	**99.64%**	**99.23%**	**95.09%**	**100.00%**
				Upper wall	BIM	94.77	22.49	71.44	0.86	0
					DYN	94.73	22	71.374	0.902	0
					Difference	-0.000422074	-0.021787461	-0.000923852	0.048837209	0
					Accuracy	**100.00%**	**99.98%**	**100.00%**	**99.95%**	**0.00%**
				Side wall	BIM	180.86	42.91	136.33	1.63	0
					DYN	180.386	42.94	135.91	1.71	0
					Difference	-0.262081168	0.069913773	-0.308075992	4.90797546	0
					Accuracy	**99.74%**	**99.93%**	**99.69%**	**95.09%**	**100.00%**
		41.2.31	Dichte puivulling, PIR Sandwichplaten aluminium (0,7mm); gecoat	Backwall	BIM	445.58	738.57	148.53	-99.2	-342.31
					DYN	442.78	734.117	147.593	-98.54	-336.256
					Difference	-0.628394452	-0.602921863	-0.630848987	-0.665322581	-1.768572347
					Accuracy	**99.37%**	**99.40%**	**99.37%**	**99.33%**	**98.23%**
				Upper wall	BIM	34.57	57.3	11.53	-7.69	-26.55
					DYN	34.584	57.339	11.528	-7.67	-26.44
					Difference	0.040497541	0.068062827	-0.017346054	-0.260078023	-0.414312618
					Accuracy	**99.96%**	**99.93%**	**99.98%**	**99.74%**	**99.59%**
				Side wall	BIM	71.52	120.76	27.84	-14.53	-50.54
					DYN	68.855	118.186	21.952	-14.507	-50.012
					Difference	-3.726230425	-2.131500497	-21.14942529	-0.158293187	-1.044717056
					Accuracy	**96.27%**	**97.87%**	**78.85%**	**99.84%**	**98.96%**
52	Afvoeren-Disposal									
		52.1.07	Dakgoten, staal; prefab goot; verzinkt en gecoat	Super-structure	BIM	7.21	4.68	3.45	-0.14	-0.57
					DYN	7.489	4.832	3.588	-0.143	-0.588
					Difference	3.86962552	3.247863248	4	2.142857143	3.157894737
					Accuracy	**96.13%**	**96.75%**	**96.00%**	**97.86%**	**96.84%**

Figure I-2: Accuracy of assessment

Appendix J

Workshop

Selection of expert panel

A workshop was conducted for validating the framework and the developed tool. A set of criteria was identified for the selection of experts to the panel. They are as follow:

1. They are involved in building sector projects.
2. They have a minimum of 3 years of experience in the same field.
3. They have expertise in any one of these topics': circularity, LCA, assessment method, and BIM.
4. They are involved in the proposed workflow.

Workshop protocol

A set of questionnaires were prepared for the workshop. The duration was around 1hr 15 minutes. The main objective of the workshop was to understand if the proposed framework 1) can be applied for all the building projects 2) can be used for making design decisions based on the assessment and 3) can bring sustainability and circularity consciousness. Also, to determine the benefits or challenges/barrier for implementation.

In addition, a protocol was followed for the workshop. The protocol is divided into three parts.

1. The workshop started with a presentation on the research topic addressing the objective, proposed framework, development of the tool and its application on a case study.
2. After the presentation, the set of questionnaires were asked to create a discussion round and get feedback.
3. After discussion round, the experts were asked to fill out the set of questionnaires which were sent to each of them individually.

It should be noted that the workshop was performed digitally through Microsoft teams and the experts were asked permission to record the session at the beginning. This helped in validating the proposed framework.

Set of questionnaires

General:

1. What is your role in the company?
2. Years of experience?
3. Do you have any experience/ knowledge regarding material circularity (MCI or DfD) and environmental impact assessment methodology (MPG)? If yes, please elaborate to what extent?
4. Do you think the proposed framework and the workflow process has any added value to the current process? If yes, please elaborate on the major benefits.
5. Do you have any comments/suggestions for improvement on the proposed framework?
6. Do you think by performing such assessment for selecting products will consume more time than acceptable? If yes, any suggestions for reducing time?
7. Do you see any major barriers that prevents the application of the framework?
8. What changes from your perspective (such as technical, organisational, or managerial) are needed to make it applicable?
9. To what extent do you think the proposed framework and workflow will help in designing a more circular or sustainable building? Any other remarks?

Architect and BIM designer:

1. Is it possible to select the product code from the proposed database and disassembly code from the provided list during the design stage? If no, what do you think is the major challenge/barrier to do so.
2. By what stage (LOD 200, 300 or above) it is easy to determine the material circularity (primary or secondary material, recyclable, reusable, recoverable or disposable (landfill) content) and disassembly type?
3. Do you think the clients will be willing to adopt the new method of product selection based on the assessment results?
4. Do you think performing the assessment will foster your awareness on circular and sustainable products design?

Sustainability and Circularity advisors:

1. Do you agree with the values regarding the color range (for both MCI and EI) and weights for multi-criteria decision making? Please make the changes in the table if you have any suggestion.
2. Do you think the proposed framework will help in the final design stage (calculating MPG score and generating sustainability report) for obtaining building permit?
3. Do you wish to see any other aspect added to the proposed assessment criteria (MCI, DfD and MKI)?
4. Do you think it is possible to have a separate database (such as the proposed CEI database) for the organisation for selecting and assessing products? If yes, do you think it is easy to develop and update it regularly? If no, do you have any suggestion for an alternative method?

BIM Coordinator:

1. Is it possible to co-ordinate the proposed method (adding product codes and disassembly codes as 'Assembly code' and 'Keynote') with the current process? Or should new parameters be created to store this information?
2. Do you think the clients will be willing to adopt the new method of product selection based on the assessment results?

Glossary

List of Acronyms

AEC	Architecture, Engineering, and Construction
ASCE	American Society of Civil Engineers
BAMB	Building as Material Banks
BCI	Building circularity Index
BIM	Building information modelling
BoQ	Bill of Quantity
BWPE	BIM-based Deconstructability Assessment Score
CBA	Circular Building Assessment
CE	Circular Economy
CI	Circularity Indicators
CoBie	Construction Operations Building Information Exchange
DBR	Design-Based Research
DfD	Design for Disassembly
EMF	Ellen MacArthur Foundation
IFC	Industry Foundation Class
LCA	Lice cycle analysis
LCI	Life cycle Inventory
LCT	Life cycle thinking
LE	Linear Economy
LOD	Level of Detail or Development or Design
MCI	Material Circularity Index
MCDM	Multi-criteria decision making
MKI	Environmental cost indicator
MPG	Milieu Prestatie Gebouwen

NMD Nationale Milieu Database
PCI Product Circularity Indicator
SS-DAS Steel Structure Deconstructability Assessment Scoring
SCI System Circularity Indicator
TOPSIS Technique for Order of Preference by Similarity to Ideal Solution
UNFCCC United Nations Framework Convention on Climate Change
UNEP United Nations Environment Program