Eindhoven University of Technology

MASTER

BIM-based Integrated Assessments of Designs for Circularity, Environmental and Financial Impacts

Karabınar, Ece

Award date:
2021

Link to publication

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

Department of the Built Environment
MSc Construction Management & Engineering
2021-2022

BIM-based Integrated Assessments of Designs for Circularity, Environmental and Financial Impacts

Ece Karabınar
1411918

Colophon

Title: BIM-based Integrated Assessments of Designs for Circularity, Environmental and Financial Impacts

Author: Ece Karabınar
Student ID: 1411918
Email: ecekarabinar@gmail.com
Education: Master of Science in Construction Management and Engineering
Department of the Built Environment
Eindhoven University of Technology

Graduation committee:

Chairman: Prof. Dr. Ir. Bauke de Vries
1st Supervisor: Dr. Ir. Qi Han
2nd Supervisor: Dr. Ir. Pieter Pauwels

In collaboration with: Royal HaskoningDHV
External Supervisor: Quirine Henry
External Supervisor: Rudolf Scholtens

Preface

Dear reader,

Before you lies my Master's thesis "BIM-based Integrated Assessments of Designs for Circularity, Environmental and Financial Impacts". This thesis has been written in partial fulfillment of the master Construction Management and Engineering at the University of Technology Eindhoven and it also marks the end of my student life.

Over the past two years in TU Eindhoven, I have learnt and grown a lot as a person. It was a journey full of ups and downs; new beginnings, new experiences, new challenges… During my studies I had the chance to explore things beyond my regular courses. I was always interested in sustainability so to enhance my knowledge on this topic, I worked for GO Green Office in the university. This experience has catalyzed my passion for sustainability, which eventually inspired me to come up with the theme of my graduation project.

I took this thesis as a final learning opportunity as a student, so I wanted to challenge myself by combining most of the things I was already interested in, in one graduation project. The interest areas that came together in this research are BIM, environmental impact assessments, circular economy, project cost estimations and automation of tasks by programming.

It was both enriching and frustrating to learn a programming language, C#, from scratch and to develop a simple plugin for Revit. Being always at the user end of technology before, I never came to realize how difficult and complex the automation processes can be for the tasks we consider "simple" and use every day. Now I greatly appreciate and respect all people who work in software development for AEC industry. They make our lives easier by making theirs difficult since their job require lots of patience and time to code, test and debug everything.

Of course, this project would not have been possible without the help and support of several people. I would like to thank my external supervisors Quirine Henry and Rudolf Scholtens, for always making time for my questions, involving me in discussions about circularity and sustainability where I could learn from them and always providing me with valuable guidance along the way. I would like to extend this thanks to my fellow team members in RHDHV as they have provided important input for my research and feedback for my plugin.

From TU Eindhoven, I would like to express special thanks to my supervisors Qi Han and Pieter Pauwels. Without their strong support, insights and guidance throughout the entire graduation project, I would never be able to finish this thesis.

Lastly, I would like to thank my friends and family for always believing in me and providing me with emotional support and motivation. Especially my mom and dad, they have always been the source of unconditional love and support in my life. They are my true heroes and I cannot thank them enough for always being there for me, putting up with my negativity during my low points and encouraging me to keep moving forward.

Thank you all who have taken the time to read this preface. I hope this thesis inspires you to work towards a more sustainable future for all of us.

Ece Karabınar

Eindhoven, September 2021

Table of Contents

6

Summary

21st century is marked with rapid changes in technology and constant developments in sustainability. Like many other sectors, while sustainability is gaining more and more attention in the construction industry, interrelated concepts such as life cycle assessment, lifecycle costing and circular economy are, now, recent key concepts taking researchers' attention. In the extant literature, it has been well documented that there is a need for evaluating the designs in terms of their circularity, environmental and financial performances during the early design phase in which the design decisions are made.

With this respect, our current knowledge gap brings to mind several questions such as: How can we combine circularity, environmental and financial aspects? How can we assess their impacts at an early design stage? What are the benefits of such a holistic approach in daily worklife of architects and engineers?
As an attempt to answer these questions, the objective of this study is twofold: First, to propose an assessment framework in which the circularity indicators, costs and environmental impacts of designs are integrated theoretically. Second, to test the effectiveness of this framework practically by designing a plugin into BIM software, Revit, and validating it via a case study.

Since the main goal is to stimulate architects and engineers to make sustainable design choices, it is important to consider different design aspects simultaneously and compare different options in the same design environment. This goal can be achieved by incorporating environmental, cost and circularity assessments as early as possible in the design process. At present, the assessment tools for embodied carbon, MCI and cost calculations are often separate; therefore, the users cannot access these information in a single environment all at once.

Most of the construction industry is currently either using or switching to use digital building information modeling (BIM) software for their projects. Therefore, due to the common use of it, to combine circularity indicators, costs and environmental impacts of a design, a BIM software tool was developed and named CECC tool (Circularity, Embodied Carbon and Costs). Considering its functions, it can be stated that this plugin, accommodated in Autodesk Revit, provides architects and structural engineers with necessary output to get insights about their designs and decisions during the detailed design phase. In this way, it enables the users to understand and evaluate the impacts of their decisions on materials and building element types. It can be concluded that the CECC tool is practical because it accommodates all functions into one plugin and facilitates decision making by allowing for iterative changes without going back and forth between Revit and another assessment software. This creates a much more efficient workflow and reduces the time spent on assessments. Last but not the least, the developed tool can be considered as user friendly since it is easy to use and it provides a dashboard displaying the results of each building element separately as well as the totals. It is considered a great advantage for the users to be able to obtain such fast data, easily and in real time.

The general framework includes circularity score, environmental impact and financial impact assessments of the projects. In a case study, limited part of the framework was implemented as a

plugin for Revit as a proof of concept. Revit application combined only the embodied carbon from an environmental impact perspective, manufacturing and construction costs from a financial impact perspective and MCI from a circularity perspective, for a case study project. In the case study, the tool was executed on the BIM model for two different floor panel alternatives of a building.

Case study provided empirical evidence showing that when the plugin was run on the BIM model for two different floor panel alternatives of a building, the results change for each alternative in terms of embodied carbon, circularity potential and costs. Assessment results suggest that when keeping all other parameters the same, only changing the floor type has a direct impact on the costs and embodied carbon results of the overall design. The particular example of comparison, given in this research, showed that while "kanaalplaatvloer" is a better option from the costs and environmental impacts perspective, "breedplaatvloer" option is slightly better in terms of circularity potential.

All in all, such an integrated assessment will contribute to sound decisions made on building designs. To put it another way, identifying hotspots quickly will facilitate decision making process so that building designs can be optimized according to financial, environmental and circular criteria embedded in a broad sustainability concern.

Abstract

Construction industry is one of the well-known sectors harming the environment in many ways such as consuming energy, exploiting resources and generating waste. As a result of this global problem, a vast body of research, now, reflects deep concern with related concepts such as life cycle assessment, lifecycle costing and circular economy. Drawing on the principles of these current concepts, this study aimed to develop a holistic framework in which circularity, environmental and financial aspects are integrated and then implemented into a practical BIM software in Revit.

There is a need in the AEC industry to combine LCA, LCC and MCI. Currently, there are several different software and tools to assess circularity, environmental and financial impacts of projects separately but none of them takes all three into account at the same time. Since the solutions are scattered across multiple platforms and solutions, it makes the process of assessment and evaluation complicated and time consuming. The architects and engineers working on their design proposals cannot conduct these assessments easily to test how well their designs perform on each aspect. This situation, most of the time, causes these assessments to be made at the end of the design process when everything is already decided. The possibility of making changes and design iterations decreases significantly. When these three aspects are considered together such obstacles can be overcome and designs that are more resource conscious and environmentally friendly can be reached.

In order to combine circularity indicators, costs and environmental impacts of a design, a BIM software tool was developed and named CECC tool (Circularity, Embodied Carbon and Costs). With the creation of such a plugin, the assessment process can be done in real-time in Revit and outcomes of changes in the design can be obtained and observed immediately inside the software. It can be stated that the generation of the assessment results and the calculations take much less time since there is no extra effort for extracting BIM data and then uploading it in a different environment. Also, since the changes in the BIM model will affect the results of the assessment in real-time, the architects and engineers can make modifications on their model and try to achieve a better design solution by checking the updated results of each design iteration.

It can be stated that all parties that are involved in a construction project can benefit from this framework. Stakeholders such as the client and investor will be able to comply with the environmental requirements for their projects while avoiding unforeseen costs. On the other hand, the architects and engineers will have guidance on how to check the performance of their designs.

Keywords: Circular economy, circularity, environmental impact, financial impact, BIM, LCA, LCC, MCI, Revit

List of Abbreviations

AEC	Architecture, engineering, construction
API	Application programming interface
BCI	Building circularity indicators
BIM	Building information modeling
BoM	Bill of materials
BoQ	Bill of quantities
BREEAM	Building Research Establishment Environmental Assessment Method
CDW	Construction demolition waste
CE	Circular economy
CI	Circularity indicators
CSV	Comma separated values
C2C	Cradle to cradle
C2G	Cradle to grave
DD	Design development
DfA	Design for adaptability
DfD	Design for disassembly
DfF	Design for flexibility
DfR	Design for recycling
DfReu	Design for reuse
DRM	Design research methodology
EC	Embodied carbon
EE	Embodied energy
EPD	Environmental product declaration
GWP	Global warming potential
IFC	Industry foundation classes
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCC	Life cycle costing
LOD	Level of detail
MCI	Material circularity indicator
NLRS	Dutch Revit standards
NIBE	Nederlands Instituut voor Bouwbiologie en Ecologie
NL-SfB	Nederlands Samarbetskommittén för Byggnadsfragor
NMD	Nationale Milieu Database
NPV	Net present value

List of Figures

List of Tables

List of Equations

1. Introduction

This chapter establishes the base of this research. It starts with the research context, which provides an overview of the current situation and background information regarding the issue that will be further examined. This is followed by the research objectives and scope, which explains the goals and clarifies the scope of this research. Then, the main research question together with its sub-questions are stated. These sub-questions divide the research objective into smaller parts so that the main research question can be answered at the end. Lastly, to make understanding the research design easier, its structure is explained and presented as a visual chart illustrating the steps to be taken to address each research question.

1.1. Research context

Following the 1997 Kyoto Protocol, in 2015 a new agreement on climate change was introduced by the United Nations. This agreement is known as the Paris Agreement and it was signed and ratified by 191 countries as of 2021, including the EU countries. Acceptance of the agreement affected lots of different industries, including the construction sector.

Sustainability is a popular topic in construction as the sector plays a critical role in it (Gervasio & Dimova, 2018). Construction can harm the environment in three major ways: by consuming energy, exploiting resources and generating waste (Bertin et al., 2020; Eberhardt et al., 2019). The sector is responsible for roughly 40% of the total carbon emissions and energy consumption globally (Lu et al., 2021; UN Environment, 2017). In addition to this, 25-30% of the waste created in the EU results from the total waste generated by the activities in the construction industry (Fregonara et al., 2017; Cottafava & Ritzen, 2021). The sector is also accountable for depletion of natural resources by consuming more than 40% of the total amount of raw materials (Bertin et al., 2020).

In order to achieve the goals of the Paris Agreement, to reduce global carbon emissions and energy consumption, the construction industry must address the extreme energy consumption, rapid depletion of resources and excessive waste generation. Tackling these issues is possible and there are actions already taken, however, the current approaches in the industry are not enough and the change is taking place very slowly. One critical way to accelerate this transition is to come up with more sustainable designs.

Sustainability has three main pillars, namely economic, environmental and social sustainability, and these pillars also apply to sustainability in the construction industry. There is also an additional complementing approach growing parallel to sustainability, which is circularity/circular economy. Circularity is complementary to sustainability as they do not mean the same thing; not all sustainable strategies are circular and not all circular strategies are sustainable. To give an example, recycling can be environmentally not friendly if the energy consumed for the process is greater than the benefits of recycled materials. Therefore, achieving sustainability in building designs depends on how well these three pillars are addressed and how efficiently circularity principles are implemented. In each of these dimensions, there is an ongoing progress, however they are often considered separately.

There are existing methods to assess environmental impacts, financial impacts and circularity aspects of designs, but currently, they are not integrated, meaning they are often measured separately with the help of different platforms or tools. For example, there are circularity indicators to look at how well the building designs perform in line with the circular economy principles. These circularity indicators can be on building level (BCI) or on material level (MCI). Currently, in order to assess environmental impacts, Life Cycle Assessment (LCA) is used and for financial impact evaluations, Life Cycle Costing (LCC) is used. There are software and tools for these assessments, but often they are not well integrated with the design environment. There can be compatibility issues or simply not every tool supports every design software. All these obstacles

make their application difficult and time consuming for the people working in the architecture, engineering and construction (AEC) industry.

Another factor to keep in mind is that these sustainability decisions should be made from the start of a project. As can be seen from Figure 1, changing a design after the design development phase significantly increases the costs while these late-stage changes remarkably decrease the ability to make an impact. It can also be seen that, in this sense, the traditional design and construction processes are inefficient. Therefore, they must be changed in a way that the design alternatives get evaluated during earlier stages.

	1	Ability to impact cost and functional capabilities	PD: Pre-design
	2	Cost of design changes	SD: Schematic Design
	3	Traditional design process	DD: Design Development
	4	Preferred design process	CD: Construction Documentation
			PR: Procurement
			CA: Construction Administration
			OP: Operation
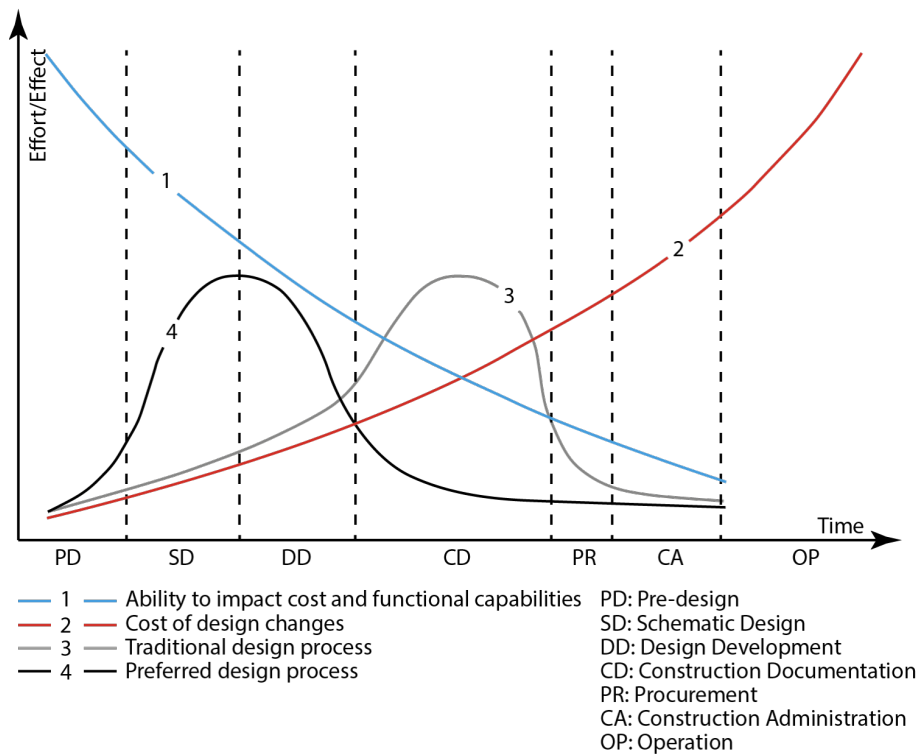
Figure 1: The MacLeamy Curve (MacLeamy, 2004)

1.2. Research objectives and scope

Based on the points mentioned in the research context, there is a need in the construction industry to evaluate the designs during the phase in which the design is developed, for their circularity, environmental and financial performances. This evaluation should be easy for the architects and engineers, well integrated in their working process and the outcome should be observed in real-time. The conceptual idea behind the proposed assessment approach is demonstrated in Figure 2.

16
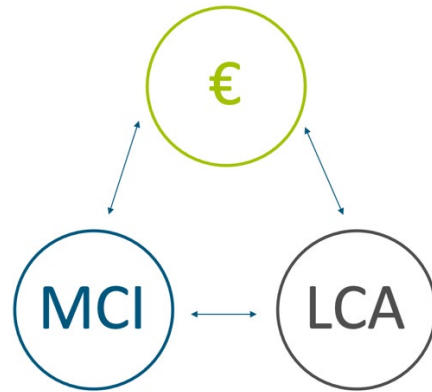
Figure 2: Combined assessment approach

This research acknowledges the previous research done by Van Gemert (2019), Zhai (2020) and Van Oeveren (2020) and expands upon their findings. The main objective of this research is to produce an assessment framework that takes into account the circularity indicators, costs and environmental impacts of designs, in a holistic manner. All parties that are involved in a construction project will benefit from this framework. Stakeholders such as the client and investor will be able to comply with the environmental requirements for their projects while avoiding unforeseen costs. Additionally, the architects and engineers will have guidance on how to check the performance of their designs. Considering three main pillars of sustainability, social aspects are beyond the scope of this research. Ideally, this framework can be further extended to include social sustainability encompassing all three sustainability pillars, plus the circularity.

Most of the construction industry is currently either using or switching to use digital building information modeling (BIM) software for their projects. For example, Royal HaskoningDHV, an international engineering and project management consultancy company, is actively using BIM in their workflows. Therefore, the assessment framework should also be accommodated in a preferred BIM software to be used in the design development stage (DD) as mentioned in the MacLeamy Curve in Figure 1.

To make it clear, the design phase that is being taken into account for this study is the detailed design stage. Detailed design stage is the term that is most often used in the AEC industry, and it equals the design development stage (DD) in the MacLeamy Curve in Figure 1. Preliminary design phase is not to be addressed in this research as this encompasses pre-design and schematic design phases in Figure 1 and these stages lack the required information for an assessment. For this study, the BIM software Revit is selected, and the assessment framework is translated into a plugin that works together with Revit.

It should be noted that the general framework proposed in this study is not limited to an application within Revit, however a part of the framework is implemented in Revit as a proof of concept. The general framework includes circularity score, environmental impact and financial impact assessments of the projects. The Revit application combines only the embodied carbon

17

from an environmental impact perspective, manufacturing and construction costs from a financial impact perspective and MCI from a circularity perspective, for a project at hand. Therefore, the scope of the Revit tool is much more specific and hence, limited.

The assessment plugin helps architects and structural engineers to get insights about their designs during the detailed design phase, when materials are selected, and to understand and evaluate the impacts of their decisions on materials, building element types, quantities and sizes. The aim is to help them to achieve the results from these assessments faster and easier, without having to leave their design environment.

With the creation of such a plugin, the assessment process can be done in real-time in Revit and outcomes of changes in the design can be obtained and observed immediately inside the software. The generation of the assessment results and the calculations will take much less time since there will not be an extra effort for extracting BIM data and uploading in a different environment. Also, since the changes in the BIM model will affect the results of the assessment in real-time, the architects and engineers can make modifications on their model and try to achieve a better design solution by checking the updated results of each design iteration. The plugin also gives visual information as charts to facilitate their decision-making process. A dashboard is provided to the users to display the results of each building element separately as well as the totals.

1.3. Research problem and questions

In order to achieve the research objectives, the following main research question has been formulated:

> *"How can the integration of circularity, cost and environmental impact aspects of a design with BIM enable an automated combined assessment process and support architects and engineers in their decision-making process during the design development stage?"*

To address the main research question, six sub-questions have been created so that the research process will be facilitated, and the information needed to answer the main question will be reached step by step:

SQ 1: What kind of data is needed to assess
        1.a) environmental impacts of a design?
        1.b) financial impacts of a design?
        1.c) circularity scores of a design?
SQ 2: What are the benefits of combining these three aspects?
SQ 3: How can these aspects be combined and what will the framework look like?
SQ 4: How can this combined assessment method be incorporated in a day to day working life of an architect/engineer?
SQ 5: What kind of output is needed after the assessment of the designs?
SQ 6: How will the architects and engineers benefit from the output?

1.4. Research design

The research consists of five main stages. It starts with a literature review, to gain in depth knowledge about the subject. This is followed by the introduction of the proposed framework and how it combines the three targeted aspects, namely environmental, circular and financial impacts. In the tool creation stage, the Revit plugin is designed based on the suggested framework. In the next stage, the tool is tested on a case study provided by the collaborating company, Royal HaskoningDHV. Lastly, there are evaluations of the results and conclusions. Since the research is conducted in collaboration with Royal HaskoningDHV, the insights gained through their "Competence Center Sustainable Buildings" and "Knowledge Group Circular Economy in the Built Environment" teams are always incorporated along the project. A schematic representation of the research design can be seen in Figure 3.
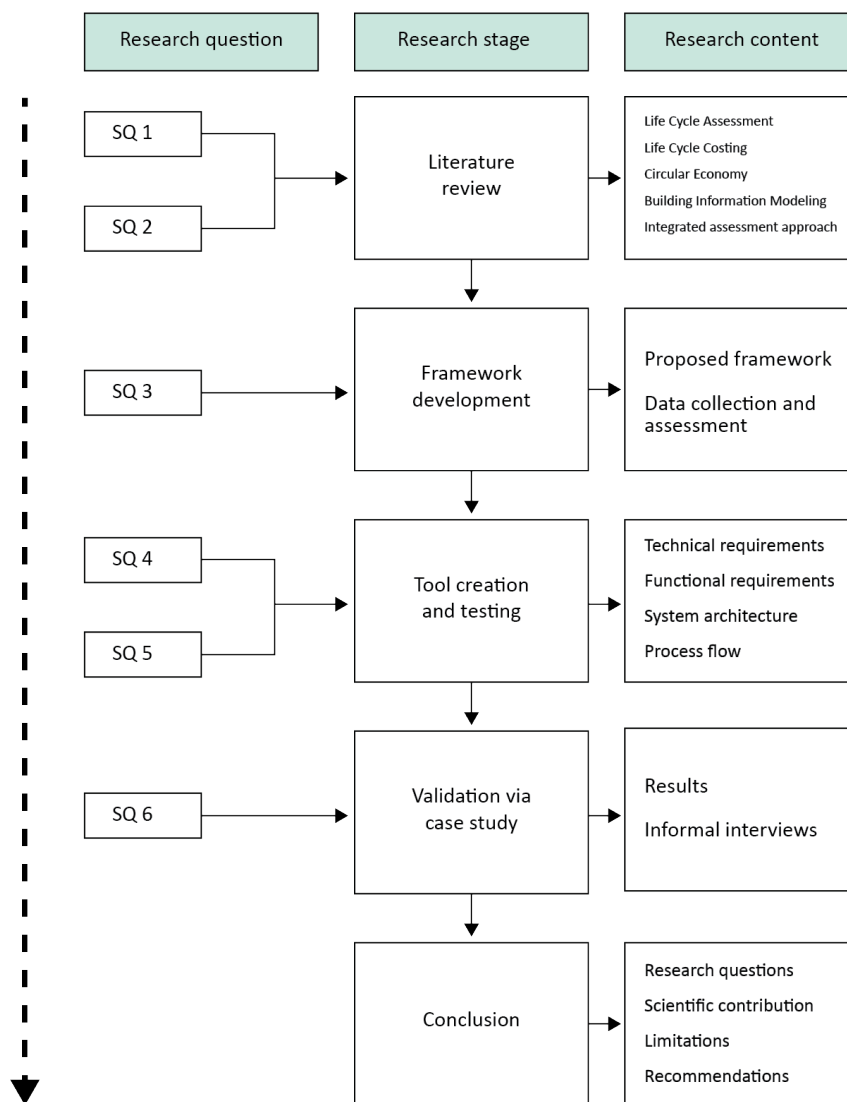
Figure 3: Research design

Figure 3 indicates each research stage with its content and corresponding sub questions to be answered during the related stage. In the conclusion stage, all six sub-questions are restated, and their answers are given so that the main research question is answered.

1.5. Reading guide

This thesis consists of five chapters. Chapter 1 is the introduction which establishes the base for the research. It provides an overview of the current situation and background information regarding the research topic. The research goals and scope are also explained in it. Chapter 2 addresses the literature review where the important concepts of the research are introduced and explained. In this chapter, the existing studies and their findings are also discussed. Then, in Chapter 3, the methodology of the research is presented. This chapter serves as the backbone of the research as it also introduces the proposed assessment framework and its essential components. This is followed by Chapter 4, which is about the tooling and the case study project. Lastly, in Chapter 5, the thesis is wrapped up with a conclusion which encompasses the restatement of research questions and how they are addressed, scientific contribution, limitations of this research and future recommendations.

2. Literature Review

In this chapter, a general understanding of the research area is delivered via decomposing it into its essential components which are life cycle assessment, life cycle costing, circular economy, building information modeling and integration of circularity, environmental impact and cost assessments in BIM environments. These key concepts are explained in the given order and definitions are provided while each key concept and their subcomponents are further elaborated. Research studies conducted so far, and their findings are discussed under each related concept.

2.1. Life Cycle Analysis

Life Cycle Analysis (LCA) is the name given to the study in which the environmental impacts of products throughout their life cycles are being analyzed and assessed (Glaumann et al., 2010; Lu et al., 2021).

LCA is widely used in different industries and in the construction sector it is also one of the most commonly accepted standards to evaluate sustainability of buildings (Röck et al., 2018). LCA utilizes life cycle thinking. Life cycle thinking is a holistic approach that takes into account a building's whole life cycle (Lavagna et al., 2021). In LCA, the main aim is to reduce the environmental impacts of the buildings during their lifetime.

Life cycle of a building is defined by an international standard, which is EN 15978. There, the stages of a building life cycle are defined as:
>   A) Embodied stage,
>   B) Use stage,
>   C) End-of-life stage,
>   D) Beyond the system boundaries stage.

Figure 4 illustrates how a building's life cycle looks like. In the diagram of Wolf, Pomponi and Moncaster (2018), a life cycle of a building is divided into four general stages mentioned above (A, B, C, D) and each category is further divided into sub-categories. It must be noted that in Figure 4, embodied stage (A) is illustrated as the combination of Product and Construction Process stages.

PRODUCT stage			CONSTRUCTION PROCESS stage		USE stage					END OF LIFE stage				BEYOND
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1	C2	C3	C4	D
Raw material supply	Transport	Manufacturing	Transport	Construction-installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Deconstruction Demolition	Transport	Waste Processing	Disposal	Reuse Recovery Recycling Potential

B6
Operational energy use

B7
Operational water use

Life cycles defined by EN 15978, adapted from [10].

Figure 4: Life cycle of a building (Wolf, Pomponi & Moncaster, 2018)

In EN 15978, the system boundaries of an LCA are defined until the "beyond stage (D)". However, it should be noted that this standard was published in 2011 and the line of thinking in this model is from a linear economy perspective (Eberhardt et al., 2019). Hence, the building life cycle

represented in this model is also linear. This is due to the fact that this life cycle model takes into account only one life cycle of a building and does not consider its possible multiple life cycles. The most common building lifespan is found to be 50 years (Cottafava & Ritzen, 2021; Lu et al., 2021).

Stages A through C in a life cycle of a building represent the "cradle to grave (C2G)" LCA, which is considered as a full LCA and is the most popular system boundary that is being used (Lu et al., 2021). This approach is from a linear economy perspective as the resources are not recovered and waste are just being disposed of. However, stages A through D encompasses the "cradle to cradle (C2C)" LCA, where all life cycle stages of a building are covered, including the potential of a building and its components for recycling, recovering or reusing after the building's intended end of life, so that the result is a closed looped system. Considering LCA in the "cradle to cradle" way is from a circular economy perspective and there lies a great potential to reduce the environmental impacts of buildings. An attempt to represent the "cradle to cradle" idea is illustrated by Tikkanen (2019), and it can be seen on Figure 5.
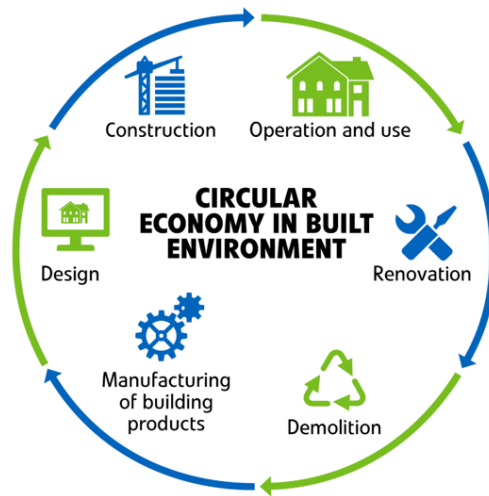
Figure 5: Circular economy in built environment (Tikkanen, 2019)

To take Tikkanen's "Circular economy in Built Environment" model one step further, the diagram can be reformulated into Figure 6, which explicitly states each corresponding life cycle stage for every step to make it clearer.
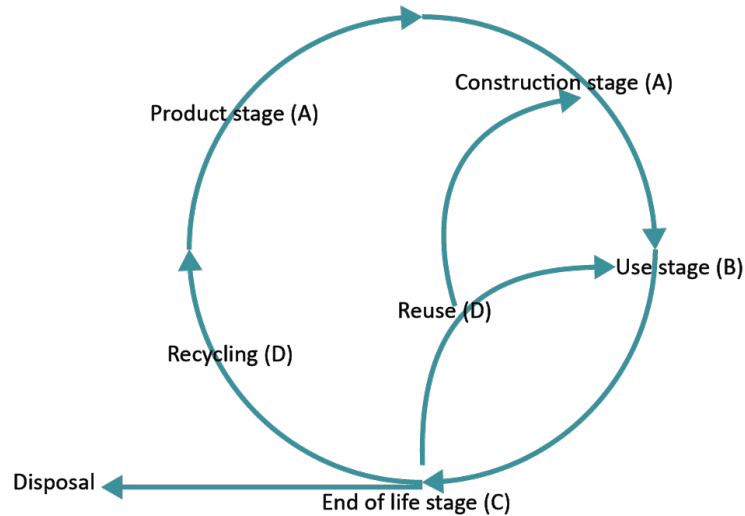
Figure 6: Circular building lifecycle

Of course, looking at LCA from a closed loop perspective has its own difficulties. Bertin et al. (2020) state that current LCA methods are not sufficient because they do not consider the advantages and disadvantages of reuse, when the life cycles are extended or multiplied. There are various uncertainties when an LCA evaluation is conducted considering reuse impacts. These uncertainties include inadequate data on full use of lifespan, the number of use cycles and reconditioning operations. Bertin et al. (2020) advocate the idea of developing different tools to evaluate the impact of reuse. An example can be the introduction of reuse potential indicators which would give information about traceability of the materials and components, their demountability and adaptability to new and different use cases. They also state that the integration of end-of-life scenarios in LCA can be improved so that various options for reuse approaches can be better anticipated.

Transportation is another factor in negative environmental impacts during a life cycle. Hence, transport distances between raw materials and finished products should be taken into account and reduced. Using local resources is a great way to reduce both costs and negative environmental impacts originating from transportation activities (Giama et al., 2019). Also, fully electrification of the transportation sector in the future will change its influence on sustainability. However, it should be noted that transportation as a factor is not at the same level as embodied energy or carbon and therefore it is not in the scope of this research.

According to ISO standards 14040 and 14041, conducting an LCA consists of four steps (Glaumann et al., 2010; Lu et al., 2021):
> 1) Goal and scope definition
> 2) Inventory analysis (Life cycle inventory)
> 3) Environmental impact assessment (Life cycle impact assessment)
> 4) Results interpretation

When conducting an LCA, there needs to be an inventory, consisting of all necessary information about the material and process quantities to calculate possible impacts of each material and processes by multiplying these quantities with the appropriate impact values. Then, the individual results can be summed up to get the overall environmental impact of a building (Carbon Leadership Forum, 2019).

In order to define the scope, there needs to be several information and decisions taken. These include a functional description of the building, a reference study period and system boundary. System boundary consists of (1) building and site scopes that defines which physical parts of the building and project site would be considered for the assessments and (2) life cycle scope that denotes which life cycle stages would be taken into account for the assessments. The minimum information required to conduct an LCA include names, types, quantities and units, lifespans of materials and life cycle stage in which the material is used (Carbon Leadership Forum, 2019).

There are several environmental impact categories present within the scope of LCA. Five most common of these categories are: global warming potential, acidification potential, eutrophication potential, ozone depletion potential and smog formation potential (Carbon Leadership Forum, 2019). The whole list of 11 environmental impact categories can be seen in Table 1.

Table 1: Environmental impact categories

Impact Category	Abbreviation	Unit
Global warming potential	GWP	kg CO_2 eq
Stratospheric ozone depletion potential	ODP	kg CFK-11 eq
Photochemical oxidation potential	POCP	kg C_2H_2 eq
Acidification potential	AP	kg SO_2 eq
Eutrophication potential	EP	kg PO_4 eq
Human toxicity potential	HTP	kg 1.4-DCB eq
Terrestrial ecotoxicity potential	TETP	kg 1.4-DCB eq
Freshwater aquatic ecotoxicity potential	FAETP	kg 1.4-DCB eq
Marine aquatic ecotoxicity potential	MAETP	kg 1.4-DCB eq
Abiotic depletion potential of elements	ADPe	kg Sb eq
Abiotic depletion potential of fossil fuels	ADPff	kg Sb eq

According to the findings of Lu et al. (2021) a single environmental indicator, like carbon emissions or energy consumption, is in the center of most LCA studies, whereas some other studies take into account multiple indicators such as acidification potential, eutrophication potential and ozone depletion potential. Embodied energy and embodied carbon are the two main factors which determine the total environmental impact of a building, according to LCA standards (Fregonara et al., 2017). The embodied carbon can be calculated by checking the global warming potential category in an LCA.

There are some LCA studies which focus more on the impact categories other than the global warming potential. For example, Marzouk et al. (2017) focused their research on comparison of different life cycle stages and their contribution to detrimental effects. They found that the manufacturing and transportation off-site produces as much as 92.83 % of ozone-depleting particles whereas the demolition phase produces eutrophication particles.

By conducting an LCA, different goals can be achieved. With an LCA:
A) environmental impact of a building such as contribution to climate change or depletion of resources can be quantified,
B) different design options or material alternatives can be compared and evaluated for their environmental impacts,
C) the biggest contributors to the total impact of a building can be identified, overall environmental performance of buildings can be declared and documented,
D) green building certifications such as BREEAM or LEED can be obtained. (Glaumann et al., 2010; Carbon Leadership Forum, 2019).

The quality of LCA depends on the quality of the input data used for the assessment. The more accurate the data are, the more accurate the LCA results will be. However, it should be kept in mind that having an idea about the environmental impacts via estimates or data available at hand is still better than completely neglecting these impacts and not conducting any LCA at all (Glaumann et al., 2010).

There are several different LCA databases. Most of these databases, however, are not free to use. In the Netherlands, the database used for environmental impact assessments is called Nationale Milieudatabase (NMD). Use of this database is the common standard and it is openly accessible by everyone via web. There is another database from Nederlands Instituut voor Bouwbiologie en Ecologie (NIBE). This database gets its data from NMD but is more user friendly because it clearly explains which indicator value represents what and it also includes the future scenario of materials in the Dutch construction industry.

Sometimes environmental product declarations (EPDs) are produced by using LCA methodology. EPDs are prepared according to ISO standards and they contain information about environmental performance of products. EPDs are often created for specific products from specific manufacturers. LCA databases can contain EPDs from various manufacturers so that the users can choose from these available options while conducting an LCA for a whole project and get more accurate results.

When talking about LCA, it is beneficial to look at which building layers are contributing how much to the overall environmental impacts in general. Six building layers were originally proposed by Stewart Brand in 1994, consisting of stuff, space plan, services, structure, and site. An expanded version of this model with an additional new layer "social" can be seen in Figure 7.
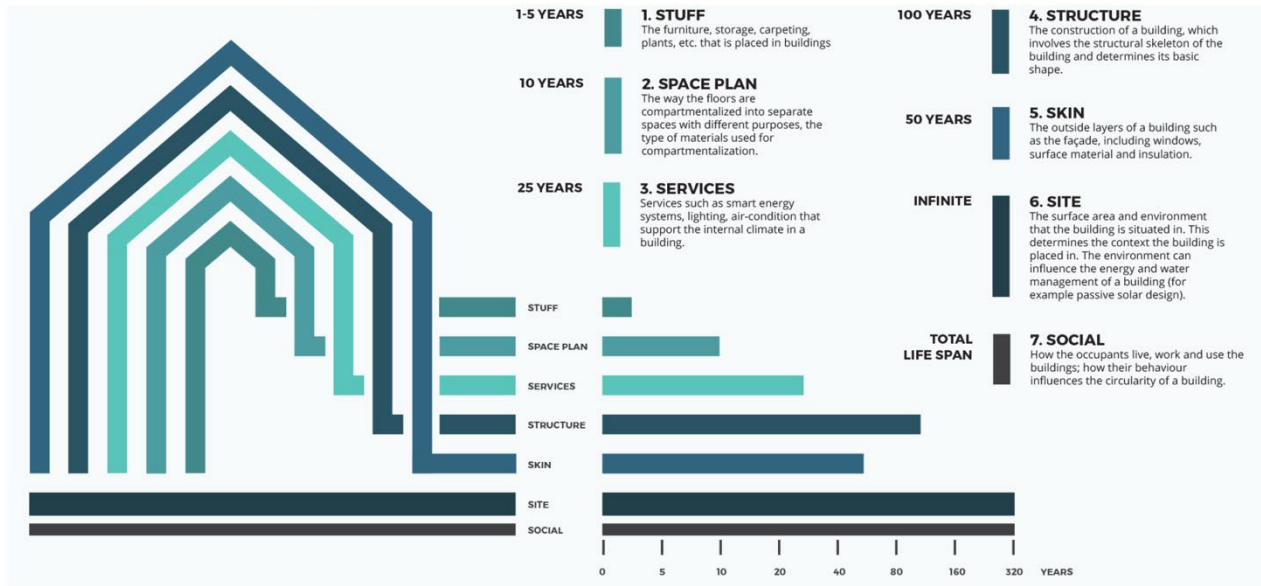
Figure 7: Building layers (World Business Council for Sustainable Development, 2020)

Regarding the embodied carbon, each building layer contributes differently. For example, according to Castro and Pasanen (2019) structure is responsible for 58% of the total embodied carbon, whereas skin is for 23% and space plan is for 18%. In another study, Bertin et al. (2020) agrees that load-bearing systems (structure layer) have the most impact in terms of embodied energy and embodied carbon. Marzouk et al. (2017) found out that 39% of the embodied energy comes from the load-bearing systems in a building. Röck et al. (2018) found out that in the context of their presented building case, partition walls (space plan layer) are also contributing highly to the overall environmental impacts. Thus, although the structure layer is generally considered as the most impacting layer, the contribution can differ depending on the project and its characteristics. It should be kept in mind that the choice of materials will have a major effect on the results of relative impact percentages.

LCA requires a lot of information and is considered as a process which is data intensive (Röck et al., 2018). LCA of a simple product is feasible regarding time and complexity. In contrast, LCA of a building project can be quite complicated and often requires a lot of time. This can be due to lack of expertise of the practitioners. The lack of expertise and knowledge also limits the practical application of LCA to support the decision-making processes (Eberhardt et al., 2019).

Moreover, it also takes time to process excessive amounts of environmental indicators during an LCA to reach a few final scores that would help decision makers to come up with conclusions. Excess information may hinder the efficiency (Cottafava & Ritzen, 2021). Therefore, in the construction sector, LCA is mostly done when the design is finalized, everything is certain, or even once the construction is completed. This is also the reason why most of the time operational stages and in-use energy consumption of the buildings are assessed for their environmental impacts (Röck et al., 2018; Lavagna et al., 2021).

In contrast, according to Kamp Albæk et al. (2020), "approximately 80% of the sustainability performance of a product over its life cycle is defined in the early stages of the product design and development process". There are several LCA tools to evaluate buildings for their environmental performance. However, since LCA is often conducted in the last steps most of the time, designs do not get affected or changed much (Lavagna et al., 2021). Nonetheless, with the ever-growing need in the world to become more and more sustainable, it is clear that LCA should be integrated in earlier phases in the construction industry. This will help architects and engineers to make more conscious design and material choices and they can also monitor the effects of their decisions (Röck et al., 2018).

Fortunately, nowadays, the main focus is shifting towards the early design stages and selection of materials (Röck et al., 2018; Lavagna et al., 2021). In order to facilitate this, the potential of BIM is being investigated currently and several methods are being developed (Lavagna et al., 2021). It is possible to link LCA data to a BIM model via plugins. By doing this, the BIM model can be evaluated preliminarily for its environmental impacts (Cottafava & Ritzen, 2021).

2.2. Life Cycle Costing

Life Cycle Costing (LCC) is a cost management approach where costs occurring over an entire life cycle of a product or asset are analyzed and aggregated (Glaumann et al., 2010). In the construction industry, it refers to the "sum of the costs incurred in a building's different life cycle stages" (Lu et al., 2021). Since it is an analysis, it is often also referred to as Life Cycle Cost Analysis (LCCA).

LCC is a standardized process and is explained in ISO 15686-5. It includes costs related to acquisition and ownership, investment, construction, operation, refurbishing and replacement, maintenance and repair, end of life, dismantling, demolition, disposal and residual value of buildings and their components (Lu et al., 2021; Fregonara et al., 2017; Glaumann et al., 2010). Global Cost is a concept which is the base of an LCC and the global cost that is obtained from an LCC typically contains initial costs of investments together with the operation and maintenance costs and disposal costs of the buildings (Fregonara et al., 2017).

Similar to LCA, LCC is also based on Life Cycle Thinking (LCT). In the construction sector, through an LCC analysis, costs and benefits of a project can be quantified and design alternatives can be compared (Glaumann et al., 2010). These projections can be done for both short term and for long term (Fregonara et al., 2017).

In a LCC analysis there are typically 4 steps. These steps include:
1) Defining the target and boundary for the analysis
2) Establishing the basic assumptions for the analysis
3) Calculating LCC by summing the costs
4) Analyzing LCC, including the net savings, savings-to-investment ratio, payback period, and sensitivity analysis (Lu et al., 2021).

The steps of an LCC can be considered similar to the steps of an LCA. They both have 4 steps, starting with goal and scope definition for the analysis. Then an LCC analysis moves on to establishing assumption whereas an LCA continues with a life cycle inventory analysis. The third step for both LCC and LCA are conducting the analysis and as a last step, they both require the user to interpret and analyze the results obtained from the respective analyses. These steps and the aforementioned basic assumptions to be be established during an LCC include choosing a consistent method of calculation, a suitable study period, deciding on an inflation and a discount rate (Sarja, 2006).

According to Glaumann et al. (2010) conducting an LCC for the whole life cycle of a building during the early decision phase is beneficial for the building owner or investor since by doing so, they can identify the cost effectiveness of different alternatives early and make decisions accordingly. For example, if the future costs of the building are estimated to be high, the rent prices of that building can be set accordingly. Glaumann et al. also mention that LCC calculations are commonly used and required for the public tendering processes.

Fregonara et al. (2017) found out that, most of the time, private clients are more interested in the design options which have more potential in terms of economic sustainability in the future since these options generally indicate potential future savings. In addition to economic sustainability, public clients are also interested in environmental sustainability when they are comparing different design alternatives. In their research, when they were conducting LCC, they calculated the net present value (NPV) of alternatives. NPV takes into account the time value of money. By using NPV, they were able to compare the global cost of different design alternatives, they could capture the impact of each cost component on the overall financial result separately and were capable to look at the costs occurring at different life cycle stages. In their study, they assumed that early design solutions highly affected the initial investment decisions. Although NPV is the most commonly used method, it should be noted that it cannot always be used. The service life of the design alternatives that are being compared should be the same when NPV is applied (Raposa et al., 2019).

In the study by Lu et al. (2021), the residual value of the buildings was found to be very important since this value contributed greatly to the benefits and loads beyond the system boundary. They observed that most of the time, when an LCC is conducted, the bill of quantities and energy consumption data are obtained from BIM as a first step. Then, these data are multiplied by the price of materials, machinery, and energy in the LCC database. For the prices, there are different options available, such as databases containing local prices, market pricing or contractors' costs. One popular LCC database is RSMeans.

Another interesting finding is by Bertin et al. (2020) that raw materials targeted by reuse in the construction industry can be around 3 billion tons. This would generate notable economic interest since 3 billion tons of raw material equals around 40–50% of the world's economy.

2.3. Circular Economy

Circular economy (CE) is a concept that has emerged in opposition to linear economy. Linear economy is the traditional economy model where the raw materials are used and processed to make products. These products typically generate waste after they have been used. In linear economy, therefore, an unsustainable "take-make-dispose" mentality is dominant (Kamp Albæk et al., 2020). This economic model results in scarcity of natural resources, increase in waste materials and the outcome is an overall negative impact on the environment.

Linear economy exceeds the limits of planetary boundaries. Planetary boundary is the concept which explains the boundaries "within which humanity can continue to develop and thrive for generations to come" without increasing "the risk of generating large-scale abrupt or irreversible environmental changes" (Lonca & Raufflet, 2020). As the linear economy model is understood to be not sustainable and environmentally damaging, countries are trying to switch from a linear economy to a circular one.

Circular economy promotes the idea of designing products that can be used in multiple life cycles. According to the Ellen Macarthur Foundation it is established on three key principles which are:
>   1) Design out waste and pollution
>   2) Keep products and materials in use
>   3) Regenerate natural systems (Ellen MacArthur Foundation, 2017).

To illustrate the idea behind CE, the famous butterfly model of Ellen MacArthur Foundation can be seen in Figure 8. The diagram consists of two value cycles which are biological value cycle (left) and technical value cycle (right).

RENEWABLES FLOW MANAGEMENT

RENEWABLES

FINITE MATERIALS

STOCK MANAGEMENT

FARMING/COLLECTION[1]

BIOCHEMICAL FEEDSTOCK

REGENERATION

BIOSPHERE

PARTS MANUFACTURER

PRODUCT MANUFACTURER

RECYCLE

SERVICE PROVIDER

SHARE

REFURBISH/ REMANUFACTURE

BIOGAS

REUSE/REDISTRIBUTE

CASCADES

CONSUMER

USER

MAINTAIN/PROLONG

ANAEROBIC DIGESTION

COLLECTION

COLLECTION

EXTRACTION OF BIOCHEMICAL FEEDSTOCK[2]

1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org

Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

MINIMISE SYSTEMATIC
LEAKAGE AND NEGATIVE
EXTERNALITIES

ELLEN MACARTHUR
FOUNDATION

31

Having all these in mind, CE is an economic model where the main goal is to retain value. The value retention can be achieved in different industries, including the construction industry, via several strategies such as reuse, repair, refurbishment, remanufacturing and recycling (Haupt & Hellweg, 2019). The adoption of technical value cycle specifically on construction industry can be seen in Figure 9.
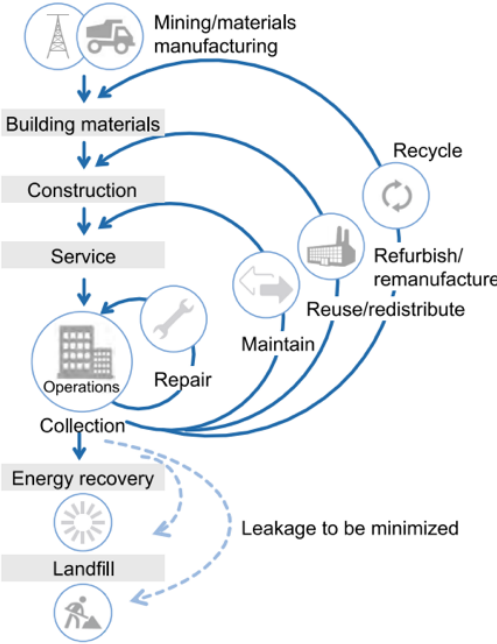
Figure 9: Circular economy principles in the construction value chain (Breene, 2016)
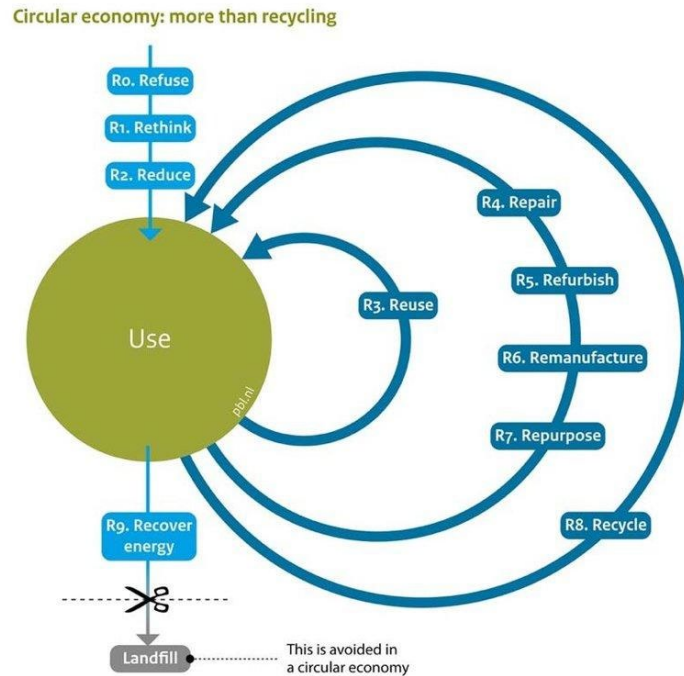
Figure 10: Circular strategies 10R ladder (Predan, 2020)

Currently, the Netherlands aims to achieve a fully circular economy by 2050 and to cut the use of primary raw materials half by 2030. The Dutch government's vision on the matter is stated in the "Nederland Circulair 2050" document from 2016. In 2018, circular economy transition agendas were made for five priority chains and sectors in the Netherlands and construction sector was one of them (Ministerie van Infrastructuur en Waterstaat et al., 2019).

Environmental Protection Agency reports that recycled, reused or recovered construction demolition waste (CDW) materials take only 40 % of the total waste whereas the remaining 60% of the waste goes to landfills. Since 25% of all waste generated belongs to the built environment in the EU, circular practices gain importance. To address the issue of circularity, several circularity indicators (CI) have been proposed. These indicators mostly focus on three points:

      1) the amount of virgin materials,
      2) the amount of unrecoverable waste, and
      3) the product lifetime/utility.

An overview of the most common circularity indicators proposed for the construction industry can be found in Table 2.

Table 2: List of circularity indicators

Circularity Indicator	Studies and organizations using the indicator
Material circularity indicator (MCI)	Ellen MacArthur Foundation, Alba Concepts, Verberne (2016), Vliet (2018), Zhai (2020), Cottafava & Ritzen (2021)
Product circularity indicator (PCI)	Alba Concepts, Verberne (2016), Vliet (2018), Zhai (2020)
System circularity indicator (SCI)	Verberne (2016), Vliet (2018), Zhai (2020)
Element circularity indicator (ECI)	Alba Concepts
Building circularity indicator (BCI)	Alba Concepts, Verberne (2016), Vliet (2018), Zhai (2020), Cottafava & Ritzen (2021)

Material Circularity Indicator (MCI) is currently described as the most popular and most used indicator for the built environment. MCI is a number between 0 and 1 and the closer the score on an MCI to 1 means the product has more circularity potential and is less linear (Ellen MacArthur Foundation & Granta Design, 2019). Information regarding how MCI is calculated can be seen in Chapter 3.3 "Data Collection and Assessment".

Circularity indicators have become the main research area of many different studies conducted in recent years. For example, in Cottafava and Ritzen's (2021) study, the Building Circularity Indicator (BCI) and their novel Predictive BCI (PBCI) are used for combining the MCI with embodied energy (EE) and embodied carbon (EC) analyses and Design for Disassembly (DfD) criteria.

Circular economy is often considered as an umbrella term which encompasses resource efficiency together with reduced environmental impacts (Lonca & Raufflet, 2020). While most of the time, a circular economy is assumed to be environmentally sustainable, it may not always be the case. As Haupt and Hellweg (2019) state, "circularity is not necessarily equivalent to environmental sustainability". They draw attention to the fact that the current circularity indicator frameworks do not include the environmental performance indicators. They emphasis that there is a clear need for an environmental impact indicator within the circular economy discussions. In their study they propose "an indicator to measure the value retention in the system in environmental terms, considering i) the life cycle impacts of an individual product or material, ii) all value retention processes and iii) the use-phase and potentially changed use-phase impacts". They suggest that "the economic value retained in the system could be compared to the financial amount invested on the original production of a product". They also support the idea of integrating a social impact indicator to assess circularity from that additional societal perspective.
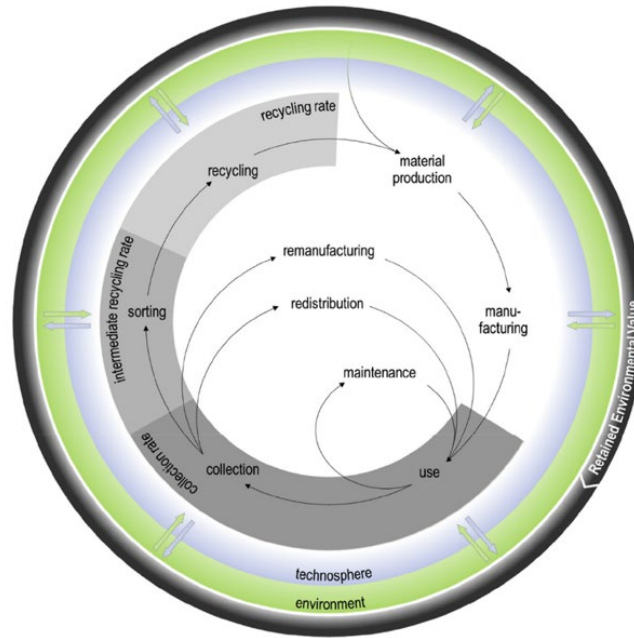
Figure 11: Schematic representation of a production system (Haupt and Hellweg, 2019)

According to the findings of Lonca and Raufflet (2020), circular economy strategies are often lacking the comprehensive perspective, such as looking into the rebound effects or environmental tradeoffs, when they are being implemented. Therefore, they are skeptical about how a circular economy can contribute to staying within the planetary boundaries and accomplish global sustainability. Harris et al. (2021) believe that merging LCA and planetary boundaries has the potential to set limits on environmental damages and to monitor the environmental effects of circular economy.

Blum et al. (2020) also agree that circularity practices do not always contribute to sustainability. To illustrate, great amounts of recycling can increase the energy consumption during the process, and this can outweigh the benefits of the act of recycling, causing more environmental harm instead. Also, in some cases, it is found that circulated materials cause more harm and perform worse in environmental aspects. Therefore, circular activities must be clearly evaluated and more carefully considered in terms of their environmental performance before they are adopted and implemented to prevent faulty decision being made during policy making in the industry (Haupt & Hellweg, 2019; Blum et al., 2020). Blum et al. (2020) call this new approach as "sustainable circular economy (SCE)".

Eberhardt et al. (2019) state the lack of existence of readily applicable tools which can measure the environmental benefits and impacts of circular economy. They also underline that circularity strategies such as reuse or recycling are not necessarily promoted by LCA.

Bocken et al. (2016) also emphasize that environmental aspects should be considered right from the start in a circular economy so that the environmental impacts of products can be determined,

and the impact can be minimized so that the maximum environmental benefit can be achieved. To make their statement more concrete they developed a high-level circularity strategies list. Their strategies can be seen in Figure 12.

Slowing effects *(long lasting products and extending product life)*
Closing effects *(recycling)*
Life cycle effects *(effects across raw material sourcing, production, transport, use and disposal- not yet captured)*
Systems effects *(wider impacts of the innovation)*

Figure 12: High level circularity strategies (Bocken et al., 2016)

Blum et al. (2020) acknowledges that circularity can prevent material shortages hence it is very critical. Most of the time, when the subject at hand is circular economy, it is common in both literature and practice to think only about the end-of-life phase, and more specifically about recycling, which is the most applied strategy. According to Lavagna et al. (2021), this thought should be revisited, and the focus should be more on the design stage where strategies enabling the life of a product to be extended, such as reuse, could be better planned and implemented. Fregonara et al. (2017) agrees with this approach as they believe prevention of the waste generation can be achieved with a design approach that is according to the cradle-to-cradle concept, which aims to close the loop. In such a design approach, buildings must be designed in a way that they can be easily recoverable or reusable for their next life cycles. In order to contribute to diminish the negative environmental impacts, they advocate circular approaches such as decreasing waste generation by recycling and reuse and abandoning consumption of raw materials which are non-renewable.

Lavagna et al. (2021) also talk about the presence of reversible technologies which enable building materials, components and connections to be returned to their original states. A material or a component being able to be disassembled does not necessarily mean that it can be reused or remanufactured. At the end-of-life stage, this situation leads them to be recycled most of the time. Recycling happens even if it results in more environmental and economic impacts. In order to be able to recover products during disassembly, it is critical to understand how those products were designed. Generally speaking, "non-destructive disassembly (or selective deconstruction) allows reuse and remanufacture components, while destructive demolition leads to recycling".

The above mentioned arguments from existing research show that not all circular strategies in the 10R ladder contribute the same amount towards environmental sustainability. Some R strategies

are better when compared to others. The order of importance and priority to be given to each R strategy can be seen in Figure 13. According to Cramer (2020) the most beneficial R strategy among all is "Refuse" which is the prevention of using raw materials as much as possible. The least performing one is "Recover" which means to recover energy when incinerating waste. Since waste incineration results in CO2 emissions, it is clearly not the best strategy to reduce environmental impacts.

Levels of circularity: 10 R's

Order of priority

High

Refuse: prevent raw materials' use

Reduce: decrease raw materials' use per unit of product

Redesign: rethink product in view of circularity

Reuse: use product again (second hand)

Repair: maintain and repair product

Refurbish: revive product

Remanufacture: make new product from second hand

Re-purpose: re-use product but with other function

Recycle: salvage material streams with highest possible value

Low

Recover: incinerate waste with energy recovery

Figure 13: Order of priority for 10R ladder (Cramer, 2020)

Circular design approaches include: Design for Flexibility (DfF), Design for Adaptability (DfA), Design for Disassembly (DfD), Design for Reuse (DfReu) and Design for Recycling (DfR).

Design for Disassembly (DfD) is an important strategy in promoting circular economy in the built environment (Bertin et al., 2020). In order to understand DfD, it is beneficial to mention that building systems can be classified in two different ways. One of them is wet building systems where different materials are connected to each other with irreversible methods such as joining by mortar or glue. The second one is reverse assembling building systems in which different materials are joined together by bolts, rivets or they are just overlapped. These systems can be reversible and therefore they are suitable for DfD (Fregonara et al., 2017).

According to Bertin et al. (2020), the main difference between design for reuse (DfReu) and design for disassembly (DfD) lies in the fact that DfReu does not include recycling and is simply for reuse whereas DfD is to enable deconstruction and it can also facilitate recycling and energy recovering by means of separation. DfD is therefore not necessarily for reuse.

Reuse strategy may be in two different forms: a "design from a stock" scenario or a "design with a stock" scenario. The former includes 100% reused materials from stock and the latter includes as many reused elements as possible to be found in the stock (Bertin et al., 2020).

In the construction industry, DfD strategy is not always considered positively since during the deconstruction phase, multiple important criteria must be taken into account such as the time and technical skills needed to disassemble the components and costs associated with these activities. Also, the data regarding the material composition, assembly/disassembly methods, potential damages on the disassembled components, their technical and structural conditions should be kept track of and documented for their future uses (Lavagna et al., 2021).

To improve general design principles and the assessment of disassembly degree of products, specific indicators are being developed, such as Environmental Product Performance Indicators (EPPI). EPPI are determined for the macro, meso or micro features of a product. Macro EPPI are used for quantifying environmental aspects, the amount of waste or energy losses. Meso level EPPI refer to recyclable/reusable parts. Finally, micro level EPPI are determined for features such as the time for disassembly, the type of connections or the number of compound materials. Micro level EPPI are particularly important if the aim is to evaluate the recovering potential of a product in a highly precise way. That is why, having micro level EPPI provides designers with the most advantage. However, there are still some problems for researchers to work on such as how to increase the effectiveness of recyclability and the feasibility of disassembly (Cottafava & Ritzen, 2021).

In their study, Cottafava and Ritzen (2021) conclude that the Design for Disassembly criteria including Types of Connection, Connection Accessibility, Crossings, and Form Containment can be used for evaluating recovery potentials of building components. As being more realistic indicators, those criteria form better predictors than their common counterparts.

While recycling is widely accepted as a practice and very common, practices such as reuse or design to eliminate waste generation are not that much endorsed or emphasized. If the waste generation is not explicitly discouraged, there is a possibility for recycling practices to reinforce the consumption cycles and therefore lead to less environmental sustainability. Bertin et al. (2020) state that reuse strategies perform better at reducing GHG emissions than recycling because reuse allows the achievement of several life cycles and decreases the environmental burdens. Therefore, they support the idea of prioritizing reuse over recycling.

Arora et al. (2019) take attention to building component reuse by examining component-level circularity of residential buildings in Singapore in their study. They found out that concrete accounts for about 16%, steel (skin, and structure layers) for 20%, windows for 13%, doors for 13% and accessories (space plan, services, and stuff layers) for about 12% of the total material outflows.

However, reuse might not always be the best solution. Inherent difficulties of reuse include certification of reclaimed components, detailed guidelines to be followed, safety guarantees (specially for structural elements) and improvement in methodology of reusing. For instance, Bertin et al. have found out that reuse of load bearing elements is a complicated issue because it brings lots of responsibilities and risks with it. For such structural components, the reused elements should meet certain safety standards.

Since value retention is the key idea in circular models, both the environmental and financial value retained by circular strategies should be taken into account. As mentioned earlier, when considering circularity strategies, it is common to refer to the end-of-life phase however the attention should be switched to the design stage where the likelihood of retaining the most value via extending the life of the product or repurposing it/reusing it in the future can be made possible.

Among existing buildings only less than 1% of them are estimated to be completely disassembled. In recent years, therefore, demountability of building components became a key element of design criteria. Yarwood and Eagan found out in 1998 that more than 70% of the environmental impact is likely to be minimized and even possibly prevented during the design phase. Akinade et al. (2015) formulated a BIM-based Deconstructability Assessment Score (BIM-DAS) for finding out the possibility of deconstructing a building during design phases.

On the other hand, Giama et al. (2019) draw the attention to the production phase. They state that the production phase plays a key role in reaching a high level of circularity and low levels of environmental impact. During this phase there are lots of different stages where waste is being produced and in order to minimize this it is very important to keep in mind that reusing, and recycling are good strategies. According to Giama et. Al (2019) material recycling and using them as input materials during production processes is a good way of increasing circularity.

Regarding future implications Cottafava and Ritzen (2021) state that there will be unlimited number of material cycles which will be enabled via urban mining. For the reuse of building materials and components in more effective ways, they emphasize the importance of recording the history of materials in a digital environment such as material passports.

There are platforms such as Madaster for storing the details of materials and evaluating the circularity of the building. However, since these platforms are quite new, according to Cottafava and Ritzen (2021) robust methodologies are still required for proper assessment of circularity. Since there is no standardized methodology, most of the indicators include only material weight of the recycled/recyclable parts or on the renewability/non-renewability of input resources. They do not include the real environmental impact as embodied energy and embodied carbon.

2.4. Building Information Modeling

BIM is a popular concept in the construction industry which typically stands for both Building Information Management and Building Information Modeling. Both of these terms are often used interchangeably and there are many different definitions to describe what BIM really means. According to ISO 19650-1, BIM is defined as "Building Information Modeling" and described as the "use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions". The term "built asset" in this definition encompasses buildings, bridges, roads and process plants.

In the context of this research, BIM will be defined as a process to facilitate the generation, storage, management and exchange of data related to building and infrastructure projects. The process makes use of various tools and technology and is considered as beneficial in reducing time, costs and effort required to perform building data management tasks throughout the project and its life cycle. The aforementioned building data can be graphic information as well as functional and physical properties about buildings, their elements and components.

Current construction projects require lots of different disciplines to be involved and collaborate throughout a project. This situation causes the sector to move towards adopting more BIM applications as BIM eases the information exchange between multi-disciplinary teams and reduces errors and rework along the way via standardization. BIM also enables the visualization of the building information on a 3D modeling software and the handling of related data embedded in the model itself. However, a BIM process does not necessarily require a 3D model. One of the greatest advantages of having a visual information component such as a 3D model in a BIM process is that the clients can see the project before the actual construction takes place.

There are numerous popular BIM software used in the industry. According to Lu et al. (2021) Autodesk Revit is the most commonly used one. Several others include ArchiCAD, SketchUp, Trimble Connect, Navisworks, Tekla BIMSight etc. How a typical working environment looks like in Revit is illustrated in Figure 14.
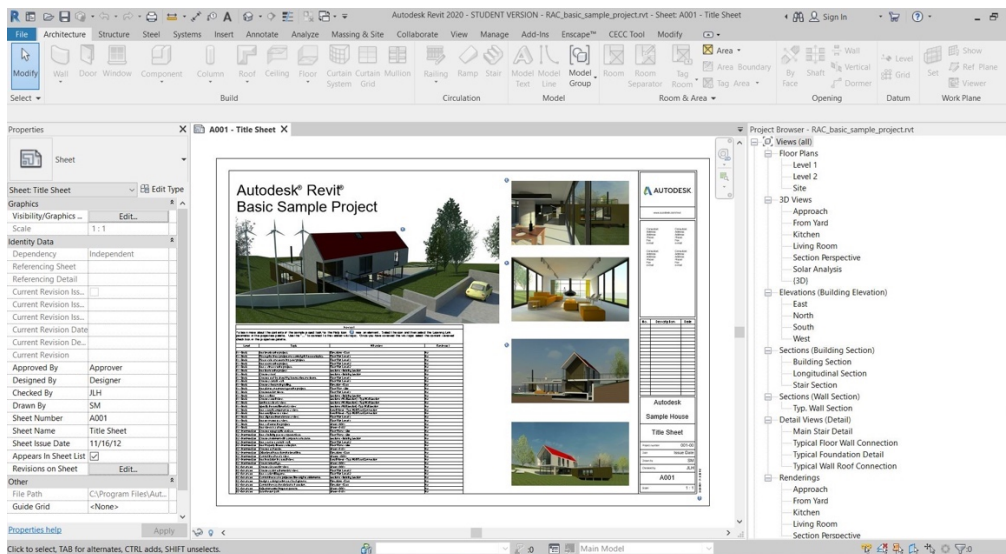
Figure 14: Revit environment with an example generic architectural project

When speaking about BIM, Level of Detail or Level of Development (LOD) must also be addressed. Introduced by American Institute of Architects in 2008, LOD distinguishes different levels of information according to development stages and details included in components within a BIM project. There are 5 different LOD categories, ranging from 100 to 500; LOD 100, LOD 200, LOD 300, LOD 400 and LOD 500. 100 contains the least information and detail whereas 500 contains the most. (Bertin et al., 2020; Victor, n.d.). Bertin et al. propose two new LOD categories in their

study, namely LOD 600 and LOD 700. The overall LOD schema including the two new proposals, applied on the structural elements as an example, can be seen in Figure 15.
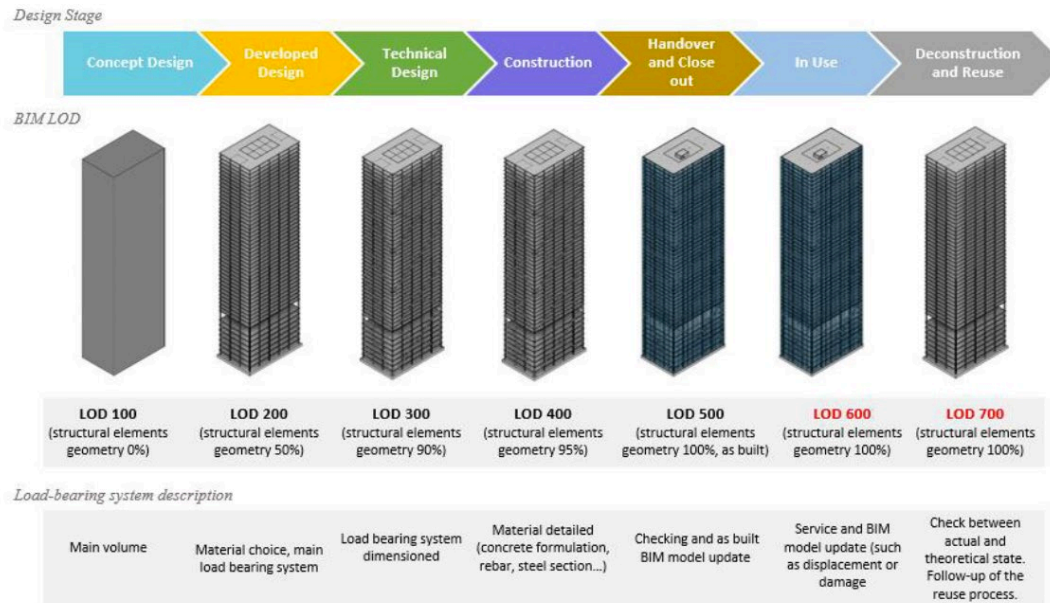
Figure 15: Different LODs and their extents (Bertin et al., 2020)

Since the majority of the construction industry is embracing BIM increasingly, there will be, and is already, a demand for LCA and LCC to be integrated within BIM workflows. Integration of LCA and LCC using BIM can provide an opportunity to assist complex decision-making processes in the sustainability area (Röck et al., 2018; Lu et al., 2021). There are existing BIM based LCA tools, which are used for environmental impact assessments such as in-use energy consumption and greenhouse gas emissions (Lu et al., 2021).

2.5. Integrated assessment approach

In the previous sections, all essential components of this research were introduced, and an overview from existing literature was given. These components include LCA, LCC, circularity assessments and BIM. Looking at this overview, there are some clear differences between each of them. BIM is a process where building data are stored and managed. Circularity is an economic model and currently there are techniques emerging to assess the circularity indicators on a material (MCI), product (PCI), system (SCI) and building (BCI) level. LCA is an assessment technique for measuring the environmental impacts of products whereas LCC is a method for calculating the costs of projects. All in all, to achieve sustainability in construction sector, these elements should be considered together. A popular way to combine LCA, LCC and circularity assessments is via the use of BIM.

In the existing literature, there are different views and approaches on how these components should come together. For example, Lu et al. (2021) focus on LCA and LCC and the importance of combining them. They also emphasize that BIM can be a beneficial tool in accommodating this need since it has the potential to simulate and visualize the results. They point out that LCA and LCC are mostly performed separately, and they acknowledge that this is due to acquiring a synthetic evaluation result being difficult for buildings since assessing buildings throughout their entire lifecycle stages is an intricate and complicated process. They analyzed 36 peer reviewed academic journal articles which were about the integration of LCA and LCC via BIM. Of those 36 articles 20 of them were about the application during the design stage. They also found out that in 77.8% of the total 36 studies, the integration of LCA and LCC was achieved via existing BIM software, while only in the remaining 22.2% of those studies a development of a BIM plugin or a new BIM-based external software were made. They categorized the main approaches to combine LCA and LCC using BIM in three categories:

> 1) using existing BIM software to obtain data such as bill of quantities and exporting these data to an Excel sheet to conduct further calculations
> 2) exporting data from BIM model to an external platform which is developed for the purpose
> 3) including information within the BIM software via developing a BIM plugin.

They found out that while choosing (1) provides users with clear and traceable results, the process is often slow and complicated and issues with compatibility can occur. On the other hand, (2) and (3) are more user friendly and quick to respond to changes in data, but they both require software developing skills, more time and effort, which makes them less attractive in research.

Lu et al. (2021) also discovered that Level of Detail (LOD) in BIM models is very important during the early design stage to conduct LCA and LCC, and that LOD 300 is the most suitable for integrating these two assessments into BIM. In the end, they propose a framework on how to integrate LCA and LCC using BIM. Their framework consists of four steps:

> 1) define the system boundaries of LCA and LCC
> 2) define the basic assumption and inventory analysis
> 3) obtain the environmental impact and cost results
> 4) analyze and optimize the results.

Their four-step approach in the integration of LCA and LCC makes sense since both assessments require four steps individually, as discussed in Chapter 2.1 "Life Cycle Analysis" and Chapter 2.2 "Life Cycle Costing". Lu et al. (2021)'s framework, therefore, sets an example for the current research framework.

Lavagna et al. (2021) take on a more holistic approach however, their main focus rests on the LCA and BIM integration. They argue that in order to ensure long term sustainability, whole life cycle phases should be considered in a life cycle approach together with different environmental indicators. Environmental, economic and social aspects of sustainability should also be taken into account. Their study mentions Level(s), a European framework, which takes into account the core sustainability indicators.

According to Lavagna et al. (2021), to decrease the time and effort put into the LCA processes applied in building designs, the preferred method should be the integration of LCA software as a BIM plugin. Röck et al. (2018) support this approach but they also draw attention to the quality and accuracy of the data related to LCA and the data coming from the BIM model, as two important points. By integrating LCA within BIM, while assessing the environmental impacts of the design proposals, LCA results would also be able to affect the critical decisions made in early stages in building design.

Lavagna et al. (2021) mention that circular strategies should also be evaluated for their effects on sustainability. To do so, environmental and economic life cycle assessments should be further developed since they play a critical role in achieving this goal. Giama et al. (2019) also support the idea of using circularity indicators together with environmental impact indicators.

Lavagna et al. (2021) argue that energy use and building materials are the two most popular topics influencing the decision making whereas construction waste and recycled materials are the least popular ones. They acknowledge that not all design solutions check all the boxes when they are evaluated by different indicators. Some perform well and others do not according to certain indicators. This happens because evaluating for circularity and sustainability is a complex issue.

Fregonara et al. (2017) propose a methodology which takes into account both environmental and economic impacts of design options. With this methodology they aim to support the decision-making processes, with a focus on end-of-life phase of buildings. To achieve this aim they benefit from the environmental indicators of LCA and economic indicators of LCC. As an addition to these two indicators, they propose a third one, which is a conjoint "economic-environmental indicator". Their method can be applied to both new buildings and retrofitting of existing buildings. They aim to "quantify the environmental and economic effects of different project options" with this method. During the process, they take into account the disposal costs of products as well as the residual value of them. As a result, their "economic-environmental indicator" gathers the results of the calculation of Global Costs in monetary terms, the environmental impacts expressed in embodied energy (EE) and embodied carbon (EC), disposal/dismantling costs and residual value. They tested their methodology by assessing two alternative window system technologies and comparing the results. At the end of their study, they found out that aluminum frames have the lowest global costs because their yearly maintenance costs are lower, so they are a better choice when compared to timber frames. However, timber frames performed better at environmental aspects since they have lower embodied carbon (EC) and embodied energy (EE) levels.

Eberhardt et al. (2019) combine life cycle assessment and circular economy in their study. They examine how multiple life cycles created by reuse and recycling strategies can affect and change the traditional linear life cycle assessment approach since this traditional LCA is not suitable for the circular economy. In their research, they look at the example of two different structural concrete column types, column A and B. Column A is a traditional column which cannot be used for multiple lifecycles and column B is a column which is designed for disassembly so that it can be used for multiple lifecycles. In the end, Eberhardt et al. find out that the accumulated embodied

carbon of column A is greater than of column B, even though column B needs to be transported at the end of its first life cycle and this transportation has embodied carbon impacts also. The main cause of high embodied carbon of column A is because column A type needs to be produced two times for two lifecycles whereas with the column B type the same column can be reused for two lifecycles, and this significantly lowers the environmental burdens. So, their study confirms that the majority of embodied impacts occur during the production stage. Figure 16 depicts their findings on these two column types.
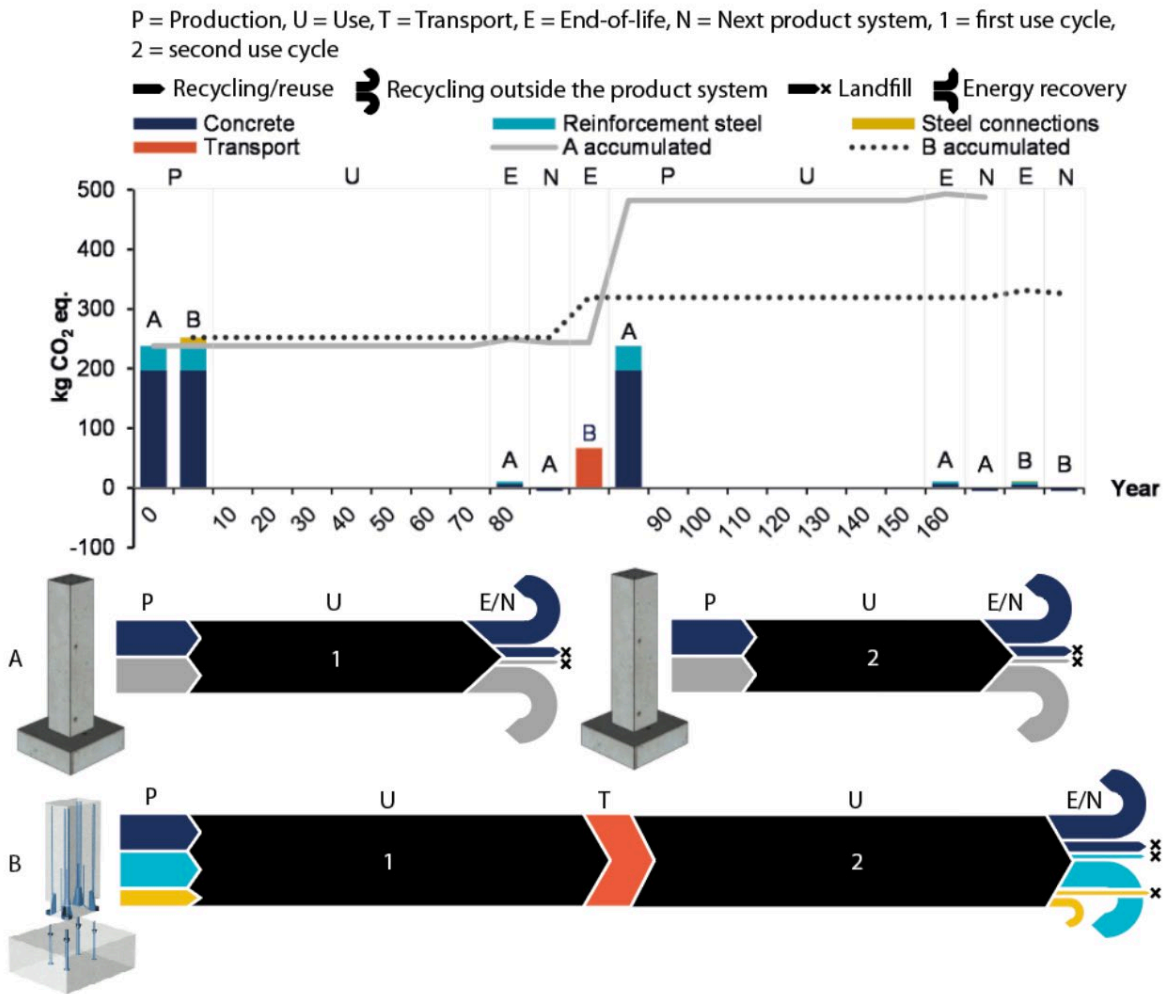
*Figure 16: Embodied carbon of Column A and B over the years*

They mention that there are, however, uncertainties associated to extending LCA into multiple lifecycles as it is not known how long these material loops can be maintained. Also, they acknowledge that "material loops are not 100% circular as additional input materials are needed to uphold the material loop due to system losses between the use cycle".

While considering multiple lifecycles, lifespan of materials and buildings are two important criteria to be taken into consideration. According to some studies a typical lifespan of a building is 50 years (Cottafava & Ritzen, 2021; Lu et al., 2021). However, structural elements can last longer than 50 years while finishing materials may have a lower lifespan due to wear and tear. The lifespan taken into account for LCA, LCC and circularity assessments will highly influence the outcomes and environmental and financial performance of these products. If a building element has a longer lifespan than the lifespan of the building itself it has the potential for reuse and go through a second life cycle, for instance. This will reduce its environmental impact, increase its circularity potential and, depending on the project, could save costs.

In Eberhardt et al.'s study, column B is considered as disassembled and reused somewhere else after 80 years, at the end of life of the given building. According to their study, even though there are embodied impacts due to transportation, these impacts are much less than of a production of a new column. However, reuse of building elements does not necessarily mean that they must be transported somewhere else. These transportation impacts can be further eliminated by keeping the structural elements of a building at the same location and by just changing the function and other building elements of the building. This can be done via renovation or adaptive reuse (Cheshire, 2019). This approach, which is not discussed in the study of Eberhardt et al. (2019), still promotes the idea of reuse and can start a new building life cycle.

The most holistic assessment approach comes from Blum et al. (2020). They define a four-dimensional framework for their sustainable circular economy (SCE) approach, including material circularity, economic sustainability, environmental sustainability and social sustainability. However, in their research, they illustrate only the three dimensions as shown in Figure 17.
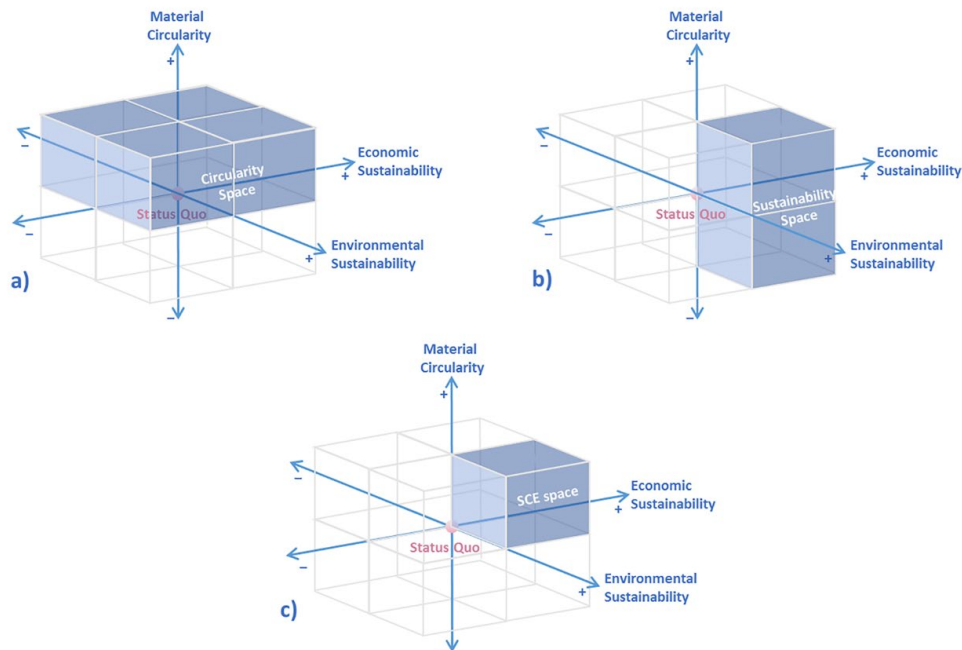
Figure 17: Sustainable circular economy (SCE) space (Blum et al., 2020)

Previous research conducted on topics related to LCA, LCC and circularity, include works by Van Gemert (2019), Zhai (2020), Van Oeveren (2020), Röck et al. (2018) and Bertin et al. (2020). Van Gemert (2019) focuses on the integration of LCA and BIM via IFC schema. By using IFC, Van Gemert aims to make the LCA process software independent. He creates his own application, MPG-ENVIE, where an IFC file is uploaded and connected with LCA data to present users the results of the environmental impacts of their designs. The application provides tabular, graphical and plotted outputs to the users. The system architecture of Van Gemert's application can be seen in Figure 18 and an example of the running application window can be seen in Figure 19.
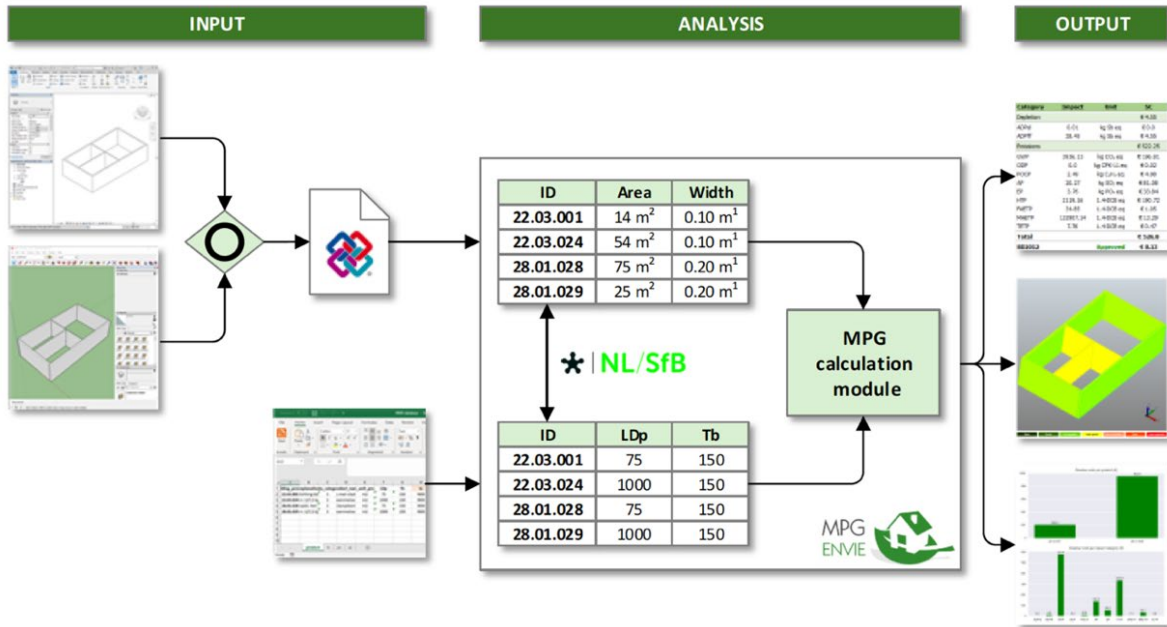
Figure 18: System architecture of MPG-ENVIE (Van Gemert, 2019)

46
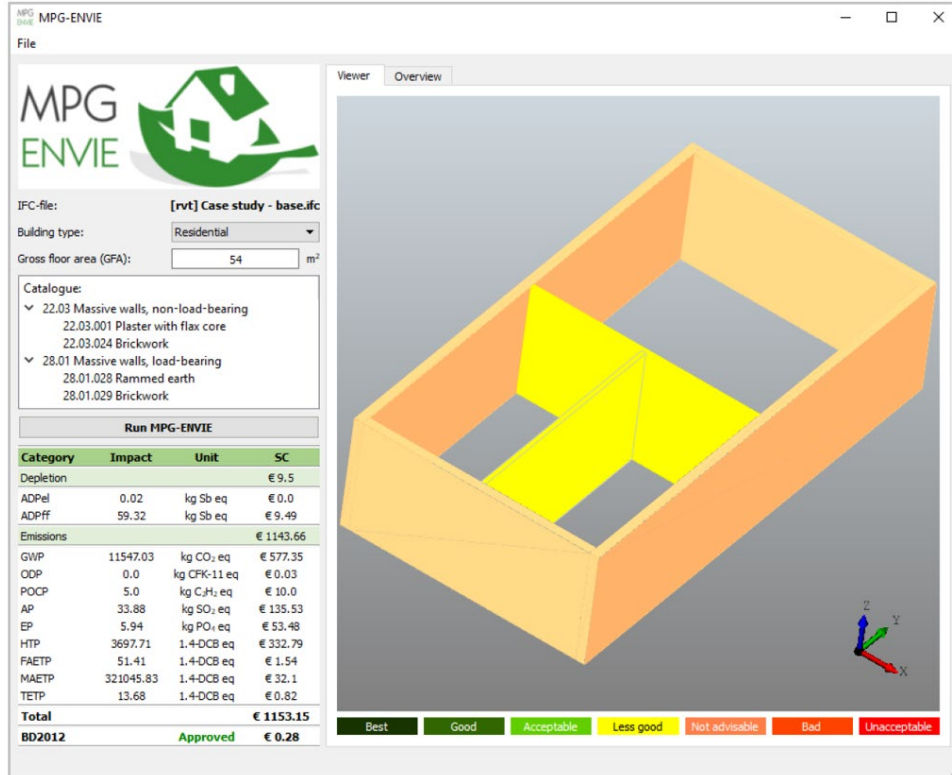
Figure 19: MPG-ENVIE window (Van Gemert, 2019)

Zhai (2020) combines building circularity assessment with BIM to facilitate the process. She proposes a BIM-based building circularity assessment framework and develops a functional tool named BCAS, based on this framework. Her tool is able to assess the circularity level of a building on four different levels, namely material, product, system, and building. It provides results in the form of charts and graphical color override. The tool is accommodated in Autodesk Revit by using Dynamo. The system architecture of Zhai's Dynamo tool can be seen in Figure 20. In addition to this, an example results window from her tool and the color override in Revit can be seen in Figure 21.
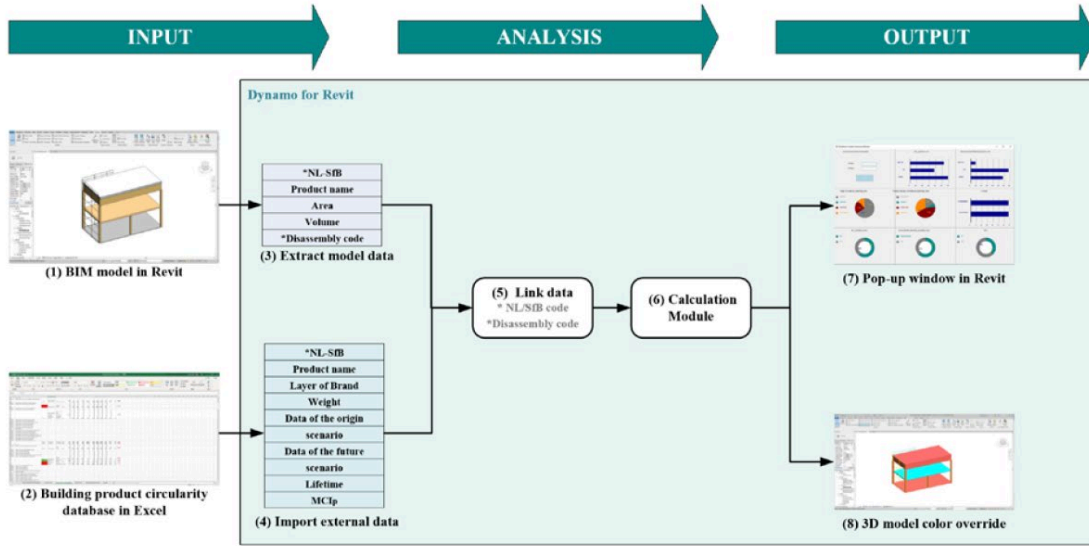
Figure 20: System architecture of BCAS (Zhai, 2020)
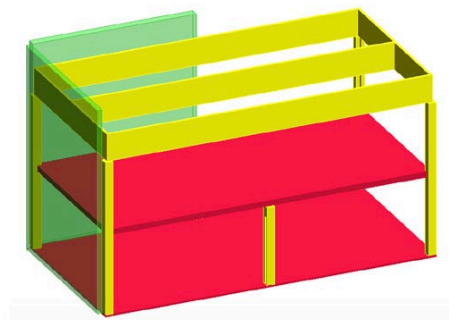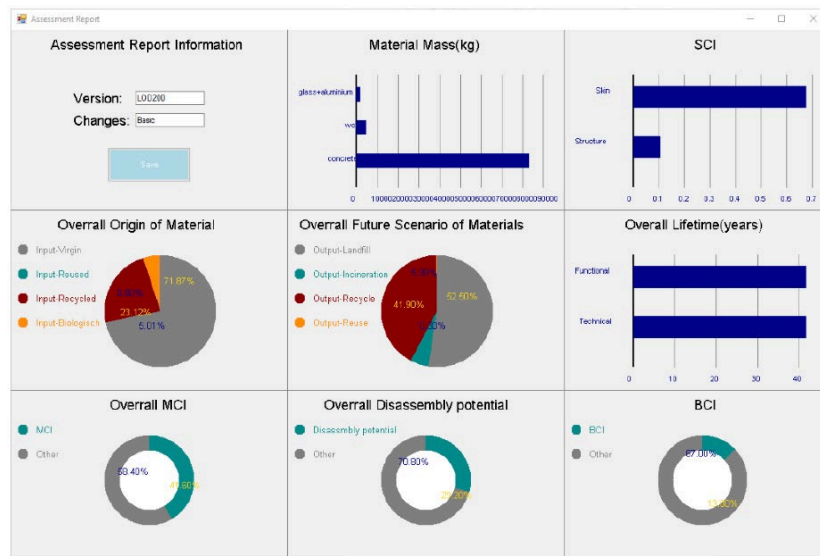
Figure 21: Results from BCAS (Zhai, 2020)

A further extended approach was adapted by Van Oeveren (2020) where he assesses both LCA and LCC of a building project by using BIM. For this, he uses IFC schema following Van Gemert (2019)'s path and creates his own application, LEICAS, where the user can upload an IFC file and see the results for all environmental impacts and costs. The application also provides users with feedback on how they can optimize and improve their design. The system architecture of LEICAS is presented in Figure 22 and an example running application window can be seen in Figure 23.
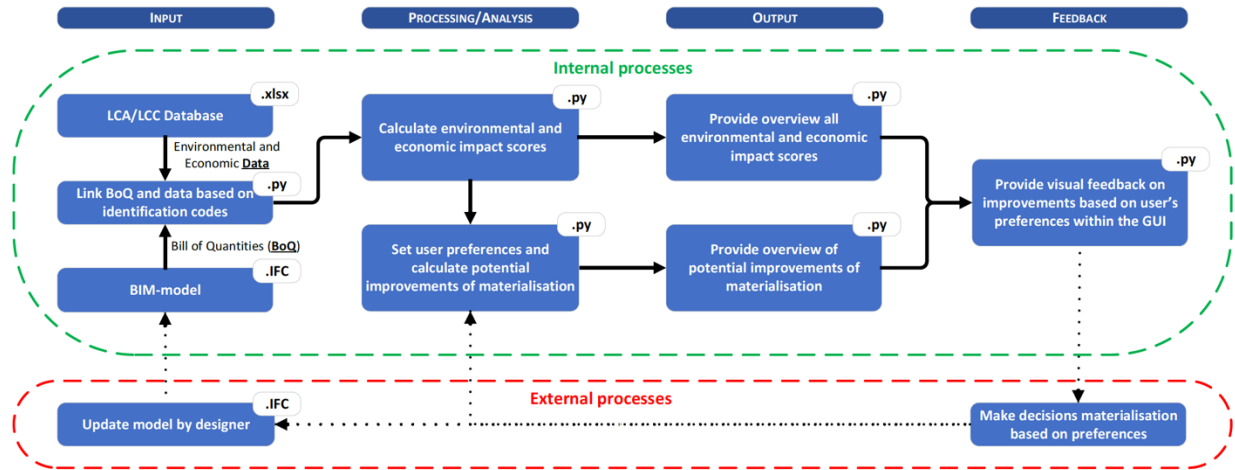
Figure 22: System architecture of LEICAS (Van Oeveren, 2020)

Figure 23: LEICAS window (Van Oeveren, 2020)

According to Röck et al. (2018), BIM enables architects and designers to focus on their designs since via BIM the effects of material and design choices on environmental impacts can be observed easily and kept track. In their study, Röck et al. integrated LCA and BIM. They used Dynamo to link the data between a BIM model in Autodesk Revit and building element library in Excel. The link that was established provided automated exchange and processing of information. They also provided visualizations of the results on the 3D BIM model. The system architecture they have proposed can be seen in Figure 24 and the visualization they achieved for their case study is presented in Figure 25.
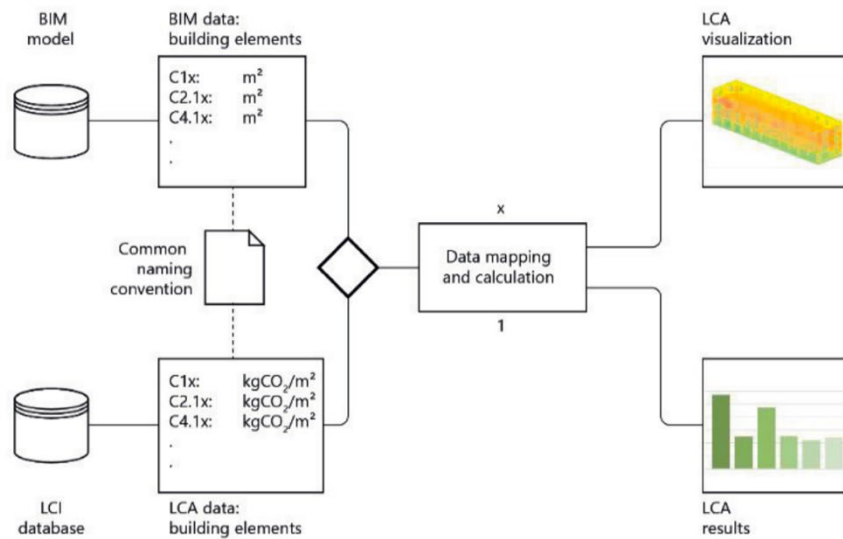
Figure 24: System architecture of LCA-BIM integration (Röck et al., 2018)
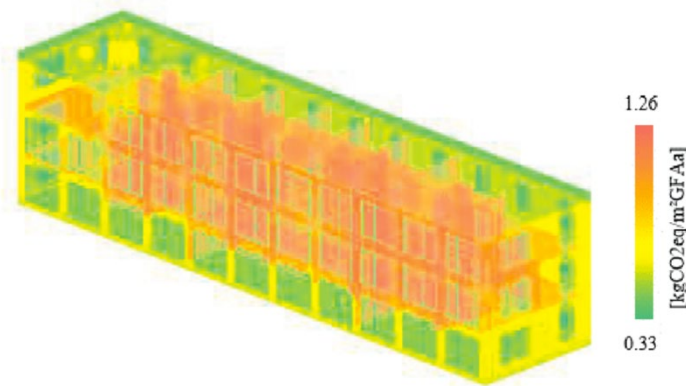
Figure 25: Visualization of the results on the 3D BIM model (Röck et al., 2018)

To link the data coming from the BIM model and LCA database, Röck et al. (2018) used a common naming convention. As a result, they were able to calculate embodied impacts of different design and construction options. They could also identify the hotspots on the design since the

50

visualization on 3D BIM model enabled the detection of contribution of individual building elements to the total impact.

In another study, Bertin et al. (2020) explored the reuse potential of structural elements by using BIM and connecting it to a material bank. They also combined LCA approach to check the environmental impacts of their reuse scenarios. They acknowledge that LCA requires large amounts of data which can be acquired only during more advanced stages of a project with high LOD in BIM models. Nevertheless, they also state that the need to conduct a simplified version of LCA during earlier design stages is present. This need comes from the desire that the architects and engineers can still make changes and influence the environmental impact of designs with lower LODs. For this purpose, they created a BIM software extension by using software API and coding in C#. Their approach to the issue and system design can be seen in Figure 26.
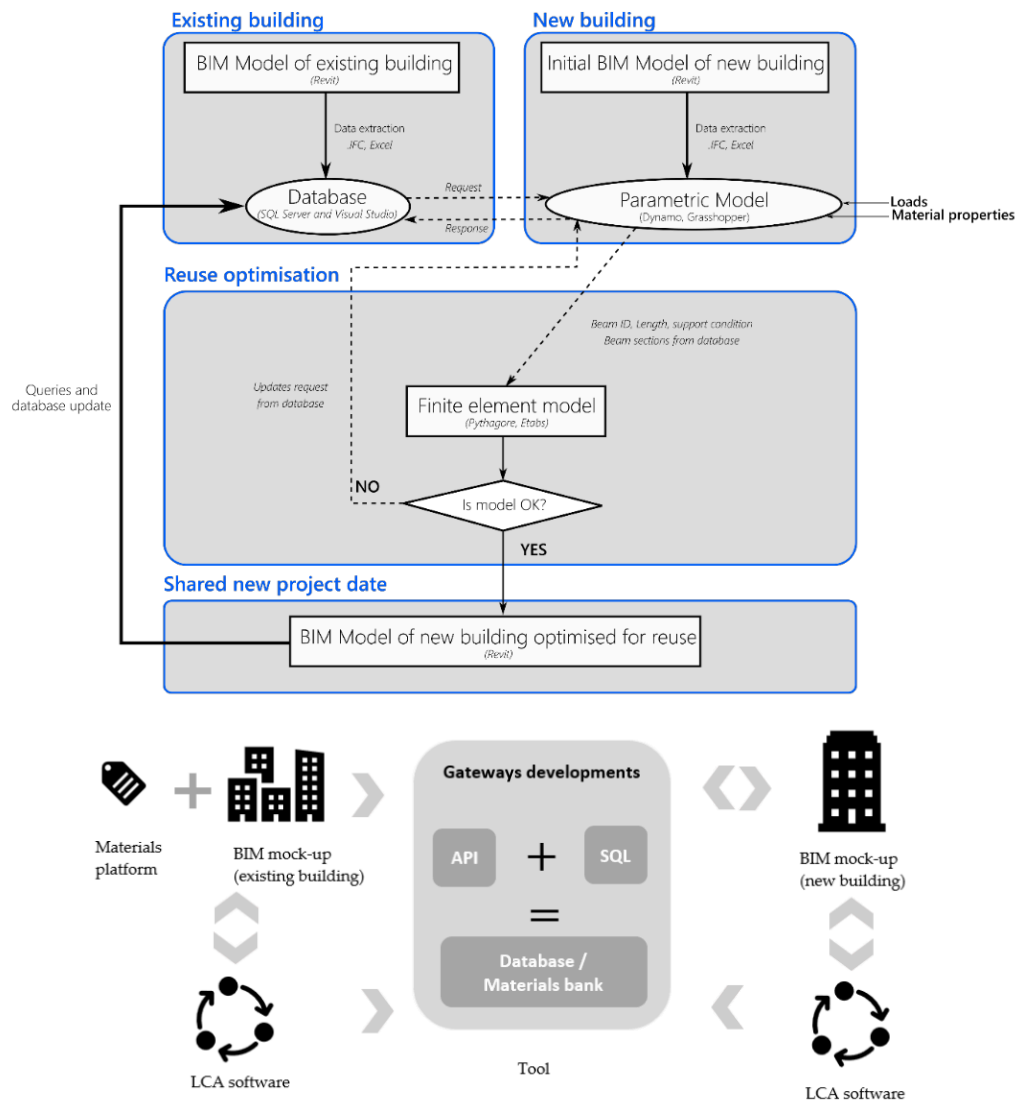
Figure 26: System design of reuse and LCA tool (Bertin et al., 2020)

Bertin et al. (2020) find the interoperability between all BIM and LCA software insufficient. They point out that these incompatibilities arise because of errors occurring during import and export of BIM files into IFC files.

Looking at the existing scientific articles and research, there is a need to combine assessments for circularity, environmental impacts and costs in the AEC industry. There are already some attempts to combine some of these aspects with the help of BIM. However, none of these works are taking all three aspects into account at the same time. In addition to the presented existing research, there are two frameworks which have the ambition to evaluate designs in terms of LCA, LCC and circularity indicators, in a holistic manner. One of them is the Level(s) framework from European Commission and the other one is a framework from Platform CB'23.

Level(s) is a framework to measure and to report environmental performance of buildings, based on circular thinking principles. It takes into account the whole life cycle of a building and tries to answer how sustainability affects the value. It is applicable for office and/or residential building projects. Level(s) has six macro objectives which are:

      1) Greenhouse gas and air pollutant emissions along a building's life cycle
      2) Resource efficient and circular material life cycles
      3) Efficient use of water resources
      4) Healthy and comfortable spaces
      5) Adaptation and resilience to climate change
      6) Optimized life cycle cost and value (Dodd, 2021a).

The name Level(s) comes from the fact that the framework defines three different levels for making assessments and reporting. These levels are:

      Level 1 – Conceptual design for the building project
      Level 2 – Detailed design and construction performance of the building
      Level 3 – As-built and in-use performance of the building (Dodd, 2021a).

The steps included within the Level(s) frameworks are:

      1) Establishing a project Level(s) plan
            1.a) Selecting the macro objectives and indicators to work with
            1.b) Selecting the level to work at
            1.c) Planning when and how Level(s) will be used and who will need to be involved
      2) Completing the building description (Dodd, 2021a).

Level(s) is a very broad framework which aims to address the most critical topics in the construction industry to achieve environmental and financial sustainability by circular thinking. At the time of this research, there are 18 user manuals explaining the use of the framework, each macro objective and their components. Some parts of the framework are still under development and not fully completed yet.

The framework from Platform CB'23 is from a Dutch industry perspective. It aims to stimulate transition to more circular construction practices in the industry and to measure the level of

circularity. Unlike Level(s), this framework can be applied on both buildings as well as infrastructure projects. The Platform CB'23 framework defines three main steps:

Step 1 – Data collection
Step 2 – A measurement process with different indicators
Step 3 – Weighing/assessment of the results (Platform CB'23, 2020).

There are three goals of the core measurement method from Platform CB'23 and three results that are aimed to achieved at the end. These goals and their respective results are:

1) Protect stock of materials - results for stocks of materials
2) Environmental protection - results for environment
3) Value retention - results for value retention (Platform CB'23, 2020).

Similar to Level(s) framework, Platform CB'23 framework also embraces the life cycle thinking and considers the whole life cycle of buildings. It recognizes the Beta version of Level(s) framework from 2017 and acknowledges that Level(s) is a more comprehensive framework when compared to Platform CB'23 framework (Platform CB'23, 2020). The calculation rules which are provided within the guide are rather generic and does not necessarily add value to the study. In a future version of this study from Platform CB'23, an aggregated result from the three main outcomes (results for stocks of materials, environment and value retention) is desired to be achieved (Platform CB'23, 2020). However, whether aggregating these three different results will generate something meaningful and useful at the end is questionable.

Assessments related to environmental impacts, costs and circularity scores require lots of information about the building design and building materials. It is safe to say that requiring such big amounts of data is one of the reasons why these three aspects are not yet combined in a standardized manner because linking these data is a complex and difficult task. Therefore, using BIM for this process is highly beneficial. Via BIM, it is possible to collect, store and organize large quantities of data and it makes it easier to oversee all this information better for the decision makers. In short, accommodating the integrated assessment approach in a BIM environment has an added value for both architects and engineers. For this reason, this approach is adopted for this study.

There are existing software and tools which can assess building designs for LCA, LCC and circularity, often separately. A list of the most popular tools and their assessment extents are listed in Table 3.

Table 3: Different tools for LCA, LCC and circularity assessments

Name	Description	Platform
One Click LCA	LCA, LCC and circularity assessments, has its own database, EPDs are available, green certifications are supported (BREEM, LEED etc.)	Online and Revit plugin (however still the user has to switch to online platform at the end)
GaBi	LCA and LCC software, has a toolkit for circularity measuring MCI, has its own database, EPDs are available	Software
DGMR Software	Operational energy use and MPGcalc where shadow costs are calculated for environmental impacts.	Software
Madaster	A digital library for buildings, products and materials. Registration and archiving for reuse. Generates web based material passports for circular economy.	Online
Tally	LCA, real time assessment inside Revit.	Revit plugin
MRPI-MPG tool	Environmental performance assessment using shadow costs.	Online

The most comprehensive of all is One Click LCA. Although it supports all three aspects, environmental, financial and circularity assessments, the results within One Click LCA platform has to be obtained separately by performing three different assessments. In addition, when the Revit plugin is used, the materials have to mapped one by one by the user for calculations to take place and the user has to see the results on the online platform at the end. These processes interrupt the design phase and require expertise. Though, it is a very beneficial tool for performing accurate assessments when exact materials are decided on from specific manufacturers. This is because the user can map specific materials from manufacturer EPDs within the platform.

2.6. Conclusion

Looking at the existing literature on the topic, it is found that there is a need in the construction industry to consider circularity, sustainability and economic feasibility all together. This idea is manifested in several academic articles and previous research as well as by the European Commission in their Level(s) framework and by Platform CB'23. Although the idea is present, the way to gather LCA, LCC and circularity indicators together and the components of the frameworks differ in each study. In addition, a practical implementation such as a combined assessment tool for BIM environment has not been yet developed. Therefore, there is a need for efficiency enhancement by a combined assessment approach.

To answer this need, this study delivers two outputs. First, a framework is developed which addresses LCA, LCC and circularity assessments. Although Level(s) is a comprehensive framework

which could have been adopted for this research, it is found to be quite extensive and detailed, making the application of it more difficult. In addition, it is still under development at the time of this research, therefore, the development of a simpler and more concise framework is better for the purposes of this research.

During the framework development phase, the ideas from both Level(s) and Platform CB'23 frameworks are utilized. This newly proposed framework in this research simply guides the user on how to conduct each assessment (LCA, LCC and circularity assessments) while considering them together. Second, this framework is translated into a Revit plugin so that the assessments can be automated inside a BIM environment. With such a plugin, the three framework components can be presented in a single design environment, while the user can see and compare the acquired results side by side during their design development phase.

3. Methodology

After establishing the background knowledge on the topic via literature review, this chapter provides the methodological justification of the research. This methodology is used to answer the main research question, which was previously mentioned in Chapter 1.3 "Research Problem and Questions":

> *"How can the integration of circularity, cost and environmental impact aspects of a design with BIM enable an automated combined assessment process and support architects and engineers in their decision-making process during the design development stage?"*

3.1. Design Research Methodology

For this research, a combination of design and research methodologies will be used. The whole research design process will follow the "Design Research Methodology" by Blessing and Chakrabarti (2009).

Design Research Methodology (DRM) framework has 4 main stages which are:
  1. Research Clarification
  2. Descriptive Study I
  3. Prescriptive Study
  4. Descriptive Study II

The overall DRM framework by Blessing and Chakrabarti can be seen in Figure 27.
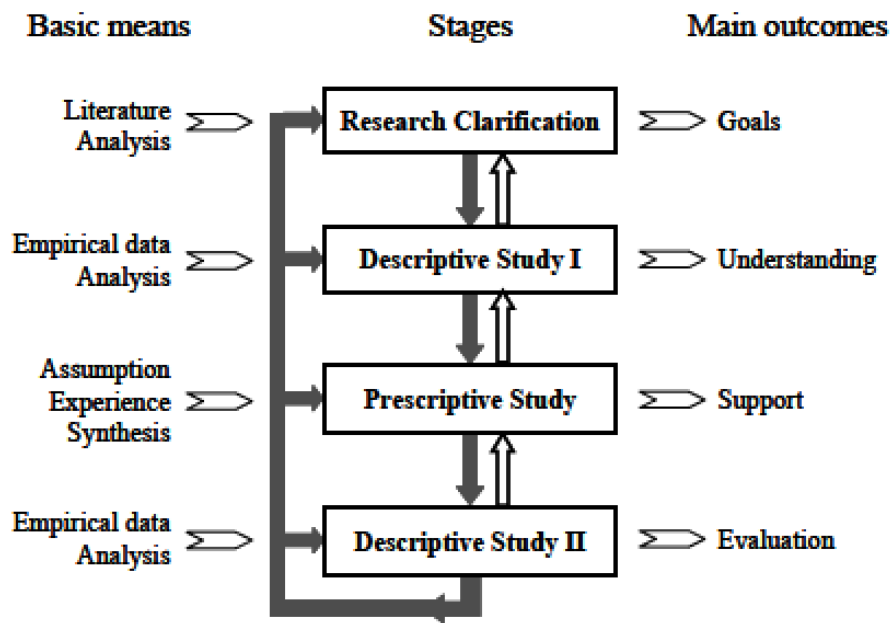
Figure 27: DRM framework (Blessing & Chakrabarti, 2009)

For this specific research, the stages defined are as follows, in Figure 28.
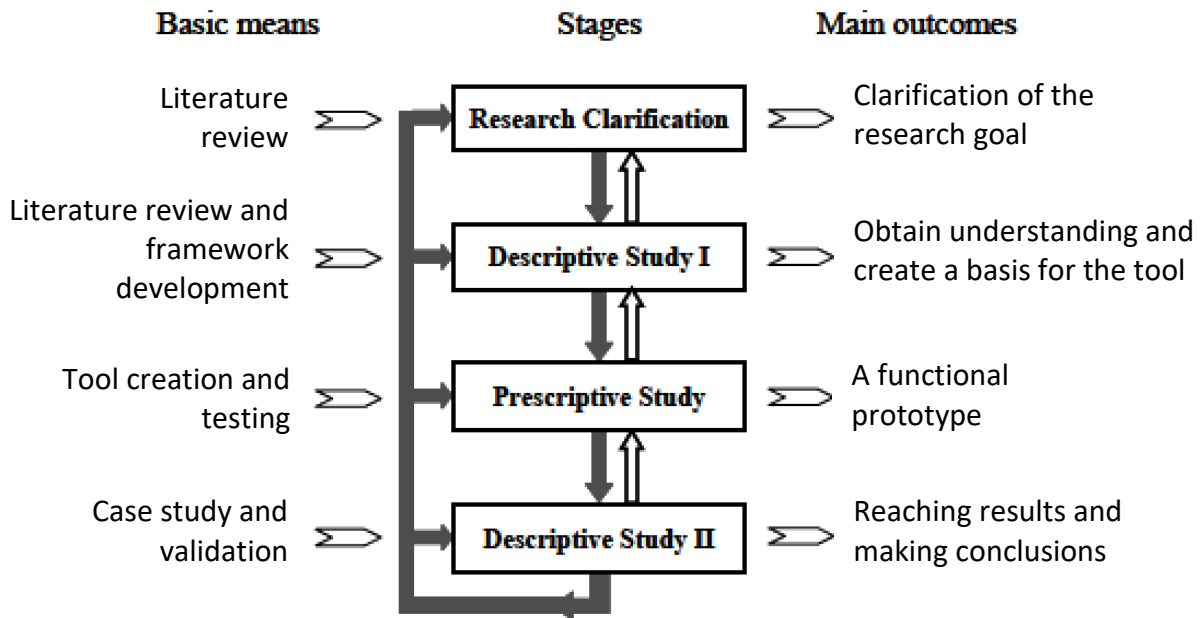
Figure 28: DRM framework applied for this research

Research Clarification stage refers to the stage where literature review takes place and more in-depth knowledge on the topic is acquired via research. By doing so, the research question and sub-questions leading to the main question are formulated, scope and objectives of the research are clarified. The current status of the topic in academia is discovered and evaluated. Limitations are found and possible improvement points are determined accordingly. This helps to establish a worthwhile research to begin with.

During Descriptive Study I, framework development takes place. In this stage the requirements for the proposed framework are also set up. This framework acts as the basis of the assessment tool. Information obtained through the literature review which was conducted during the Research Clarification stage is used to formulate this framework.

Descriptive Study I is followed by the Prescriptive Study stage. In this stage, the framework defined during Descriptive Study I is translated into a practical assessment tool. So, tool creation and testing processes take place. The system architecture, process flow, functional and user requirements are decided and defined for the plugin. The outcome of this stage is a functional prototype which acts as a proof of concept.

Last stage is the Descriptive Study II, where the developed tool is tested on a case study project and validated. The results obtained from the case study are evaluated to see if the proposed framework and developed Revit plugin are useful. By checking this, conclusions are made, limitations and recommendations for future research are stated.

As it can be seen in Figure 27, all the stages in the DRM framework are interconnected and their relationships to each other are bi-directional. This means that the information flow is not just in one direction as in the form of strictly from A to B and then B to C, but it can also be the case that information reached at C can affect B reversely and then subsequently affect back A too. Therefore, this is an iterative process.

3.2. Proposed Framework

The proposed framework for this research consists of three key assessment elements which are LCA, LCC and circularity indicators. A visual representation of the proposed framework can be seen in Figure 29.
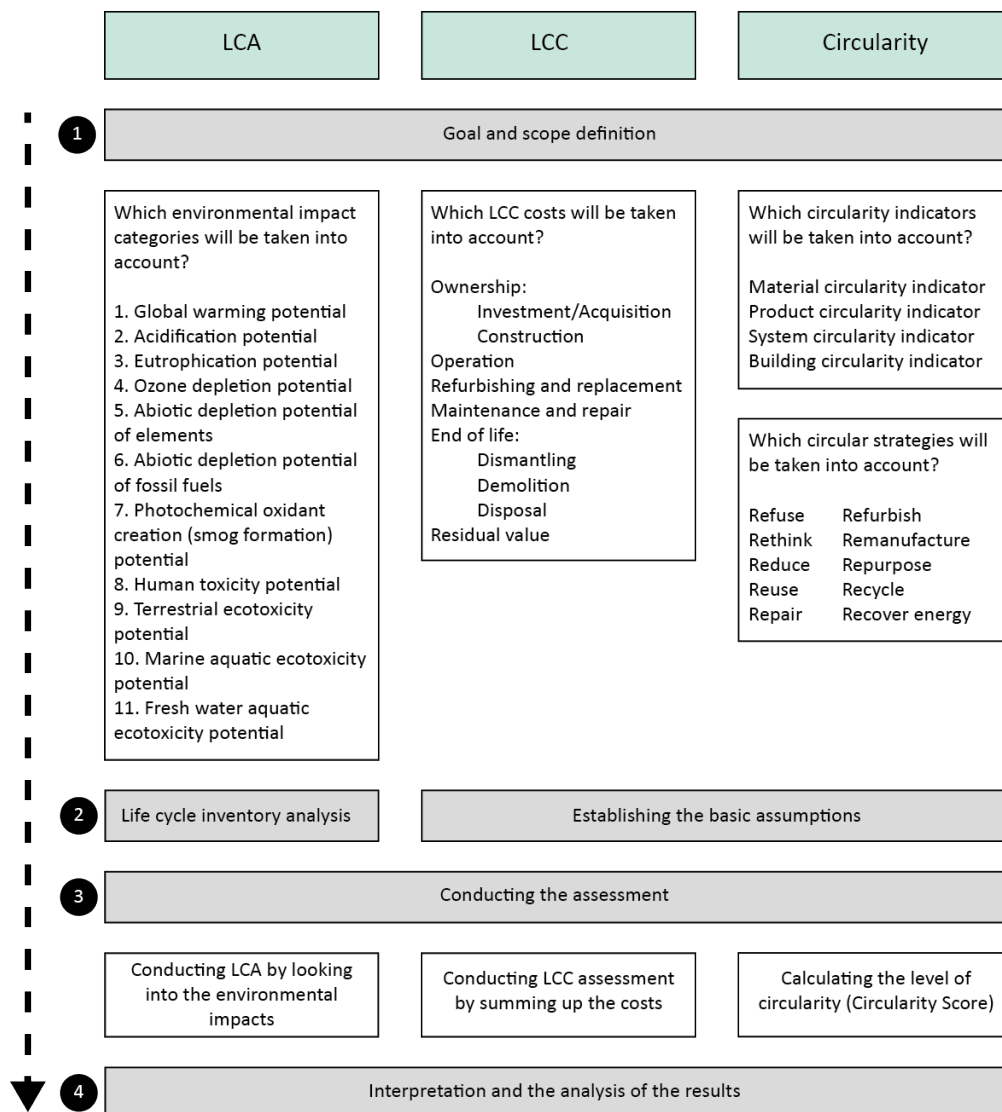
Figure 29: Proposed assessment framework

The framework consists of four steps for each assessment element. The first step which is the "goal and scope definition", the third step which is the "conducting the assessment" and the last step which is the "interpretation and the analysis of the results" are the same for each element. The second step of LCA is "life cycle inventory analysis". The second step for both LCC and circularity are "establishing the basic assumptions". The assumptions to be established during an LCC include choosing a consistent method of calculation, a suitable study period, deciding on an inflation and a discount rate, as previously stated in Chapter 2.2 "Life Cycle Costing". The assumptions to be established for circularity include deciding on a lifespan and choosing a coherent strategy.

The most important step is the first step according to this framework where goal and scope definition takes place for each element. What this means for each element can be seen in more detail when looked at the white boxes underneath the first step in Figure 29. The framework is applicable on different levels, meaning it can be used on a material level, product level, system level or a whole building level. The level in which the framework will be applied is, again, decided during the goal and scope definition phase. The framework can be applied to assess all three elements in equal importance or to establish hierarchy in importance between the three elements based on the project needs and ambitions. This order of importance can be decided during the goal and scope definition phase.

The implementation of this framework is not limited to a BIM environment, although in this study it is used to further develop a Revit plugin. This framework can be used for making assessments without a tool or software development. It can guide its users to perform calculations by using a combination of methods including Excel sheets, reports, existing software and/or other manual/traditional methods.

The framework can also make use of any available data source regarding LCA, LCC and circularity information, including online or offline databases. The type of data that is needed for the framework to be used depends on the decisions taken in the first step "goal and scope definition". For example, if a whole LCC is going to be conducted, then data regarding costs for ownership, operation, refurbishing and replacement, maintenance and repair, end of life and residual value will all be needed. When the scope is larger, more data is needed. The quality of data and the methods used will eventually affect the results obtained from the assessments, but it is better to use the data available and to have an overview of the impacts rather than not to conduct any assessment at all.

If the framework is to be implemented via BIM, then the LOD needed for the assessments to take place is at least LOD 200. The framework cannot be used together with LOD 100 because in such cases, there are not any available data regarding the materials or their quantities. In LOD 200 there are data available about materials and the general volume of the building (see Figure 15). LOD 300 is found to be the most suitable level of detail for LCA, LCC and circularity assessments (Lu et al., 2021). For example, by using LOD 300, a much broader scope can be chosen and more goals can be achieved when implementing this framework. This is because when compared to LOD 200, LOD 300 includes more precise dimensioning of building elements. On the contrary, when LOD 200 is

used, the goal and scope definition must be narrower because the available data is less than of LOD 300.

The goal of this framework is to approach LCA, LCC and circularity indicators in a holistic manner by considering them side by side. It provides a clear summary of what are the steps needed to be taken to conduct each assessment. Having these steps laid out explicitly makes the whole process more systematic and shows the users what the attention points are and what to do next. This assessment framework which gathers circularity, LCA and LCC together, can inform architects and structural engineers better about their design decisions and guide them to reach more sustainable and circular design solutions.

3.3. Data collection and assessment

In order to develop a plugin as a proof of concept, there has been a set of decisions taken. These decisions are taken to limit the scope to achieve reasonable goals within the project timeframe and they are all decided according to the proposed framework. As can be seen on the framework schema, the first and most important step is to establish the goal and scope. For this research, for the requirements of the plugin, the scope for LCA, circularity and LCC calculations as well as project elements that would be taken into consideration are as follows:

BIM model data comes from the structural model of the newly built extension part of the case study project. Structural elements are chosen for this study because as can be seen from the findings in Chapter 2 "Literature Review", structural components are the main contributors for environmental impacts in a building. They are built to survive for longer periods of time than any other building element, so they have more potential to be used for multiple life cycles. As stated in Chapter 2 "Literature Review", the reuse of structural building elements can be achieved by keeping the structure in its original place and renovating/transforming the building for a new use or by designing the structural elements for disassembly so that they can be transported and reused in another location. This creates the potential to significantly decrease environmental impacts and increase circularity. Structural elements are also the heaviest components of buildings which comes into importance when calculating MCI because MCI is calculated by looking at the masses of components.

From these structural elements just floors and load bearing walls are selected as a starting point to be used in the assessments by the tool. This choice has been made to limit the scope and complexity of the tool for now and to see if the tool works as a proof of concept. The tool can be further extended to include other structural elements such as columns, beams etc., but these are currently not included.

For the LCA assessment the scope is defined as just taking one environmental impact category which is found to be the biggest contributor to the climate change during Chapter 2 "Literature Review", the global warming potential. The current interest around minimizing CO2 emissions and emerging legislations around this topic are also supplementary reasons why this impact category was selected. Global warming potential translates into embodied carbon values for materials in a

product and is expressed in kqCO2eq. These values are obtained from NIBE to follow the Dutch standards. NIBE is an open-source database which can be accessed by the web. In cases where the exact same product was not found in NIBE, the closest matching product was selected for the calculations. The products found in NIBE are mostly generic and therefore the information related to them are considered as industry averages.

The calculations for embodied carbon values are done by multiplying the kgCO2eq per functional unit that is stated on NIBE with the value for the functional unit obtained from the BIM model. For this research, the functional unit is always meter square for both floor elements and wall elements. This is because NIBE provides all indicator values per meter square of a product. They calculated the kilograms per meter square and found the corresponding values to make things easier for the users. Equation 1 shows how to calculate the embodied carbon of a product.

$$EC = GWP \times Q$$

Equation 1

Where:
EC is the embodied carbon value of a product in kgCO2eq,
GWP is the global warming potential indicator per m^2 of a product,
Q is the quantity in m^2 of a product.

For assessing circularity, Ellen MacArthur Foundation's material circularity indicator (MCI) method is used. This method is a commonly accepted approach in the industry. Data acquired from NIBE database is also used for MCI calculations, as the database states Dutch industry average end of life scenarios for recycling, reuse, landfill or incineration for each building element type depending on their material. However, it should be noted that NIBE has its limitations as a database to be used for circularity because, originally, it is a database designed to be used for LCA and it also does not include all 10R strategies for circularity.

MCI focuses on the flow of materials throughout their use time and shows how much of the materials of a product can circulate by reuse or recycling. Equation 2 shows the calculation of MCI of a product.

$$MCI = 1 - (LFI \times f(X))$$

$$LFI = \frac{(V + W)}{2M}$$

$$f(X) = \frac{0.9}{X}$$

$$X = \frac{IA}{AL}$$

$$MCI = \left(1 - \left(\frac{(V + W)}{2M} \times \frac{0.9}{\frac{IA}{AL}}\right)\right)$$

<div align="right">Equation 2</div>

Where:

MCI is the material circularity indicator of a product which is a value between 0 and 1,
LFI is the linear flow index,
f(X) is the function of the use factor X,
X is the use factor which is calculated by dividing industry average by actual product life,
IA is the industry average lifetime of a product in years,
AL is the actual lifetime of a product in years,
V is the total mass of virgin materials in kilograms,
W is the total mass of waste materials in kilograms,
M is the total mass of all materials in a product in kilograms.

The lifespan of the products is taken as 75 years for embodied carbon and MCI calculations. This is because the data for both calculations are obtained from NIBE and NIBE takes 75 years as material lifespan reference point. Product data which was gathered from NIBE can be found in Appendix 1 for more detailed information. As the use factor (X) depends on the industry average and actual lifetime of products, for this research both of them were considered as 75 years so the use factor (X) is always 1. This assumption was made because the relevant information about actual lifetime of products were not found.

Another assumption made for MCI calculations was the origin scenario of materials as the calculation method asks for the total mass of virgin materials. For this study, all the products in the database were considered as manufactured out of 100% virgin materials.

For the LCC assessment the data comes from the ArchiCalc database. This database consists of different cost values for each product and most of these values are generic/industry averages. Therefore, the averages of the values for each product are taken. In cases where the exact same product was not found in ArchiCalc, the average of the closest matching product was used for the calculations. Equation 3 shows the calculation of manufacturing and construction costs of a product.

$$AC = UC \times Q$$

<div align="right">Equation 3</div>

Where:

AC is the total of manufacturing and construction costs of a product in Euros,
UC is the cost of a product per m^2 (unit cost),
Q is the quantity in m^2 of a product.

At the end, a "Database.csv" file created with the obtained data. This file contains the following information for each product which can be observed in Table 4.

Table 4: Contents of the database

		Example product
Assembly code	Assembly codes associated with that specific product	23.21.02
Name	Name of the product	Kanaalplaatvloer
Embodied carbon	Embodied carbon equivalent per m2 of a product (kgCO2 per m2)	95.2
Functional unit	Functional unit selected for all the calculations to take place (for this research it is always m2)	m2
Kg per m2	Mass of the products per m2	527.8
Costs	Cost of a product for manufacturing and construction per m2 in EUR	58.855
New (%) Origin scenario	Percentage of virgin materials used in the origin scenario of the product	1
Reused (%) Origin scenario	Percentage of reused materials used in the origin scenario of the product	0
Recycled (%) Origin scenario	Percentage of recycled materials used in the origin scenario of the product	0
Biologic (%) Origin scenario	Percentage of biomaterials used in the origin scenario of the product	0
Landfill (%) Future scenario	Percentage of materials that will go to landfill in the end-of-life scenario of the product	0.036
Incineration (%) Future scenario	Percentage of materials that will go to incineration in the end-of-life scenario of the product	0
Recycling (%) Future scenario	Percentage of materials that will go to recycling in the end-of-life scenario of the product	0.964
Reuse (%) Future scenario	Percentage of materials that will go to reuse in the end-of-life scenario of the product	0.001
Use factor (X)	Use factor which is calculated by dividing industry average lifetime of a product by the actual product lifetime	1
MCI	Material circularity indicator of a product	0.54505

4. Tooling and Case Study

This chapter provides explanation on the implementation of the proposed framework with a tool and the validation of this tool via case study project. First, the case study is introduced so that the project at hand is better understood. Then, Circularity, Embodied Carbon and Costs (CECC) tool is explained by stating the technical requirements, functional requirements, system architecture of the tool and the process flow on how to use the tool. Next, CECC tool is tested on the case study project. Lastly, the results obtained from this validation are discussed at the end of this chapter.

4.1. Case study

A case study project is provided by the collaborating company RHDHV to test the developed Revit plugin. The project consists of the renovation of an existing office building located in the Netherlands and a newly built extension to the existing building. Only the new-built extension part is the subject of this research. It consists of a ground floor plus four upper floors, and it has a GFA of 1937 m2. A preview of the case study project can be seen in Figure 30 and Figure 31. The existing building is the rectangular part, whereas the semicircular part is the new-built extension and the subject of this research.
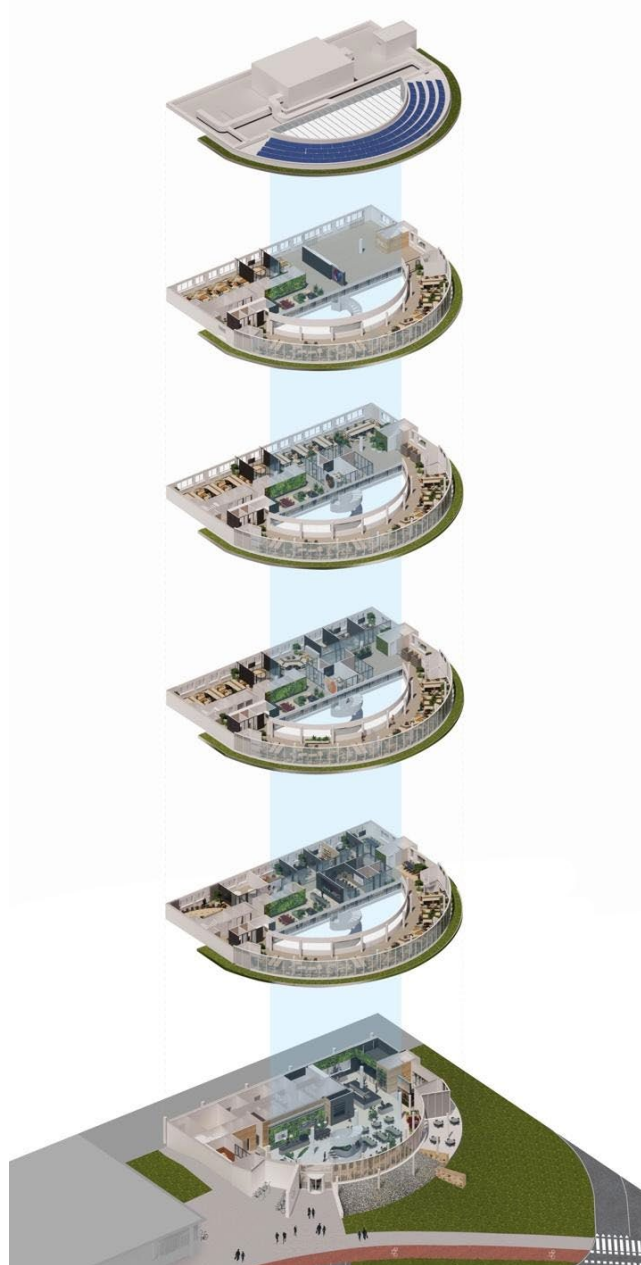
Figure 30: Axonometric view of the case study project
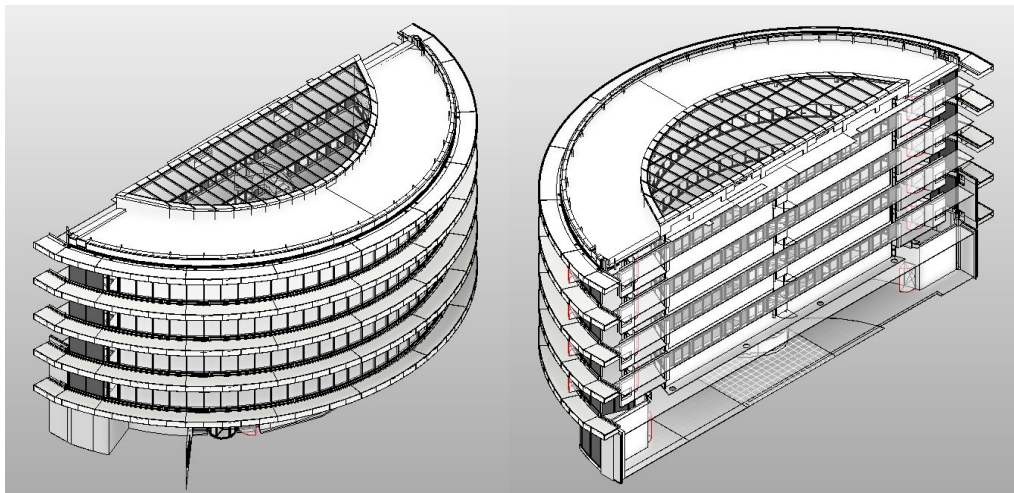
Figure 31: 3D model views of the new-built extension part

The project was initiated in 2016. Preliminary design was delivered by RHDHV and the architect of the building, Paul de Ruiter. Last design stage was in a "Bouw-team" configuration where the design responsibility was transferred to the contractor, RHDHV represented the client in the further development and realization of the project. For this research, the structural model of this project is used, and the structural model was delivered by the contractor. An image of the structural BIM model can be seen in Figure 32.
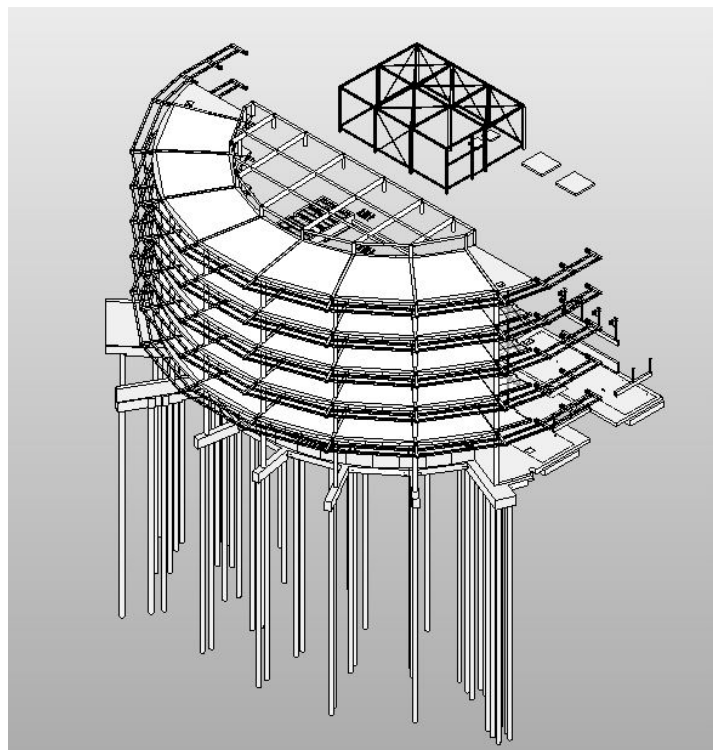
Figure 32: 3D structural model of the case study project

Sustainability ambition was present in the program of requirements for this project from the beginning because the client wanted this project to get a BREEAM NL certificate. There were no explicit circularity goals in the program of requirements from the client. However, when the whole project is considered, there was a higher overall circular strategy adoption since the existing building was reused and repurposed instead of being demolished and built completely from scratch. This decision has clearly avoided a lot of CO_2 emissions. For that reason, the client wanted to know how much CO_2 emission has been avoided by refurbishment instead of new-built.

After an expert analysis, it was found out that only 35% of the GFA has been newly built by realizing an extension to the existing building instead of building a completely new office. This resulted in a CO_2 emission reduction of approximately 1342408 kg CO_2 eq of building materials, as they do not have to be produced, transported and constructed again. For these calculations it was assumed that the entire new building would have been designed with materials that lead to the same shadow price as the renovation. The residual environmental impact of the existing materials as well as the materials removed during demolition were not taken into account. The related calculations can be seen in Appendix 2.

The client was looking for cost-effective expansion of the office space within Aalsmeer and wanted to achieve the maximum sustainability that was attainable within the allocated budget. Here, it should be noted that there is not any internationally agreed and standardized benchmarking system to define "maximum" sustainability in general. Certifications such as BREEAM or LEED try to evaluate the performance of a building based on their own criteria and then compare these performance results with predefined reference values (Gervasio et al., 2018). However, each certification system has its own assumptions, goals and scopes so their benchmarking systems are also different. Therefore, the "maximum sustainability" mentioned here is a relative condition with respect to other possible options for the same project, so that each decision affects the overall maximum attainable sustainability level.

Later in the design process the issue of circularity was raised to the client as an important complimentary sustainability topic. Based on this topic, a change for the fit-out design was proposed to include this as an additional criterion. This criterion was set for wall and floor finishes, partition walls and loose and fixed furniture.

During the design development phase, data delivery for environmental impact calculations was mostly done by exchanging reports and excel sheets. Excel files with material quantities were extracted from the BIM-model, using the Schedules function in Revit, but it was not an integrated process, as the environmental impact calculations were done when the design was already finished. The motivation to do the environmental impact calculations was two-fold: firstly, to meet legislation for building permit (MPG ≤ 1,0 €/m2 GFA/yr for new office buildings) and secondly, to obtain extra BREEAM points for the material credits (MAT01). The BIM model was used mainly for design coordination and graphical representation. This manual and static process created less interaction between the structural engineers working on the BIM model and sustainability consultants working on the calculations, resulting in a structural design where environmental impact was not considered as a design parameter.

4.2. Circularity, Embodied Carbon and Costs (CECC) Tool

4.2.1. Technical Requirements

The implementation of the framework into practice is done via Autodesk Revit environment. Revit is chosen for this research as it is one of the most popular software used in the AEC industry. The popularity stems from the fact that architects, structural and MEP engineers can all work together at the same time, in the same software environment. It is also selected because it is an efficient BIM software where both nonvisual model data and visual 3D representation are stored and can be modified. It is closer to the architects and engineers and is more accessible than other software. Also, the BIM model can be made accessible to the client, so that s/he can check the progress and be more involved in the process.

The decision to develop a plugin for a specific software, Revit in this case, stems from the fact that open standards, such as IFC, often complicate the process and sometimes errors occur during import and export of BIM files into IFC files (Bertin et al., 2020). With a plugin specifically designed for Revit, the import-export process is eliminated and therefore the aim is to clear off any possible complications arising because of it.

There are three different ways to build an assessment tool for Revit. One option is to create it using Dynamo. Dynamo is a visual programming language which is open source and lets users create algorithms that consist of nodes that require minimal coding knowledge. An example for using Dynamo to create a tool for Revit was realized by Zhai (2020), which was explained in Chapter 2.5 "Integrated Assessment Approach". The second option is to code in scripting language Python using Revit Python Shell. The third option is to write a plugin using C#. Both Python and C# are traditional programming languages. To illustrate the main difference between visual programming and traditional programming at a glance, is presented in Figure 33 below.
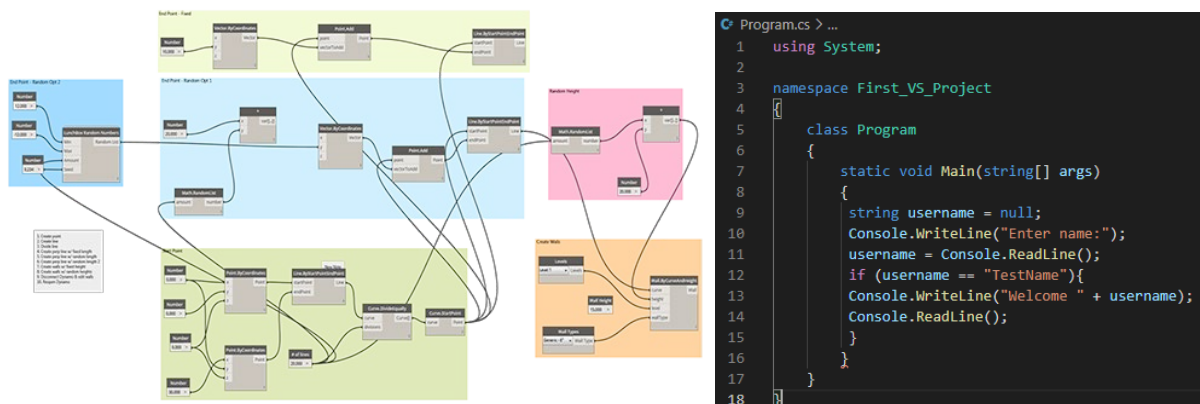
Figure 33: Visual programming (left) versus traditional programming (right)

C# is a general-purpose object-oriented programming language. Both C# and Python require proper coding skills when compared to Dynamo. However, if implemented successfully, using C#

yields the best results and has more flexibility during the plugin development. The execution of a plugin created with C# is also faster in Revit for heavily loaded project files when compared to a tool made with Dynamo. In addition, C# is the native scripting language that Revit uses, and Revit API can be used together with it. For all these reasons, C# method is selected to develop a Revit plugin in this research. Core parts of the codes written in C# for the realization of CECC tool and how to access the whole project package can be found in Appendix 3.

The coding is done via Microsoft Visual Studio 2019. Visual Studio is an integrated development environment (IDE) which lets users design, develop and test computer programs, websites, web and mobile apps. It supports C# as well as multiple other programming languages. For this research, Visual Studio's code editor, debugger and Windows Forms Designer components are used.

The Autodesk Revit version chosen for this research is 2020. Therefore, the framework that is used for the entire project in Visual Studio when coding is .NET Framework 4.7. This is important since different Revit versions support different .NET Frameworks and choosing a different framework may result in problems when building and running a plugin within Revit. When the code was ready, all the debugging and running was done in Revit 2020.

It should be noted that whenever the code needs to be tested and debugged, Visual Studio starts running Revit. This process usually takes time (depending on the hardware specifications of the user's computer) as Revit and the project file loads each time. This can be considered as a drawback for software developers and may demotivate them to select this method for tool development. However, once the development is finished, the newly added plugin will be built inside Revit. It will run automatically together with Revit, every time the software is launched, saving the users time and effort.

For this plugin to work effectively, the Level of Development (LOD) of the BIM model should be at least 200 since LOD 200 includes relevant material information. LOD 100 is not suitable for this study as the information in the model is limited and this level of detail is found to be insufficient by earlier studies for such assessments (Zhai, 2020; Van Oeveren, 2020). The BIM model chosen for this study has LOD 300 since, in addition to the required material information, it also consists of the dimensions for the structural elements. Different LODs and their extents can be seen in Figure 34.
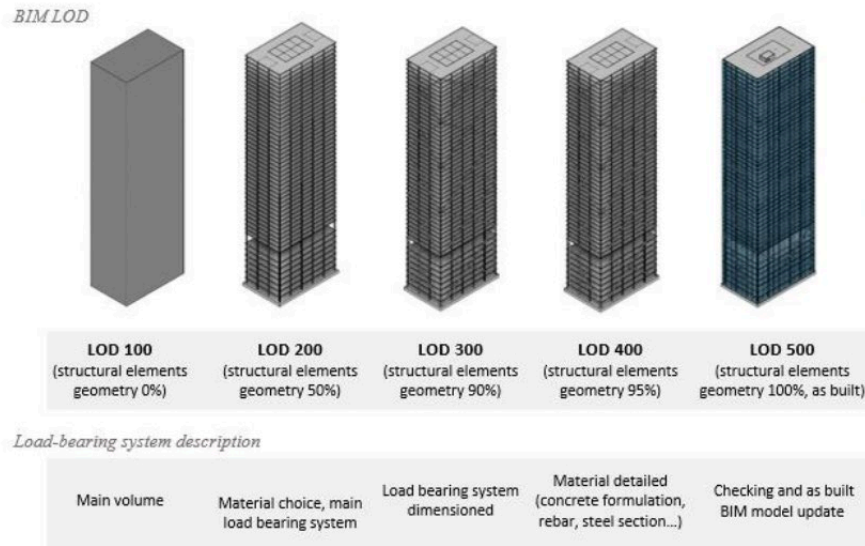
Figure 34: Different LODs for structural BIM models (Bertin et al., 2020)

In addition to the LOD, the BIM model should include the relevant NL-SfB codes. NL-SfB is a standardized classification system for building elements and is used in the Dutch construction industry widely. It is used in BIM and CAD environments to organize project information related to different building elements. NL-SfB is an open standard and is under the management of BIM Loket. Dutch Revit Standards, NLRS (Nederlandse Revit Standaard), also make use of the NL-SfB coding system (BIM Loket, n.d.).

How to apply the NL-SfB coding is elaborated in an official Excel document. This document consists of five tables, namely Table 0, Table 1, Table 2, Table 3 and Table 4. Table 0 is the "physical environment" and it provides means of classifying spaces in and around buildings, such as offices, residential buildings, restaurants etc. Table 1 is the "building elements" and it provides means of classifying functional building parts such as external walls, internal walls, floors, roofs etc. Table 2 is the "constructions" and it provides means of classifying construction methods such as cast in situ work, brick work etc. Table 3 is the "materials" and it provides means of classifying materials such as marble, glass, cement etc. Table 4 is the "activities and requirements" and it provides means of classifying activities and requirements such as grading, selection, quantifying, completion etc.

An example of an NL-SfB code is given in Figure 35. From left to right, when the code is read, the following information is acquired: It is an office facility (32) and the building element is an exterior wall (21). The exterior wall is bricked (F) with fire clay (g2). P2 shows that sound isolation is a performance requirement of this wall.

Figure 35: Example NL-SfB coding (Zorzi, 2020)

For this research, NL-SfB code information from Table 1 "building elements" is used to identify each different building element type. The acquired case study project for this research was already structured according to NLRS but the model did not include NL-SfB codes. Therefore, it is important that the BIM model should be checked also for the NL-SfB codes and structured accordingly, if necessary.

4.2.2. Functional Requirements

In order to determine the functional requirements of the tool, several interviews are conducted. The interviewees include different experts in different fields such as sustainability consultants, architects, parametric designers and engineers. The meetings were done in an unstructured manner meaning that the interviews were informal and progressed in the form of natural conversations. For this reason, there is no official documentation of the meetings as meeting notes. A list of interviewees can be found in Appendix 4.

According to the acquired information about the user desires and needs from the conducted interviews, a list of functional requirements was formed. The requirements for CECC tool were then prioritized according to the "MoSCoW method" and also taking into consideration the given timeframe for completion of this research.

MoSCoW method is a common technique to help software developers, project managers, business analysts, product developers to prioritize the requirements. It was developed by Dai Clegg back in 1994 for rapid application development and since then it is highly popular for agile software development processes. MoSCoW is an acronym which stands for:
    1) "Must haves"
    2) "Should haves"
    3) "Could Haves"
    4) "Won't Haves"
These four categories are the prioritization categories of the method (The Agile Business Consortium, n.d.).

1) **"Must haves"** consists of the non-negotiable, highly critical requirements that need to be met during the given project delivery timeframe. These requirements are mandatory for a project to be considered successful. If these requirements are not met, there is no point in delivering the project since the project is considered as a "failure". "Must" is also sometimes referred to as an acronym for "Minimum Usable SubseT".

2) **"Should haves"** are important requirements which are not as vital as "Must haves". These requirements do not change the viability of the solution but add significant value. They are not time-critical so that they can be postponed to a later time.

3) **"Could haves"** are desirable, nice to have initiatives which are not as critical as the first two categories. If the time and resources are sufficient then "Could haves" can be implemented. However, if they are left out, the outcome is not much affected. The requirements in this category are the first ones to be deprioritized if the deadline is at risk or a problem occurred along the way.

4) **"Won't haves" (this time)** are the functionalities that are not a priority for the specific timeframe and therefore will be kept outside the scope of delivery. These requirements are listed in order to manage expectations, clarify the scope and keep the focus on "Must Haves" and "Should Haves". By having them listed under "won't haves", it is avoided that these requirements are being informally reintroduced during the process later, again and again.

The requirements of the CECC tool according to the MoSCoW method are listed in Table 5.

Table 5: Functional requirements of the CECC tool

MoSCoW Category	Requirements
Must Haves	Must be able to process data stored in a Revit file.
	Must be able to process data stored in an external data file.
	Must be able to link the data from both sources.
	Must be able to perform calculations with the linked data.
	Must be able to show results related to at least one aspect of LCA (embodied carbon), one aspect of LCC (manufacturing and construction costs) and one aspect of circularity (MCI) per building element.
Should Haves	Should have a graphical user interface.
	Should be able to display results in both tabular and graphical data formats.
	Should have an option to export the results to save externally.
Could Haves	Could have filtering options for the users to see results related to only embodied carbon, only MCI or only costs.
Won't Haves	Won't show results related to all aspects of LCA, LCC or circularity.
	Won't be compatible with web-based databases.
	Won't be able to color override onto 3D BIM models.

The main goal of this tool is to optimize the workflow of architects and engineers. Since the data used for this tool is generic and consists of industry averages, the CECC tool can act as a preliminary rapid assessment tool before specific materials and products from specific suppliers are selected and more detailed assessments have to be made with more advanced software which can connect data from environmental product declarations (EPD). Therefore, all the functionalities listed in this section is to contribute to the ease of use, reduced time and increased efficiency in performing assessments.

4.2.3. System Architecture

The functional and technical requirements stated in the previous sections are translated into building blocks of the CECC tool. These blocks helped the formation of a system architecture. The system architecture of the CECC tool is depicted in Figure 36. As can be seen, the process follows three major steps, namely input, analysis and output. This linear flow of information constitutes the backbone of the system design.
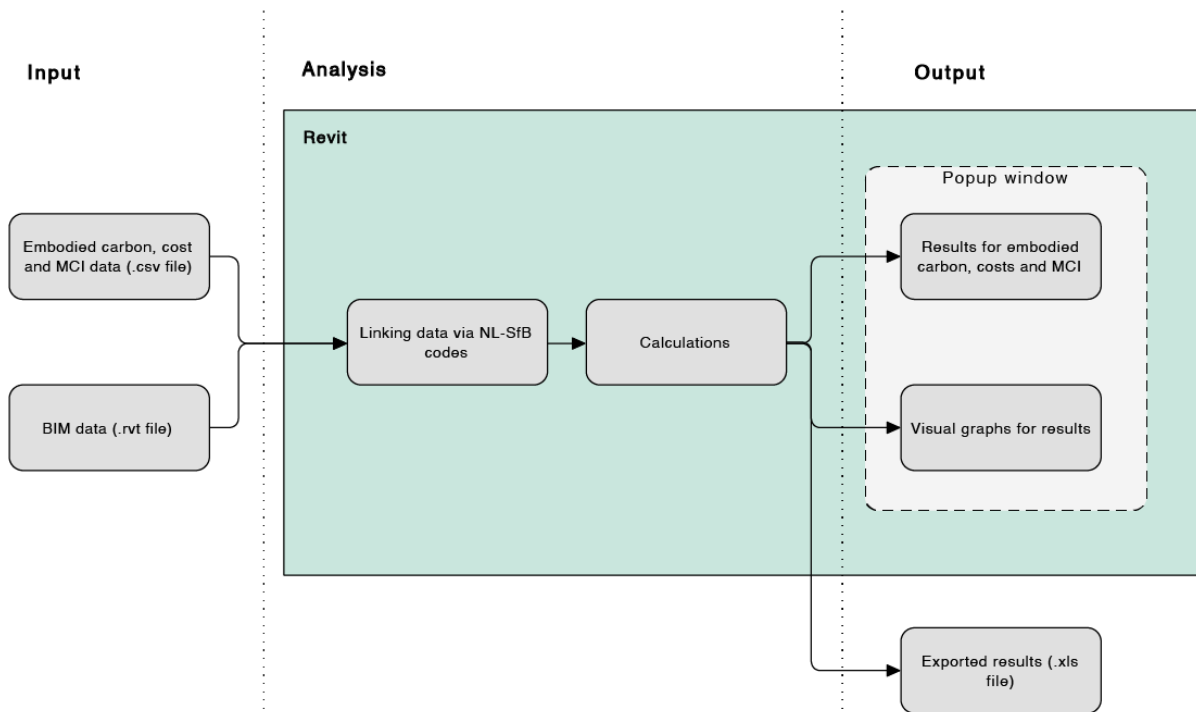
Figure 36: System architecture of CECC tool

As input, there are two main components which are the BIM data that is coming in, in the form of a Revit project file, and the embodied carbon, cost and MCI data which are gathered inside a CSV file. The data included in the CSV file are generic and represent industry averages, as stated in Chapter 3.3 "Data collection and assessment". Therefore, the system architecture does not include any information coming from environmental product declarations (EPD). A snippet from this CSV file can be seen in Figure 37.

Figure 37: Contents of "database.csv"

These input data are then linked together via NL-SfB codes. This linking process enables calculations to take place. Data linkage and calculations are the two components of the analysis part and this takes place inside Revit environment since CECC tool is accommodated inside the software. After the calculations take place, an output is reached. The output obtained include tabular results for embodied carbon, costs and MCI per product and visual graphs derived from these results, providing further information. These tabular and graphical output are presented inside a popup window in Revit environment. In addition to these, a third output can also be obtained in the form of an Excel file, if the user wants to export the results outside of Revit.

4.2.4. Process Flow

A typical use case of the developed plugin and the process flow is illustrated in this section. First, the architects or the structural engineers start working on a detailed design of a project. By doing so, they create a BIM model which has at least LOD 200, preferably LOD 300, in Revit and select materials for each building element. The most common way to assign materials for building elements is to select the desired family type in Revit. Families can be created for individual components with their designated material information according to the NL-SfB coding system. If families are not to be created, there are existing family libraries so that items from these libraries can also be used. Often, architecture and engineering companies have their own material libraries with specific names for commonly applied materials. However, the architect or the structural engineer should make sure that the related NL-SfB code is assigned and specified in the "Assembly Code" parameter inside the family type properties in Revit. The ideal way of having these codes is to have all Revit family libraries to be standardized so that the codes are already included as a parameter by the Revit family suppliers.

The presence of these codes is important in order to match the incoming BIM data with the embodied carbon, cost and MCI data from the CSV file, since the CSV file also contains the same NL-SfB code information for each building element. Therefore, this coding system acts as a key for all assessments to take place.
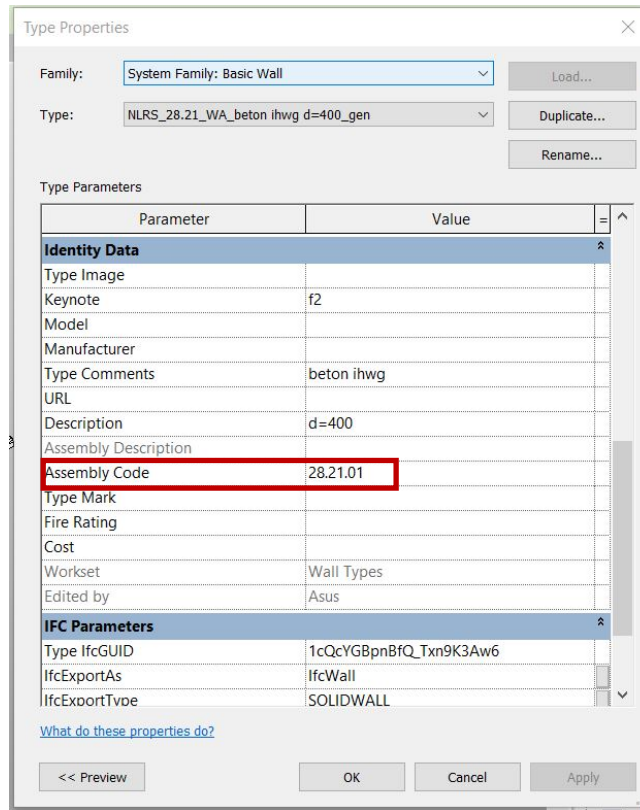
Figure 38: Assembly codes in Revit

Next, the architect or the structural engineer executes the integrated assessment for embodied carbon, costs and MCI of the building elements of the design by clicking the "CECC Tool" tab button. All necessary buttons are added within this ribbon so that the components of the plugin are kept organized and all the functionalities can be accessed individually but in one place. Creation of a ribbon also enables the further extension of the tool with new functionalities in the future. There is one main button in this ribbon tab, which is "Calculate Values".
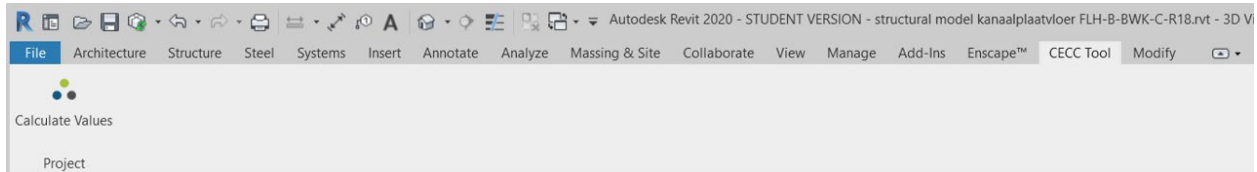
Figure 39: Ribbon for CECC Tool in Revit

The person executing the integrated assessment simply clicks the "Calculate Values" button. This button, first, loads the so-called "Database", which is a CSV file with data about embodied carbon from an LCA perspective, data related to manufacturing and construction costs from an LCC perspective and data about MCI from a circularity perspective, all of which are per building element. This file also contains the NL-SfB code for each element, as previously stated.

76

The assembly codes used for this research is from the official NL-SfB documentation Table 1 "building elements". According to this, 23.21 refers to "Floors, load bearing, Suspended floors". In order to accommodate different types within 23.21 classification, two new digits are added by the author. For example, 23.21.02 refers to "kanaalplaatvloer" and 23.21.03 refers to "breedplaatvloer".

When clicked on the "Calculate Values" button the data which is present in the CSV file is being read and stored. Then, a Windows forms application appears on the screen as a new popup window running inside Revit. This window can be seen in Figure 40.
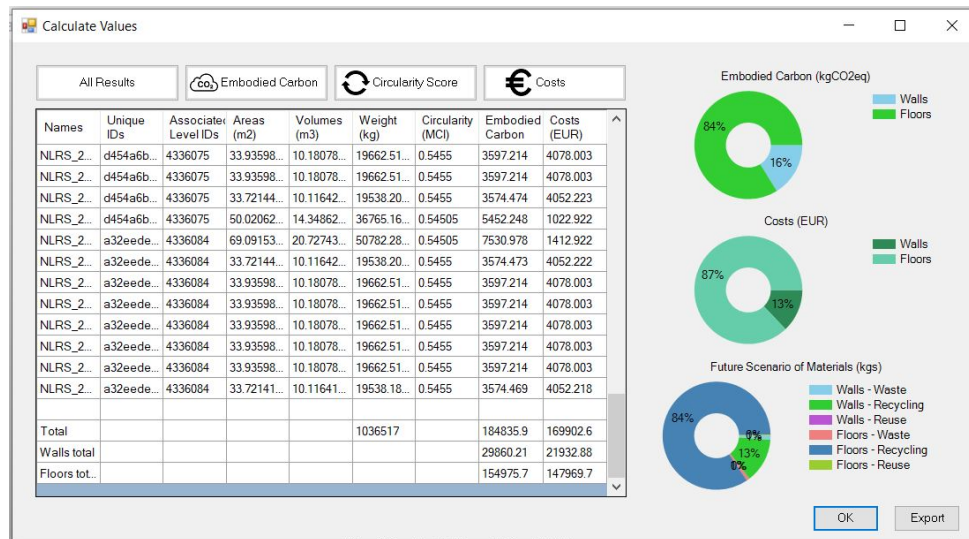
Figure 40: Popup window showing up the results

"Calculate Values" button checks the BIM model that is currently open in Autodesk Revit, and gets the building element information such as names, unique IDs, associated level IDs, areas in meter square, volumes in meter cubes and masses in kilograms. It also checks the NL-SfB codes for each element in Revit and matches them with the same codes existing inside the "Database" CSV file. Once the information from Revit is matched with the information inside "Database", the appropriate calculations take place for embodied carbon, manufacturing and construction costs and MCI scores of each building element, according to the equations presented in Chapter 3.3 "Data Collection and Assessment".

As a result, the user is presented with all the captured element information as well as their respective calculated values for embodied carbon, costs and MCI scores. At the end of the results table, the total of all the elements can also be found. The results can be filtered if the user prefers to have a look at the individual assessment components separately. If, for example, the user clicks "Embodied Carbon" only the embodied carbon results are shown. The same thing applies to the buttons for "Costs" and "Circularity Score". When clicked on "All Results" all obtained results can be viewed at once again.

On the right-hand side of the window, there are three donut charts. The first donut chart shows the contribution percentages of different building element types to the total embodied carbon amount. The second donut chart shows the contribution percentages of different building element types to the total costs. The last donut chart is slightly different from the first two. This chart shows the kilogram percentages of possible future scenarios for each building element type when compared to the total mass of all materials/products. For example, in Figure 40, walls which will go to recycling makes up the 13% and floors which will go to recycling makes up the 84% of the total mass that was assessed.

When the popup window inside Revit is closed, the results are not saved somewhere within Revit and they are lost. Therefore, the architect or structural engineer should click "Export" on the window, before closing it. This action exports the obtained results in an Excel file and saves it on the user's computer automatically so that the results are not lost once the user exits the popup window or Revit completely. The export option does not apply to the donut charts. Therefore, to keep these donut charts for future reference, a solution is that the user can take screenshots of the chart results whenever needed. The popup window can be closed when the "OK" or the exit button is clicked.

As a second round, the architect or engineer can select different materials for their BIM model with different NL-SfB codes or change the design of their BIM model with the same materials but with different size and quantities and execute another calculation. To do the first option when selecting different materials, the user simply needs to change the family types for some or all of the elements and press the "Calculate Values" button once more. To perform a design change while keeping the materials the same, the user needs to change the size and/or quantities of the building elements and then press the "Calculate Values" button. In return, since the data is coming directly from the BIM model inside Revit, the updated material, family types, size and/or quantities will be automatically acquired and processed by the plugin. New calculations will take place, the user can obtain different results on the new pop-up window and save these results by clicking the "Export" button again.

Lastly, the architect or engineer can compare the two results and select the best option according to the project ambitions and client's requirements. If it is not satisfying, the user can iterate the process by selecting different materials and/or changing the design by size or quantities and conducting more calculations. After reaching the satisfying results, the user can decide on the material option. A summary of the process flow of the use case of this plugin is illustrated in Figure 41.

As can be seen in the process flow diagram in Figure 41, the architect or structural engineer can execute this assessment as soon as they have a detailed design BIM model which is structured according to the Dutch Revit Standards (NLRS), since NLRS uses NL-SfB system. The traditional way of doing such assessments is to have a design and BIM model first, then to export it outside of the design environment (most commonly into IFC format) and then import it into the different assessment software which would perform the calculations and provide the users with results. By using the CECC tool within Revit, architects and engineers are able to conduct these assessments

parallel to their design process. As opposed to the traditional way of working, their workflow is not interrupted. The process flow of traditional way of working can be seen in Figure 42. When Figure 41 and Figure 42 are compared side by side, the process facilitation by automation via using CECC tool can be observed.

When there are multiple design and material choice ideas during the design development phase, the architects and/or structural engineers should apply these options in their BIM models that they are developing. These BIM models can be in the same Revit project file as different "design options" or they can create separate Revit project files. The number of assessments to be conducted in parallel to the design development phase depends on how many different options the architects and engineers are considering and want to test for that specific project. At the end of each assessment, the results should be exported and saved so that different options are accompanied with their respective assessment scores and these results can be compared later.

An ideal way to use the CECC tool is when there is information about generic materials/products and quantities but no information regarding specific materials/products from specific suppliers. In this situation, it is often difficult to conduct assessments with existing software as the sustainability consultants and cost estimators have to pick the specific materials one by one. Since this process costs a lot of time, it is often done when the design is almost finished. With the CECC tool "Calculate Values" operation can be performed multiple times on different design options, results can be checked and compared to see which ones are performing well on which criteria and which ones are not. By doing so, the architects and engineers can already eliminate the options which are not worth considering further.
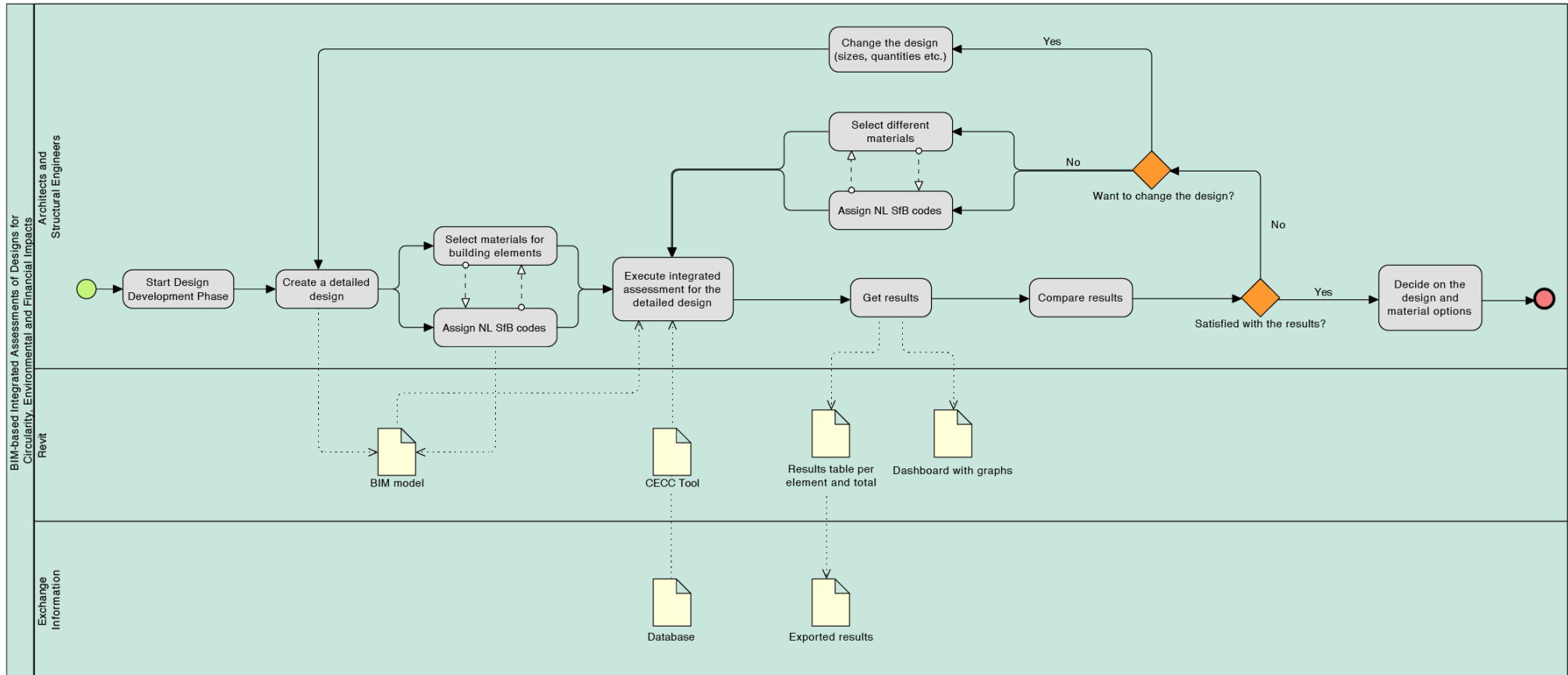
Figure 41: Proposed process flow diagram by using CECC tool
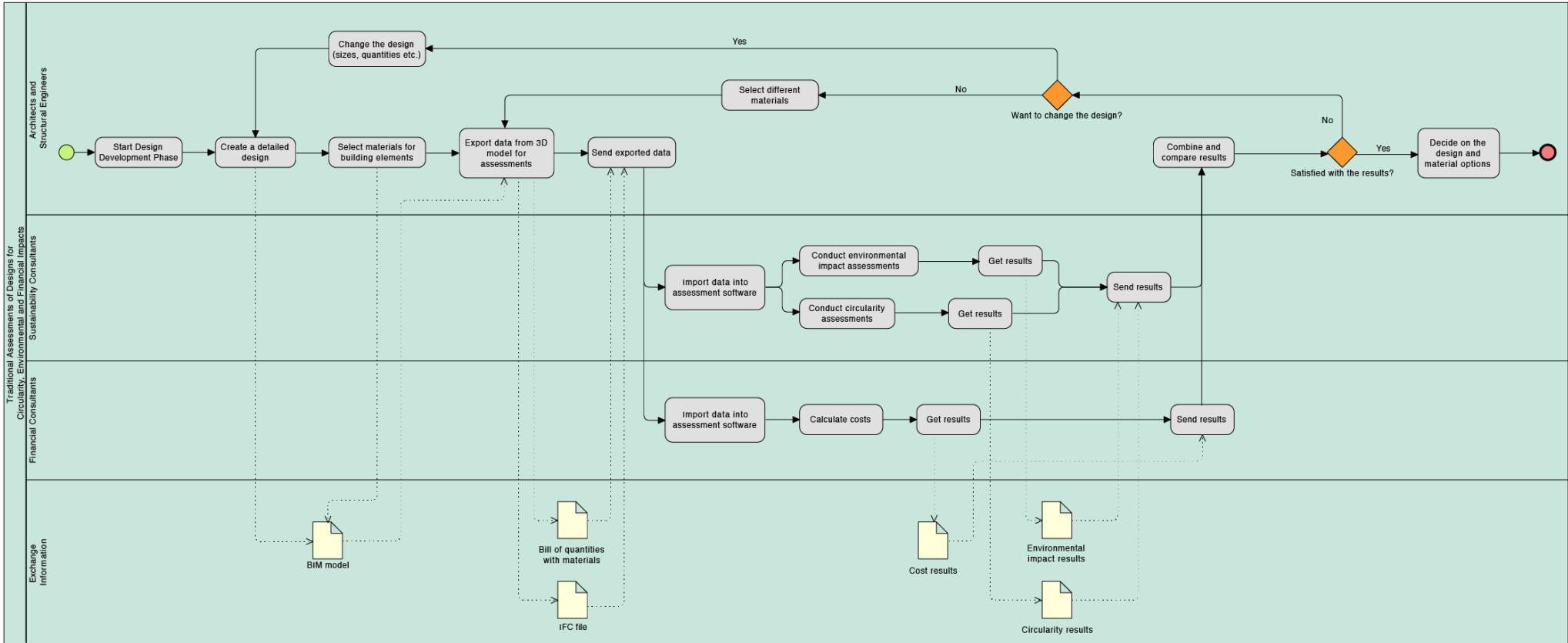
Figure 42: Process flow diagram of traditional methods

4.2.5 Scripts

CECC tool consists of seven different class files written in C# and one ".addin" file which is an XML script. These files and their functionalities within the application is explained as follows:

MyProject.addin

This is an XML file which refers to all the other class files that are used for the CECC tool. The ".addin" extension makes this file a "manifest" file for Revit, meaning whenever users want to invoke an application within Revit, they have to create an ".addin" file to register it into Revit (*Create a .addin Manifest File*, 2014).

ExternalApplication.cs

This is a class file where the "external application" is defined to Revit to add new functionalities to realize CECC tool. With this script the new Revit ribbon tab and push buttons are created.

Indicator.cs

Within this class file, several different empty indicator holders are created. These indicator holders will store the values coming from the data loading operation by "Calculate Values" button.

CalculateValues.cs

This script functions as the core of the CECC tool. First, it reads the "database.csv" file for every row and column and parses the values obtained from this database into the "Indicator.cs" file to be stored for calculations. Then, it filters the BIM model which is open in Revit for wall and floor elements. Then, for each wall and floor element, it checks if their assembly codes within Revit match with the assembly codes stored inside "Indicator.cs" holders. If they match, the script gets information from the element such as name, unique ID, level ID, and calculates the area, volume, embodied carbon, cost and MCI of each element. Then it creates a table to present all of the obtained results from elements. It also calculates the total mass, embodied carbon and costs of all elements. For embodied carbon and costs, it also calculates just the totals for walls and totals for floors separately. Then, it also defines the filtering system of the results when the user hits buttons for "all results", "embodied carbon", "circularity score" and "costs". In addition to these, within this script the data content of the donut charts presented to the user as results are also defined.

FormMain.cs

This is the class file where the popup window for displaying the results within Revit is defined and visualized. This class file works together with "FormMain.Designer.cs" class file. Each button, their positions, position of the donut charts, used colors, position of the results table, functionalities of the buttons are defined.

FormViewModel.cs

This class file acts similarly to the "Indicator.cs" file because it is created to hold and store values. These values are captured in "Calculate Values" operation and then they will be used again during "Calculate Values" operation to display the results.

ResultsWindow.cs

This is the script that calls for the "FormMain.cs" script and makes the popup window appear inside Revit.

4.3. Application on the case study

In order to test the developed plugin, the structural BIM model of the newly built extension part of the case study project was assessed by using the CECC tool. To do this, two different types of structural floor panel elements were selected. The location of these floor panels within the BIM model can be seen in Figure 43. As can be seen on the same image, these floor panels have surrounding frame-like components. These components are also classified as "floor" elements in the BIM model, however their material type is "in-situ concrete". Since they are considered as transition/connection points between beams and floor panels these parts were not changed. Therefore, only the highlighted floor panel elements were changed in types.

One of the selected floor panel types is precast concrete panel floor (breedplaatvloer) and the other is concrete hollow core slab floor (kanaalplaatvloer). Therefore, the case study validation is conducted on a product level. The effects of product level choices are then reflected on the overall aggregated scores.
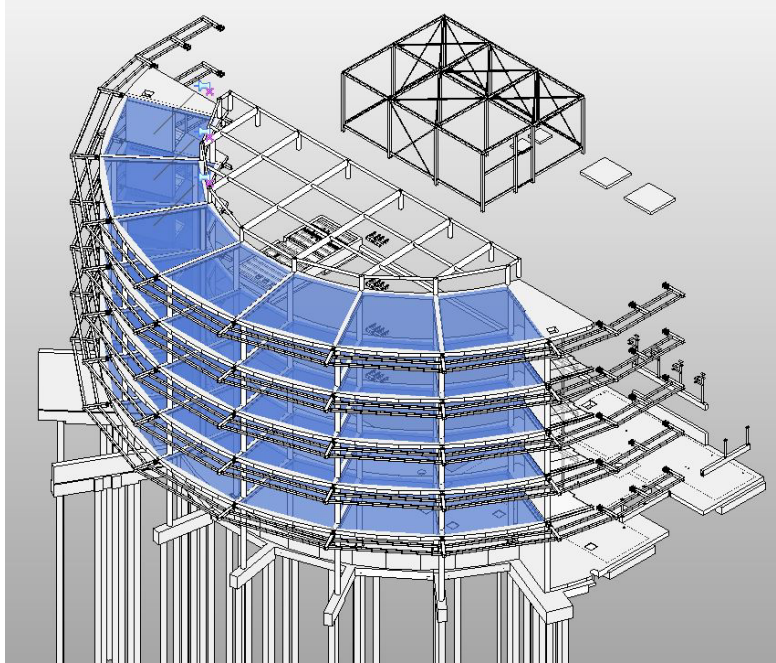
Figure 43: Highlighted structural floor elements

The design, all material choices for the other structural elements and other parameters are kept the same in the BIM model so that the effects of selecting different type of floor elements on embodied carbon, circularity potential and costs can be compared at the end. For this research, two separate BIM models are created to accommodate these two different floor options but it is also possible to create different "design options" inside the same Revit project file to decrease the number of separate files.

Once the BIM models were ready, including the necessary NL-SfB code data embedded into their "Assembly Code" parameter inside the family type properties in Revit, the plugin was run. For both options, the CECC tool filtered the BIM model for all the wall and floor elements, matched their assembly codes with the assembly codes present in the "database" file and performed the calculations whenever there was a match. Then, the results were acquired on a popup window inside Revit.

4.4. Results

After the assessments are conducted for the two alternatives on the case study project, results for embodied carbon, circularity potential and costs are found to differ. The results obtained from the CECC tool inside Revit for the two alternative structural floor panel types can be seen in Figure 44 and Figure 45. Complete results tables can be found in Appendix 5.
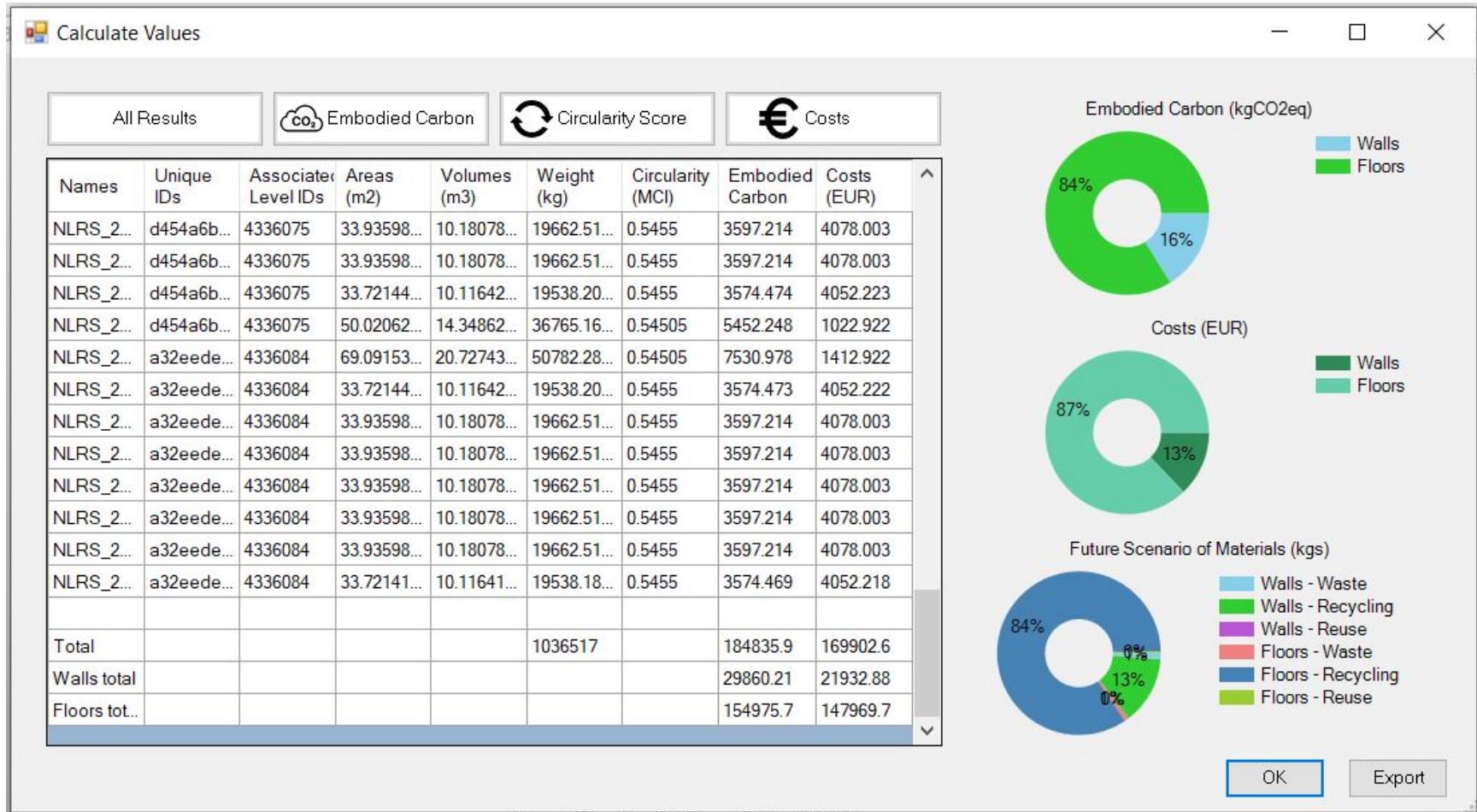
Figure 44: Results window for "breedplaatvloer"
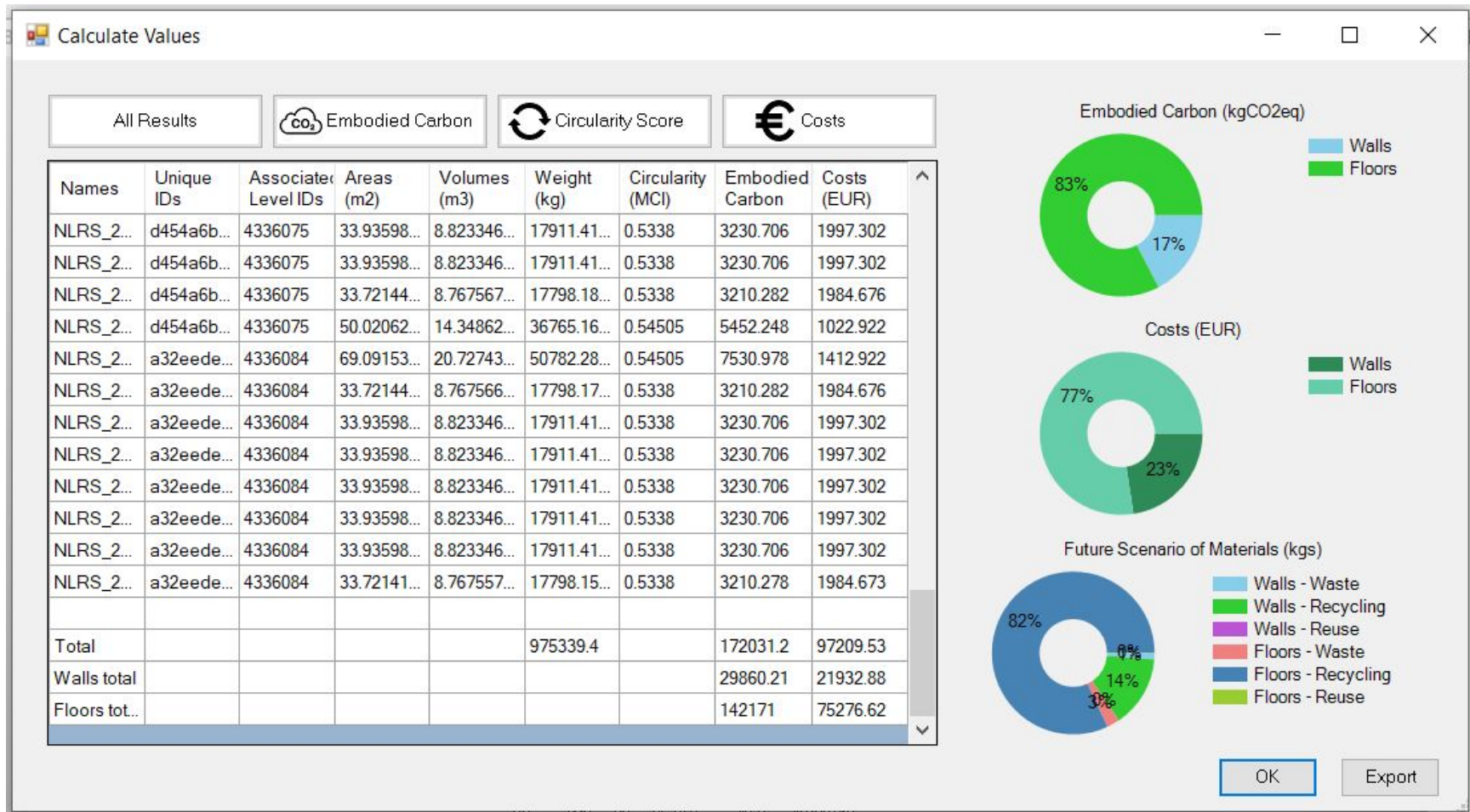
Figure 45: Results window for "kanaalplaatvloer"

When the plugin is run on the BIM model with "breedplaatvloer" option, the total embodied carbon for all structural walls and floor elements is found as 184 835.9 kgCO2eq and the total cost as 169 902.6 EUR. The contribution of structural walls to the total embodied carbon value is by 29860.21 kgCO2eq (16%) and floors was by 154 975.7kgCO2eq (84%). Wall elements cost 21932.88 EUR (13%) while floor elements cost 147 969.7 EUR (87%).

When the assessment is conducted for the "kanaalplaatvloer" option, the total embodied carbon for all structural walls and floor elements is found as 172 031.2 kgCO2eq and the total cost as 97209.53 EUR. The contribution of wall elements stayed the same for embodied carbon at 29860.21 kgCO2eq and for costs at 21 932.88 EUR, as there were no changes applied to the walls. However, contribution of floors in terms of embodied carbon changed to 142 171 kgCO2eq and their cost to 75 276.62 EUR. This also reflected on the relative percentages: 83% of the total embodied carbon results from floors while 17% of it belongs to walls and 77% of the total costs belongs to floors while 23% of these costs is due to walls.

These two results show that when keeping all other parameters the same, only changing the floor type has a direct impact on the costs and embodied carbon results of the overall design. In this example, opting for the "breedplaatvloer" increases the overall costs by 72693.07 EUR and it also causes 12804.7 kgCO2eq more embodied carbon when compared to "kanaalplaatvloer" option.

Considering MCIs of these two floor types, "breedplaatvloer" has an MCI of 0.5455 whereas "kanaalplaatvloer" has an MCI of 0.5338. The closer the score on an MCI to 1 means the product has more circularity potential and less linear, as discussed in Chapter 2.3 "Circular Economy". Therefore, "breedplaatvloer" performs slightly better than the "kanaalplaatvloer" in terms of circularity.

An important point here is that although "breedplaatvloer" or "kanaalplaatvloer" elements can be different in terms of size/mass, an MCI score of a "breedplaatvloer" element will be the same when compared to another "breedplaatvloer" element. This also applies to any other building element type. This is simply because they are the same type of element and the MCI calculation method used in this research takes into account the proportions of masses. An example calculation demonstrating this can be found in Appendix 6.

For the future scenarios of materials, the donut chart on the bottom right of the popup window can be checked. There, the results for "breedplaatvloer" show that floor elements which will end up going to recycling makes up the 84% of the total mass of all evaluated materials. The total mass in this scenario is 1 036 517 kgs therefore the mass coming from the floors going to recycling equals to 870 674.28 kgs. Mass coming from reuse and waste scenario of floors are insignificant when compared to the recycling scenario.

On the other hand, the results for "kanaalplaatvloer" show that floor elements which will end up going to recycling makes up the 82% of the total mass of all evaluated materials. In this case, the total mass is 975 339.4 kgs, which makes the mass coming from the floors going to recycling is

equal to 799 778.31 kgs. Again, the mass coming from reuse and waste scenario of floors are insignificant when compared to the recycling scenario.

In both cases recycling scenario is more predominant than the reuse scenario. When considering the order of importance of 10R strategies (Figure 13), having a more predominant reuse scenario would have been a much better option for achieving a more sustainable circularity for this project. Still, it is positive to see the waste scenarios are also very insignificant meaning that in a future scenario, the products and materials used in this project will not end up in landfills or being incinerated.

In short, this last donut chart can be consulted when the architects and designers are curious to know how much of which type of building element will go to waste, recycling or reuse and to compare them.

4.5. Validation

After the plugin was tested on the case study project successfully and results were obtained, a tool demonstration session was held with several experts in the field of sustainability. The session was in an unstructured interview manner and no official meeting notes were documented. However, the key feedback and suggestions from the experts are explained in this section. A list of attendees of this demo session can be found in Appendix 7.

The experts liked the fact that CECC tool can be used in preliminary assessments where the design is still under development but the information is not that detailed yet. Most of the time, the problem with such assessments is that they are conducted when everything is much more certain, with specific materials selected from specific suppliers with their related EPDs. However, CECC tool can be used when such specific information is not yet available, to already eliminate some of the alternatives and reduce choices. Also, with this approach they can test more options. Then, in a more advanced stage of design, more precise assessments can be made for the last few choices by switching to other software which makes use of EPDs or such detailed data. This will increase efficiency and ultimately save them time.

Another point they found useful about CECC tool is that it does not require expertise from the user. It is easy to use, architects or engineers do not have to map materials one by one in the popup window and that it shows three important values (embodied carbon, cost and MCI) together in the same window which would not be the case with other software.

The experts acknowledged that the CECC tool has limited functionalities. In the future they would like to have a column on the results table where they can see the building element types (ex. Floor or Wall). At the moment in order for users to understand which element is which type (if it is a wall or a floor) they have to read the element name and see the abbreviation of the type from the name. This makes it less clear and harder to reach that information for the users. Another functionality they would like to have is to filter the results according to the building element types. For example, filtering the results only for the floors or only for the walls etc. They also want the

tool to be able to perform assessments on building elements other than just walls or floors so the element types included in the CECC tool assessments should be further extended.

4.6. Conclusion of Tooling and Case Study

The results in the previous section show that the developed assessment tool works as a proof of concept. With this tool a preliminary test was made by checking the effects of changing only one building element type in a BIM model. During the process a very limited database (CSV file) was used. Though, in the end, the plugin is able to retrieve data from a BIM model about materials and their quantities, match them with the data from a pre-defined database and calculate the embodied carbon, MCI and costs for each building element in the design. The plugin is also able to show the totals for embodied carbon and costs, relative percentages of floor elements to wall elements for these two categories and the percentages of future scenarios of wall and floor elements in terms of recycling, reuse or landfill. It also shows the MCI scores of each floor and wall elements. As previously mentioned in Chapter 4.4 "Results", an interesting point here to mention is that the results for all MCI are the same for the same type of product regardless of the differences in their sizes/masses. This is because the calculation method is taking proportions into account. A detailed explanation on how these calculations were made can be found in Appendix 6.

Regarding the results obtained from the case study project, it can be concluded that while "kanaalplaatvloer" is a better option from the costs and environmental impacts perspective, "breedplaatvloer" option is slightly better in terms of circularity potential. Therefore, the choice from these two options can be made according to the project ambitions and client requirements.

In the example project at hand, the client was more inclined towards a cost-effective project while trying to achieve the highest sustainability possible without any explicit circularity ambitions. As explained during Chapter 4.1 "Case Study" what "highest" or "maximum" sustainability refers to is not clear with the existing methods because there is not any standardized benchmark/limit. The ideal solution would be to have these limits on an international level so that the reference points would be very clear. The best practice that can be done at the moment is to compare different options and see the better performing option relatively.

Since "kanaalplaatvloer" option has less embodied carbon than the "breedplaatvloer", a higher degree of sustainability can be achieved by choosing "kanaalplaatvloer". It also costs less than the "breedplaatvloer" option so it is in line with the client requirements. Therefore, it is appropriate to say that "kanaalplaatvloer" should be selected when looked at the results obtained from the plugin assessments while considering the project ambitions.

The added value of this tool is that it enables architects and engineers to perform calculations for embodied carbon, MCI and costs for building elements in an easy way while working on their designs without leaving the BIM environment they are using. At the end of the day, the main goal is to stimulate architects and engineers to make sustainable design choices. This can be achieved

by incorporating environmental, cost and circularity assessments as early in the design process as possible, which is currently not the case because at the moment, the assessment tools for embodied carbon, MCI and cost calculations are often separate so the users cannot access these information in a single environment all at once. In this situation, a set of assessments has to be conducted separately and then combined manually to reach the desired results. Also, with the existing tools and software, each element and material have to be mapped one by one in different environments, which causes much time and energy while leaving the design environment to see the results. This creates a problem for the users' workflows as they cannot iterate their design and see the changes on the results fast enough. With the proposed tool, these drawbacks are eliminated as the assessments related to embodied carbon from an LCA perspective, manufacturing and construction costs from an LCC perspective and MCI from a circularity perspective are conducted simultaneously in the same single environment. The users do not have to leave their design software (Revit) so that they can change their design and perform another assessment with a single click, resulting in a much more efficient workflow, ease of use and reduced time.

5. Conclusion

After the CECC tool is developed, tested with a case study project and results are collected, this chapter finally provides a conclusion for this research. The primary objective of this research was to approach circularity, environmental impacts and financial aspects of a project in the AEC industry in a holistic manner and develop a framework and a tool to assess them during the design development phase. In order to achieve this objective, the following main research question of this study was answered:

> *"How can the integration of circularity, cost and environmental impact aspects of a design with BIM enable an automated combined assessment process and support architects and engineers in their decision-making process during the design development stage?"*

This chapter responds to this main research question by providing answers to individual sub-questions related to it. In addition to these answers, scientific contribution of this research is discussed in this chapter. Limitations of the research are identified and recommendations are provided for future research.

5.1. Research questions

SQ 1: What kind of data is needed to assess
1.a) environmental impacts of a design?
1.b) financial impacts of a design?
1.c) circularity scores of a design?

For the environmental impact assessments, data related to LCA are needed. These data include the material composition of the products (Bill of Materials), material quantities (Bill of Quantities), lifespan of the materials and impact indicator values per functional unit for each environmental impact category, including global warming, acidification, eutrophication, ozone depletion, abiotic depletion, smog formation, human toxicity, terrestrial ecotoxicity, marine aquatic ecotoxicity and freshwater aquatic ecotoxicity potentials. Number of these impact categories to be taken into consideration can be decreased according to the desired LCA scope.

To calculate the financial impacts of designs, LCC data are needed. Similar to environment impact assessment, the material composition of the products (BoM) and quantities (BoQ) should be known. In addition to these, costs per functional units related to acquisition and ownership, investment, construction, operation, refurbishing and replacement, maintenance and repair, end of life, dismantling, demolition, disposal and residual value of buildings and their components are needed. The number of cost categories can be reduced according to the LCC assessment scope.

For obtaining circularity scores, MCI method is used. MCI requires data related to the material composition of the products (BoM) and quantities (BoQ), especially masses of the materials. The lifetime of the product also becomes an important criterion. Industry average lifetime and actual lifetime of the product must be known to calculate the use factor of a product. Mass of the virgin materials and mass of the waste materials when the product is being produced is also critical; therefore, these data should be accessible for the selected products.

SQ 2: What are the benefits of combining these three aspects?

There is a need in the AEC industry to combine LCA, LCC and MCI. Currently, there are several different software and tools to assess circularity, environmental and financial impacts of projects separately but none of them takes all three into account at the same time. Since the solutions are scattered across multiple platforms and solutions, it makes the process of assessment and evaluation complicated and time consuming. The architects and engineers working on their design proposals cannot conduct these assessments easily to test how well their designs perform on each aspect. This situation, most of the time, causes these assessments to be made at the end of the design process when everything is already decided. The possibility of making changes and design iterations decreases significantly. When these three aspects are considered together such obstacles can be overcome and designs that are more resource conscious and environmentally friendly can be reached.

Another good point to mention here is that circular does not always mean sustainable, as explained previously in detail in Chapter 2.3 "Circular Economy" (Haupt & Hellweg, 2019; Lonca & Raufflet, 2020; Blum et al., 2020). Currently there is some confusion in the industry about these terms. A holistic approach on all these three aspects can aid to clarify this confusion. Looking at the results of an MCI and LCA of a product side by side can show that something that scores high on circularity level can have a higher environmental impact than something that scores less (and vice versa).

Sometimes, there needs to be an optimum solution where compromises are made. For example, an option can be scoring high on circularity potential, and it can also have very low embodied carbon, however the costs of implementing that option can be higher than the others. However, this cost can be then reduced via multiple life cycle possibilities that comes with the circularity potential. This, again, shows the importance of understanding the consequences of choices made during a design development stage since the architects and engineers can look at all the possibilities and decide on the most feasible option by checking the outcomes according to the parameters of circularity, sustainability and financial consequences.

SQ 3: How can these aspects be combined and what will the framework look like?

Combining circularity, environmental impacts and costs is a complicated process. There are two existing frameworks which targeted this ambition. One of them is the European Level(s) framework and the other one is from Platform CB'23.

In this research a new framework is established, benefitting from the existing research and frameworks. This is because although the Level(s) framework is a comprehensive one, it is quite detailed and complex, making the application and use of the framework difficult. It has 18 different user manuals in pdf format to explain how the framework should be used and what its contents are. As for Platform CB'23 framework, it is much more limited in terms of scope when compared to Level(s). Its focus is more on circularity, therefore, the idea of keeping a balanced emphasis on environmental, financial and circularity assessments is not strongly pronounced and can be lost. In addition to these reasons, both of these frameworks are under development at the time of this research and they are not yet completed. At the end, it is decided that it is better to propose a simpler and more concise framework for the purposes of this research. This new framework is developed by benefitting from the ideas presented in both Level(s) and Platform CB'23 frameworks. The proposed framework for this study is depicted in Figure 46.
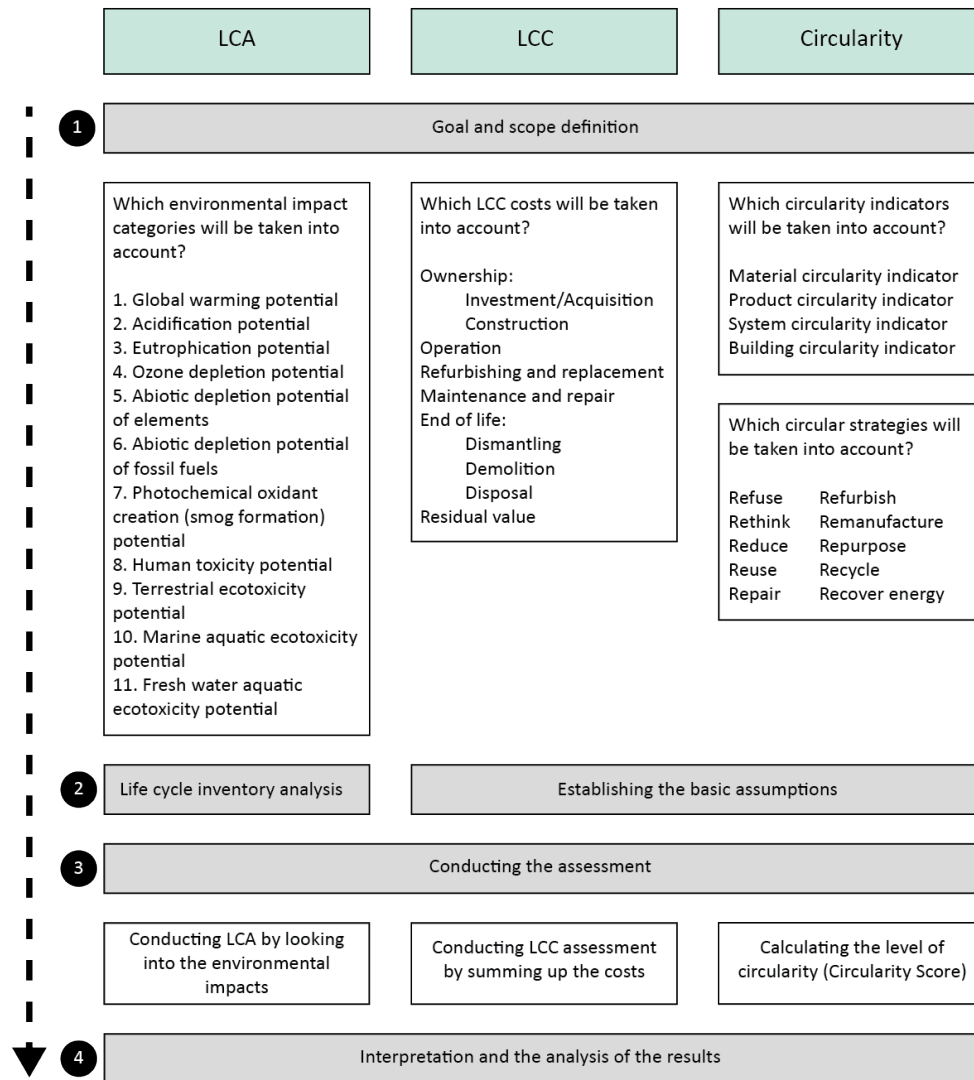
Figure 46: Proposed assessment framework

The framework proposed in this research consists of four main steps, indicated by grey boxes in the figure. The first, third and the last steps are all the same for each assessment type. First step is always "goal and scope definition", third step is always "conducting the assessment" and the last step is always "interpretation and the analysis of the results". The only difference occurs in the second step. For LCA it is "life cycle inventory analysis" and for both LCC and circularity the second step is "establishing the basic assumptions". The assumptions to be established during an LCC include choosing a consistent method of calculation, a suitable study period, deciding on an inflation and a discount rate. The assumptions to be established for circularity include deciding on a lifespan and choosing a coherent strategy.

According to this framework, the most important step is the first one where the goal and scope definition takes place for each assessment. The questions and things to consider in this step are written down inside the white boxes underneath the first step in Figure 46 above. The framework

can be applied at a material level, product level, system level or a whole building level, so it is versatile. The level for framework application is typically decided during the goal and scope definition phase.

Having this framework will benefit the architects and engineers who are the potential users of it since the framework explicitly shows the steps for the whole process, makes the assessments more systematic and draws the attention of the users to the points which are important to consider.

SQ 4: How can this combined assessment method be incorporated in a day to day working life of an architect/engineer?

A good way to incorporate this combined assessment method in a day to day working life of an architect or an engineer is by creating a software or an application for them. Through such an app, the process can be automated and made much easier for them. For this reason, a plugin for Revit was created. This plugin was named CECC tool which stands for Circularity, Embodied Carbon and Costs Tool. The functional requirements for this plugin are determined according to the MoSCoW method described in Chapter 4.2.2 "Functional Requirements". These requirements are listed in Table 6.

Table 6: Functional requirements of the CECC tool

MoSCoW Category	Requirements
Must Haves	Must be able to process data stored in a Revit file.
	Must be able to process data stored in an external data file.
	Must be able to link the data from both sources.
	Must be able to perform calculations with the linked data.
	Must be able to show results related to at least one aspect of LCA (embodied carbon), one aspect of LCC (manufacturing and construction costs) and one aspect of circularity (MCI) per building element.
Should Haves	Should have a graphical user interface.
	Should be able to display results in both tabular and graphical data formats.
	Should have an option to export the results to save externally.
Could Haves	Could have filtering options for the users to see results related to only embodied carbon, only MCI or only costs.
Won't Haves	Won't show results related to all aspects of LCA, LCC or circularity.
	Won't be compatible with web-based databases.
	Won't be able to color override onto 3D BIM models.

With such a plugin, the users can obtain the assessment results inside their design environment without any need to stop their design process for a while for conducting the assessments for embodied carbon, costs and MCI separately in different environments. Similarly, after obtaining results, there is no need to go back to design environment to make the necessary changes. In other words, with the CECC tool, material changes and new assessments can be done iteratively without leaving Revit. This creates a much more efficient workflow and reduces the time spent on such assessments.

SQ 5: What kind of output is needed after the assessment of the designs?

The needed output is determined according to expert views gathered from the interviews conducted with them for the purpose of checking functional requirements of the tool. After the assessment, there needs to be at least three parameters showing up the results for circularity, environmental impacts and costs. These results can be obtained per building element and/or for the whole design. The CECC tool conducts the assessment for each building element; therefore, related information for each product is also needed to identify them. As a result, the outputs needed after the assessment include name, unique ID, associated level ID of the product (these three are for identification purposes), MCI for circularity, embodied carbon for environmental impacts and manufacturing and construction costs per product. Mass, volume and area of each product are also useful to know; therefore, they are added to the results table. At the end of the table, there are cumulative totals for the embodied carbon and costs of all the products that are being assessed in the design. A cumulative total for the MCI of the whole products under assessment can also be shown. However, this is not included in the current plugin as MCIs of different products are sufficient to make a comparison and a decision between options.

In addition to these tabular data, some graphical output is also needed to better understand what these quantitative results actually mean. There are three donut charts for this purpose. The first is a donut chart showing the relative contribution percentages of building element types in terms of embodied carbon and the second showing the relative contribution percentages of the same building element types in terms of costs. The last donut chart depicts the future scenario of materials. This chart shows the mass percentage of walls and floors for different end of life scenarios including reuse, recycle and waste. These percentages are relative to the total mass of all materials which are being assessed.

SQ 6: How will the architects and engineers benefit from the output?

The output obtained by using the developed plugin helps the architects and engineers to get results for embodied carbon, costs and MCI of building elements. By using this output, they get insights about their design choices during the design development stage and understand the impacts of their decisions. They can change the materials they have selected, conduct another assessment, get new results and compare them. The generation of output is accomplished in an easy way with the help of the developed CECC tool. The output is obtained inside Revit where the design is being developed so that the material changes and new assessments can be done iteratively without leaving the design environment. This enhances the efficiency and improves the

workflow. The acquired results, then, can be compared, and the outputs will guide the architects and engineers to make more informed decisions in the end. The users can pick the best alternative according to the project ambitions by looking at the output. These benefits were validated during the tool demonstration session with experts.

5.2. Scientific contribution

There are two main scientific contributions of this research. One of them is the theoretical contribution. The research establishes a clear distinction between circularity and sustainability, making the reader aware of the fact that they do not necessarily mean the same thing but rather they are complementary to each other. In addition to that, it improves the understanding of circular economy, as it is a relatively new concept, and how it relates to the built environment and AEC sector. Finally, better established and more standardized concepts such as LCA, LCC and BIM are also explained in this research. How these elements can come together with circularity assessment and which steps should be taken during the combined assessment approach are made more concrete with a proposed framework.

The second contribution is about the practical side. A circularity, embodied carbon and costs (CECC) plugin for Autodesk Revit is developed in this research to implement the proposed framework into a functional product. This plugin acts as a proof of concept and incorporates some of the most prominent components of LCA, LCC and circularity indicators. With this plugin, the readers are provided with the added value of the automation of the proposed combined assessment method within a single design environment. CECC plugin fills the current gap where existing software and tools for LCA, LCC and circularity assessments are data intensive, complicated, taking too much time, requiring expertise and most importantly not incorporating all three aspects.

5.3. Limitations and recommendations

Even though the research has significant contributions, there are several limitations which can be listed as follows:

Limited scope of the research: The research at hand takes into account only the two pillars of sustainability out of the three. It considers economic and environmental sustainability whereas the social sustainability aspect is not in the scope of this research. In the future, the research can be extended to include social sustainability as well to accommodate all three pillars.

Limitations of the tool: The developed CECC tool in this research has limited functionalities as it acts like a proof of concept and focuses only on the embodied carbon from an LCA perspective, manufacturing and construction costs from an LCC perspective and MCI from a circularity perspective. The proposed framework in this research is more comprehensive and it is recommended that the plugin is further extended to accommodate all the environmental impact

categories, circularity indicators and cost components on different levels. In addition, the total MCI score of all the assessed building elements can be provided at the end of the results table. Currently, this is not included in the plugin. The current subject of assessment components are only wall and floor elements from a structural model. The assessment components can be further extended to include all building elements to get an overview of the whole project. Moreover, in the current results window, the element floor IDs are presented to the user. Instead of the floor IDs, the names of the floors (ex: Level 1, Level 2 etc.) can be presented to make it more understandable for the users. Such an attempt was undertaken during the project but because of technical difficulties it could not be achieved. Therefore, this functionality was excluded. Also, one of the comments made during the expert session was that the building element types (ex. Floor or Wall) can be extracted as information and be presented in the results window in an extra column next to the names of the elements. Such an extra column will again aid the users to distinguish which element belongs to which type in a much easier way rather than reading the names and understanding the element types from the names. Another functionality that was requested by the experts is to add filtering options to the tool to filter the results based on building element types. For example, appropriate buttons may only show the results for the floors separate from the walls etc.

Single software environment restriction: The developed CECC tool is only functioning inside Autodesk Revit. It is a plugin specifically designed for Revit users and it makes use of the Revit API. This acts as both an advantage, as the users can benefit from the tool without having to leave their design environment with some simple clicks of buttons, and a disadvantage, as the chosen design environment must be Revit. For the specific purpose of this research, Revit was a conscious choice as one of the main goals was to facilitate the assessment process and eliminate the data exports between different software. However, in another research, a similar tool can be created by using open standards, so that it can be platform independent.

Data being static: The data used for the developed CECC tool is static and it is stored in a CSV file. This data holds the necessary information to calculate the embodied carbon and costs per m2 of a product and MCI per product. This file also contains the relevant NL-SfB code for each element. As this is a CSV file, the data inside the file was manually generated and it is a static source of data. In a future research, a tool can be developed to extract the necessary data from the web so that the data coming in for the calculations can be dynamic and get automatically updated as the web database gets updated and there will not be a need to create a manual data file. Another interesting idea would be to connect the plugin to a material bank so that designers can search for a reusable existing material to achieve better circularity performance. Additionally, the results obtained are shown as tabular and graphical output in the current tool. To make the results more visually informative and intelligible for the users, a color override can be provided on the building elements in Revit model. This was requested during the expert session and having this functionality will make the obtained data more dynamic for the users. Similar color override approaches in 3D models are available in the studies of Zhai (2020) and Van Gemert (2019).

Lack of providing suggestions for users: The CECC tool is able to make calculations and represent the relevant results. However, the tool itself does not provide explicit suggestions to its users. The users have to interpret the results themselves and come to conclusions according to their interpretations. Therefore, in the future, the tool can be extended to accommodate better product and/or material option suggestions automatically according to the calculated results. For example, it can scan its existing product database, find a better performing product alternative, and suggest the user to replace the existing product that performs worse with this new option. It can also provide the users with suggested materials with lower embodied carbon or higher circularity scores etc.

Lack of validation for the tool from multiple users: The developed CECC tool is not tested by multiple users. This makes the validation of the tool very limited as it is important to get as many users' feedback as possible to identify possible drawbacks. The tool was mainly designed and tested from the author's perspective. However, there were inputs from other potential users and they gave their feedback based on the tool demo they had witnessed through online meetings. To extend this research, more organized and systematic user tests are recommended to be conducted and according to the feedback gained, key weak points of the plugin can be identified and the tool can be improved for a better user experience.

References

Akinade, O. O., Oyedele, L. O., Bilal, M., Ajayi, S. O., Owolabi, H. A., Alaka, H. A., & Bello, S. A. (2015). Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources, Conservation and Recycling*, *105*, 167–176. https://doi.org/10.1016/j.resconrec.2015.10.018

Akinade, O. O., Oyedele, L. O., Omoteso, K., Ajayi, S. O., Bilal, M., Owolabi, H. A., Alaka, H. A., Ayris, L., & Henry Looney, J. (2017). BIM-based deconstruction tool: Towards essential functionalities. *International Journal of Sustainable Built Environment*, *6*(1), 260–271. https://doi.org/10.1016/j.ijsbe.2017.01.002

Arora, M., Raspall, F., Cheah, L., & Silva, A. (2019). Residential building material stocks and component-level circularity: The case of Singapore. *Journal of Cleaner Production*, *216*, 239–248. https://doi.org/10.1016/j.jclepro.2019.01.199

Bertin, I., Mesnil, R., Jaeger, J. M., Feraille, A., & Le Roy, R. (2020). A BIM-Based Framework and Databank for Reusing Load-Bearing Structural Elements. *Sustainability*, *12*(8), 3147. https://doi.org/10.3390/su12083147

BIM Loket. (n.d.). *BIM Loket - NL-SfB*. Retrieved June 30, 2021, from https://www.bimloket.nl/p/107/NL-SfB

Blessing, L. T. M., & Chakrabarti, A. (2009). DRM, a Design Research Methodology. Springer London Ltd. https://doi.org/10.1007/978-1-84882-587-1

Blum, N., Haupt, M., & Bening, C. (2020). Why "Circular" doesn't always mean "Sustainable." *Resources, Conservation and Recycling*, *162*, 105042. https://doi.org/10.1016/j.resconrec.2020.105042

Bocken, N., Miller, K., & Evans, S. (2016, June 16). *Assessing the environmental impact of new Circular business models*. ResearchGate. https://www.researchgate.net/publication/305264490_Assessing_the_environmental_impact_of_new_Circular_business_models

Breene, K. (2016, May 4). *Can the circular economy transform the world's number one consumer of raw materials?* World Economic Forum. https://www.weforum.org/agenda/2016/05/can-the-circular-economy-transform-the-world-s-number-one-consumer-of-raw-materials/

Carbon Leadership Forum. (2019, June). *Life Cycle Assessment of Buildings: A Practice Guide*. https://carbonleadershipforum.org/download/1762

Cheshire, D. (2019). Circular economy principles for buildings. *Building Revolutions*, 31–34. https://doi.org/10.4324/9780429346712-6

Cottafava, D., & Ritzen, M. (2021). Circularity indicator for residential buildings: Addressing the gap between embodied impacts and design aspects. *Resources, Conservation and Recycling*, *164*, 105120. https://doi.org/10.1016/j.resconrec.2020.105120

Cramer, J. (2020, September 28). *The market does not organise itself to you*. Amsterdam Economic Board. https://amsterdameconomicboard.com/en/news/the-market-does-not-organize-itself-to-you

Create a .addin manifest file. (2014, April 18). Revit | Autodesk Knowledge Network. https://knowledge.autodesk.com/support/revit/learn-explore/caas/CloudHelp/cloudhelp/2014/ENU/Revit/files/GUID-7577712B-B09F-4585-BE0C-FF16A5078D29-htm.html

Denyer, D., Tranfield, D., & van Aken, J. E. (2008). Developing Design Propositions through Research Synthesis. Organization Studies, 29(3), 393–413. https://doi.org/10.1177/0170840607088020

Dodd, N., Donatello, S., & Cordella, M. (2021a, January). *Level(s) User Manual 1: Introduction to the Level(s) common framework*. European Commission. http://susproc.jrc.ec.europa.eu/product-bureau//sites/default/files/2021-01/UM1_Introduction_to_Level(s)_v1.1_27pp.pdf

Dodd, N., Donatello, S., & Cordella, M. (2021b, January). *Level(s) User manual 2: Setting up a project to use the Level(s) common framework*. European Commission. http://susproc.jrc.ec.europa.eu/product-bureau//sites/default/files/2021-01/UM2_Setting_up_a_project_to_use_Level(s)_v1.1_26pp.pdf

Eberhardt, L., Birgisdottir, H., & Birkved, M. (2019). Comparing life cycle assessment modelling of linear vs. circular building components. *IOP Conference Series: Earth and Environmental Science*, *225*, 012039. https://doi.org/10.1088/1755-1315/225/1/012039

Ellen MacArthur Foundation. (2017). *The Circular Economy In Detail*. https://archive.ellenmacarthurfoundation.org/explore/the-circular-economy-in-detail

Ellen MacArthur Foundation & Granta Design. (2019). *Circularity Indicators An Approach to Measuring Circularity - Methodology*. https://emf.thirdlight.com/link/3jtevhlkbukz-9of4s4/@/preview/1?o

Fregonara, E., Giordano, R., Ferrando, D. G., & Pattono, S. (2017). Economic-Environmental Indicators to Support Investment Decisions: A Focus on the Buildings' End-of-Life Stage. *Buildings*, *7*(4), 65. https://doi.org/10.3390/buildings7030065

Gervasio, H., & Dimova, S. (2018). *Model for Life Cycle Assessment (LCA) of buildings* (Rep.). doi:10.2760/10016

Gervasio, H., Dimova, S., & Pinto, A. (2018). Benchmarking the Life-Cycle Environmental Performance of Buildings. *Sustainability*, *10*(5), 1454. https://doi.org/10.3390/su10051454

Giama, E., Mamaloukakis, M., & Papadopoulos, A. M. (2019). Circularity in production process as a tool to reduce energy, environmental impacts and operational cost: The case of insulation materials. *2019 4th International Conference on Smart and Sustainable Technologies (SpliTech)*. Published. https://doi.org/10.23919/splitech.2019.8783007

Glaumann, M., Malmqvist, T., Peuportier, B., Wetzel, C., Scarpellini, S., Zabalza, I., Díaz de Garayo, S., Staller, H., Krigsvoll, G., Stoykova, E., Horváth, S., Szalay, Z., & Degiovanni, V. (2010, March). *Guidelines for LCA Calculations in Early Design Phases*. http://kth.diva-portal.org/smash/get/diva2:478408/FULLTEXT01.pdf

Government of the Netherlands. (2016, September). *A Circular Economy in the Netherlands by 2050*. https://www.government.nl/binaries/government/documents/policy-notes/2016/09/14/a-circular-economy-in-the-netherlands-by-2050/17037+Circulaire+Economie_EN.PDF

Harris, S., Martin, M., & Diener, D. (2021). Circularity for circularity's sake? Scoping review of assessment methods for environmental performance in the circular economy. *Sustainable Production and Consumption*, *26*, 172–186. https://doi.org/10.1016/j.spc.2020.09.018

Haupt, M., & Hellweg, S. (2019). Measuring the environmental sustainability of a circular economy. *Environmental and Sustainability Indicators, 1-2*, 100005. doi:10.1016/j.indic.2019.100005

Kamp Albæk, J., Shahbazi, S., McAloone, T. C., & Pigosso, D. C. A. (2020). Circularity Evaluation of Alternative Concepts During Early Product Design and Development. Sustainability, 12(22), 9353. https://doi.org/10.3390/su12229353

Kravari, M. (2017). *Environmental impact assessment of building materials in BIM models* (Unpublished master's thesis). TU Eindhoven. Retrieved 2020, from https://www.ofcoursecme.nl/?mdocs-file=3806

Lavagna, M., Dalla Valle, A., Giorgi, S., Caroli, T., & Campioli, A. (2020). Circular Processes and Life Cycle Design for Sustainable Buildings. *New Metropolitan Perspectives*, 1448–1457. https://doi.org/10.1007/978-3-030-48279-4_135

Lonca, G., & Raufflet, E. B. (2020, July 2). *Is material circularity enough to achieve environmental sustainability? Linking circular economy and. . .* ResearchGate. https://www.researchgate.net/publication/342748115_Is_material_circularity_enough_to_achieve_environmental_sustainability_Linking_circular_economy_and_planetary_boundaries_narratives

Lu, K., Jiang, X., Yu, J., Tam, V. W., & Skitmore, M. (2021). Integration of life cycle assessment and life cycle cost using building information modeling: A critical review. *Journal of Cleaner Production*, *285*, 125438. https://doi.org/10.1016/j.jclepro.2020.125438

MacLeamy, P. (2004). *The Macleamy Curve*. Researchgate. https://www.researchgate.net/figure/The-Macleamy-Curve-2004_fig3_266054953

Marzouk, M., Abdelkader, E. M., & Al-Gahtani, K. (2017). Building information modeling-based model for calculating direct and indirect emissions in construction projects. *Journal of Cleaner Production*, *152*, 351–363. https://doi.org/10.1016/j.jclepro.2017.03.138

Ministerie van Infrastructuur en Waterstaat, Ministerie van Economische Zaken en Klimaat, Ministerie van Binnenlandse Zaken en Koninkrijksrela;es, Ministerie van Landbouw, Natuur en Voedselkwaliteit, & Ministerie van Buitenlandse Handel en Ontwikkelingssamenwerking. (2019, February). *Uitvoeringsprogramma Circulaire Economie 2019-2023*. Retrieved from https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2019/02/08/uitvoeringsprogramma-2019-2023/ uitvoeringsprogramma-2019-2023.pdf

MoSCoW Prioritization. (n.d.). ProductPlan. Retrieved July 25, 2021, from https://www.productplan.com/glossary/moscow-prioritization/

Platform CB'23. (2020, July). *Measuring circularity Working agreements for circular construction*. https://platformcb23.nl/images/downloads/Platform_CB23_Guide_Measuring_circularity_2.0.pdf

Predan, B. (2020). Circular Design in Design Education: A Case Study on the Use of Paper in Interior Design. *The International Journal of Design Education*, *14*(4), 47–59. https://doi.org/10.18848/2325-128x/cgp/v14i04/47-59

Raposo, C., Rodrigues, F., & Rodrigues, H. (2019). BIM-based LCA assessment of seismic strengthening solutions for reinforced concrete precast industrial buildings. *Innovative Infrastructure Solutions*, *4*(1). https://doi.org/10.1007/s41062-019-0239-7

Röck, M., Hollberg, A., Habert, G., & Passer, A. (2018). LCA and BIM: Integrated Assessment and Visualization of Building Elements' Embodied Impacts for Design Guidance in Early Stages. *Procedia CIRP*, *69*, 218–223. https://doi.org/10.1016/j.procir.2017.11.087

Sarja, A. (2006). *Predictive and Optimised Life Cycle Management: Buildings and Infrastructure* (1st ed.). Routledge.

The Agile Business Consortium. (n.d.). *Chapter 10: MoSCoW Prioritisation*. Agile Business Consortium. Retrieved July 25, 2021, from https://www.agilebusiness.org/page/ProjectFramework_10_MoSCoWPrioritisation

Tikkanen, S. (2019, October 23). Circular Economy in Construction - Experiences from Finland [Slides]. European Commission. https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupMeetingDoc&docid=35644

UN Environment. (2017). *Towards a zero-emission, efficient, and resilient buildings and construction sector: Global Status Report 2017*. https://www.worldgbc.org/sites/default/files/UNEP%20188_GABC_en%20%28web%29.pdf

Van Gemert, S. (2019). *MPG-ENVIE A BIM-based LCA application for embodied impact assessment during the early design stages* (Unpublished master's thesis). TU Eindhoven. Retrieved 2020, from https://pure.tue.nl/ws/portalfiles/portal/121931979/Gemert_v_1036326.pdf

Van Oeveren, C. (2020). *Integrating Building Information Modeling with Life-Cycle Assessment and Life-Cycle Costing* (Unpublished master's thesis). TU Eindhoven.

Verberne, J. (2016). *Building circularity indicators: An approach for measuring circularity of a building* (Unpublished master's thesis). TU Eindhoven.

Victor, L. (n.d.). *BIM Level of Development | LOD 100, 200, 300, 350, 400, 500*. United-BIM | BIM Services - Architectural, Structural, MEP-FP & 3D Rendering. Retrieved June 15, 2021, from https://www.united-bim.com/bim-level-of-development-lod-100-200-300-350-400-500/

Vliet, M. V. (2018). *Disassembling the steps towards building circularity: Redeveloping the building disassembly assessment method in the building circularity indicator* (Unpublished master's thesis). TU Eindhoven.

Wolf, C., Pomponi, F., & Moncaster, A. (2018, July 31). Fig. 4. Life cycles defined by EN 15978, adapted from [10]. Retrieved June, 2020, from https://www.researchgate.net/figure/Life-cycles-defined-by-EN-15978-adapted-from-10_fig3_313022090

World Business Council for Sustainable Development. (2020). *The Building System Carbon Framework*. https://www.wbcsd.org/contentwbc/download/9731/146973/1

Zhai, J. (2020). *BIM-based Building Circularity Assessment from the Early Design Stages* (Unpublished master's thesis). TU Eindhoven. Retrieved 2020, from https://www.ofcoursecme.nl/mdocs-posts/bim-based-building-circularity-assessment-from-the-early-design-stages/

Zorzi, I. (2020, May 26). *NL-SfB codering | Wat is het [Download Excel] | CAD & Company*. CAD & Company B.V. https://cadcompany.nl/nl-sfb/

Appendices

Appendix 1: Data obtained from NIBE

IN SITU BETONVLOER (DIKTE 300 MM)

Milieu-informatie

NIBE Milieuklasse:

2b

Schaduwkosten: € 8,59

Producteigenschappen:

Massa per FE	735,0	kg
Levensduur	75	jaar
Transportafstand naar fabriek	150	km

Afvalscenario:

Stort	1,1	%
Verbranding	0,0	%
Recycling	98,9	%
Hergebruik	0,0	%
Eigenprofiel	0,0	%

Omschrijving functionele eenheid

Een in het werk gestorte, 300 mm dikke, gewapende tunnelkistvloer (exclusief dekvloer). De grondstoffen voor de betonmortel zijn cement, zand, grind, metselwerkgranulaat, betongranulaat en water. De grondstoffen voor cement zijn kalksteen, poederkoolvliegas, hoogovenslak, gipsgesteente en klei. Voor 1 m² vloer is ca. 720 kg beton en 15 kg wapeningsstaal nodig.

Opvallende milieu-eigenschappen

Dit product valt in milieuklasse 2b en is daarmee milieutechnisch een goede keuze. Het product is 11,8 keer zo zwaar als het lichtste product in deze functionele eenheid, dit heeft een nadelige invloed op de milieueffecten veroorzaakt door transport. Het basisprofiel 019 Insitu Betonmortel C20/25, 0% granulaat veroorzaakt met 94,6% het grootste deel van de schaduwkosten en het basisprofiel 767pr - 767pr SBK Wapeningsstaal veroorzaakt 5,4% van de schaduwkosten.

De productiefase (A1-3) is verantwoordelijk voor 84,5% van de totale schaduwkosten gedurende de beschouwde periode van 75 jaar. Het transport naar de bouwplaats (A4) tijdens de constructiefase veroorzaakt 22% van de schaduwkosten. De constructie (A5) van het product veroorzaakt -0,1% van de schaduwkosten. In deze fase wordt het afval dat vrijkomt op de bouwplaats (o.a. verpakkingen en snijverlies) en processen die plaatsvinden bij constructie meegewogen. Er treden geen milieueffecten op die voortvloeien uit emissies naar lucht, bodem of water tijdens het gebruik (B1). Voor onderhoud (B2) treden geen milieueffecten op gedurende de beschouwde periode. Er vinden geen vervangingen (B3) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er vinden geen reparaties (B4) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er zijn geen schaduwkosten voor energieverbruik door het product (B6) om te kunnen functioneren in de beschouwde periode. Er zijn geen schaduwkosten voor waterverbruik door het product (B7) om te kunnen functioneren in de beschouwde periode. In de afvalfase van het product (C & D), exclusief het transport in deze fase (C2), worden -13,1% van de schaduwkosten veroorzaakt van wieg tot graf (bij recycling en re-use weer tot de wieg).Het transport in de afvalfase van het product (C2) veroorzaakt 6,7% van de schaduwkosten. De som van alle fases is 100%. Omdat er in de afvalfase een minwaarde behaald wordt, zijn de gesommeerde waarden van de andere fases meer dan 100%. Deze minwaarde wordt behaald doordat de recyclings-/hergebruikspotentie van het product in de afvalfase wordt toegerekend.

Milieucriteria

Emissies

br	broeikaseffect	1,09E+2	kg CO_2 eq
oz	ozonlaagaantasting	7,49E-6	kg CFC-11 eq
hu	humane toxiciteit	1,27E+1	kg 1,4 DB eq
aq	aquatische toxiciteit (zoet)	4,48E-1	kg 1,4 DB eq
aq	aquatische toxiciteit (zout)	1,76E+3	kg 1,4 DB eq
te	terrestische toxiciteit	1,34E-1	kg 1,4 DB eq
fo	fotochem. toxiciteit	2,35E-2	kg C_2H_4 eq
ve	verzuring	2,99E-1	kg SO_2 eq
eu	eutrofiëring (vermesting)	5,27E-2	kg PO_4 eq

Uitputting

ab	abiotische grondstoffen	1,10E-4	kg Sb eq
en	energiedragers	4,59E-1	kg Sb eq

Landgebruik

Hinder ten gevolge van

BREEDPLAATVLOER (DIKTE 230 MM)

Milieu-informatie

NIBE Milieuklasse:

2b

Schaduwkosten: **€ 9,01**

Producteigenschappen:

Massa per FE	579,4	kg
Levensduur	75	jaar
Transportafstand naar fabriek	150	km

Afvalscenario:

Stort	1,0	%
Verbranding	0,0	%
Recycling	98,5	%
Hergebruik	0,5	%
Eigenprofiel	0,0	%

Omschrijving functionele eenheid

Verdiepingsvloer van in het werk gestort beton (180 mm) op een geprefabriceerde bekistingsplaat (breedplaat, 50 mm). Dit is dus exclusief dekvloer . De cementmortel bestaat uit cement, zand en water. Het beton bestaat uit cement, zand, grind en water en de grondstoffen voor cement zijn kalksteen, poederkoolvliegas, hoogovenslak, gipsgesteente en klei. Voor 1 m² verdiepingsvloer is ca. 552 kg beton nodig en 27,4 kg wapeningsstaal.

Opvallende milieu-eigenschappen

Dit product valt in milieuklasse 2b en is daarmee milieutechnisch een goede keuze. Het product is 9,3 keer zo zwaar als het lichtste product in deze functionele eenheid, dit heeft een nadelige invloed op de milieueffecten veroorzaakt door transport. Het basisprofiel 019 Insitu Betonmortel C20/25, 0% granulaat veroorzaakt met 54,1% het grootste deel van de schaduwkosten, daarop volgen het basisprofiel 331 - middelzwaar constructiestaal (o.a. geleiderails), c2 met 26,8% en het basisprofiel NM0540 - Prefab beton; C45/55; 0% granulaat met 19,1% van de schaduwkosten.

De productiefase (A1-3) is verantwoordelijk voor 111,7% van de totale schaduwkosten gedurende de beschouwde periode van 75 jaar. Het transport naar de bouwplaats (A4) tijdens de constructiefase veroorzaakt 16,3% van de schaduwkosten. De constructie (A5) van het product veroorzaakt -1,2% van de schaduwkosten. In deze fase wordt het afval dat vrijkomt op de bouwplaats (o.a. verpakkingen en snijverlies) en processen die plaatsvinden bij constructie meegewogen. Er treden geen milieueffecten op die voortvloeien uit emissies naar lucht, bodem of water tijdens het gebruik (B1). Voor onderhoud (B2) treden geen milieueffecten op gedurende de beschouwde periode. Er vinden geen vervangingen (B3) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er vinden geen reparaties (B4) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er zijn geen schaduwkosten voor energieverbruik door het product (B6) om te kunnen functioneren in de beschouwde periode. Er zijn geen schaduwkosten voor waterverbruik door het product (B7) om te kunnen functioneren in de beschouwde periode. In de afvalfase van het product (C & D), exclusief het transport in deze fase (C2), worden -31,6% van de schaduwkosten veroorzaakt van wieg tot graf (bij recycling en re-use weer tot de wieg).Het transport in de afvalfase van het product (C2) veroorzaakt 4,8% van de schaduwkosten. De som van alle fases is 100%. Omdat er in de afvalfase een minwaarde behaald wordt, zijn de gesommeerde waarden van de andere fases meer dan 100%. Deze minwaarde wordt behaald doordat de recyclings-/hergebruikspotentie van het product in de afvalfase wordt toegerekend.

Milieucriteria

Emissies

br	broeikaseffect	1,06E+2	kg CO_2 eq
oz	ozonlaagaantasting	6,67E-6	kg CFC-11 eq
hu	humane toxiciteit	1,64E+1	kg 1,4 DB eq
aq	aquatische toxiciteit (zoet)	4,18E-1	kg 1,4 DB eq
aq	aquatische toxiciteit (zout)	1,86E+3	kg 1,4 DB eq
te	terrestische toxiciteit	1,32E-1	kg 1,4 DB eq
fo	fotochem. toxiciteit	3,27E-2	kg C_2H_4 eq
ve	verzuring	3,47E-1	kg SO_2 eq
eu	eutrofiëring (vermesting)	5,31E-2	kg PO_4 eq

Uitputting

ab	abiotische grondstoffen	8,24E-5	kg Sb eq
en	energiedragers	4,81E-1	kg Sb eq

Landgebruik

Hinder ten gevolge van

KANAALPLAATVLOER INCL DRUKLAAG (DIKTE 260 MM)

Milieu-informatie

NIBE Milieuklasse:

2a

Schaduwkosten: € 7,47

Producteigenschappen:

Massa per FE	527,8	kg
Levensduur	75	jaar
Transportafstand naar fabriek	150	km

Afvalscenario:

Stort	3,6	%
Verbranding	0,0	%
Recycling	96,4	%
Hergebruik	0,1	%
Eigenprofiel	0,0	%

Omschrijving functionele eenheid

Verdiepingsvloer van geprefabriceerde kanaalplaten (260mm), waarbij de naden zijn gevuld met een cementmortel en de vloer voorzien is van een druklaag. De betonnen platen hebben holle kanalen en voorgespannen wapening. Voor 1 m² vloer is ca. 376 kg beton, 7,7 kg wapeningsstaal, 144 kg cementmortel nodig.

Opvallende milieu-eigenschappen

Dit product valt in milieuklasse 2a en is daarmee milieutechnisch een goede keuze. Het product is 8,5 keer zo zwaar als het lichtste product in deze functionele eenheid, dit heeft een nadelige invloed op de milieueffecten veroorzaakt door transport. Het basisprofiel NM0540 - Prefab beton; C45/55; 0% granulaat veroorzaakt met 72,3% het grootste deel van de schaduwkosten, daarop volgen het basisprofiel 019 Insitu Betonmortel C20/25, 0% granulaat met 22,1% en het basisprofiel 331 - middelzwaar constructiestaal (o.a. geleiderails), c2 met 3,5% van de schaduwkosten.

De productiefase (A1-3) is verantwoordelijk voor 86,9% van de totale schaduwkosten gedurende de beschouwde periode van 75 jaar. Het transport naar de bouwplaats (A4) tijdens de constructiefase veroorzaakt 17,6% van de schaduwkosten. De constructie (A5) van het product veroorzaakt -0,2% van de schaduwkosten. In deze fase wordt het afval dat vrijkomt op de bouwplaats (o.a. verpakkingen en snijverlies) en processen die plaatsvinden bij constructie meegewogen. Er treden geen milieueffecten op die voortvloeien uit emissies naar lucht, bodem of water tijdens het gebruik (B1). Voor onderhoud (B2) treden geen milieueffecten op gedurende de beschouwde periode. Er vinden geen vervangingen (B3) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er vinden geen reparaties (B4) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er zijn geen schaduwkosten voor energieverbruik door het product (B6) om te kunnen functioneren in de beschouwde periode. Er zijn geen schaduwkosten voor waterverbruik door het product (B7) om te kunnen functioneren in de beschouwde periode. In de afvalfase van het product (C & D), exclusief het transport in deze fase (C2), worden -10% van de schaduwkosten veroorzaakt van wieg tot graf (bij recycling en re-use weer tot de wieg).Het transport in de afvalfase van het product (C2) veroorzaakt 5,7% van de schaduwkosten. De som van alle fases is 100%. Omdat er in de afvalfase een minwaarde behaald wordt, zijn de gesommeerde waarden van de andere fases meer dan 100%. Deze minwaarde wordt behaald doordat de recyclings-/hergebruikspotentie van het product in de afvalfase wordt toegerekend.

* Prefab beton wordt veelal vervaardigd met CEM I als bindmiddel, i.v.m. de benodigde (snelle) droogtijd. Het van klinker gemaakte CEM I heeft een hogere milieulast dan andere CEM soorten.

Milieucriteria

Emissies

br	broeikaseffect	9,52E+1	kg CO_2 eq
oz	ozonlaagaantasting	6,00E-6	kg CFC-11 eq
hu	humane toxiciteit	1,17E+1	kg 1,4 DB eq
aq	aquatische toxiciteit (zoet)	3,42E-1	kg 1,4 DB eq
aq	aquatische toxiciteit (zout)	1,39E+3	kg 1,4 DB eq
te	terrestische toxiciteit	1,21E-1	kg 1,4 DB eq
fo	fotochem. toxiciteit	2,18E-2	kg C_2H_4 eq
ve	verzuring	2,51E-1	kg SO_2 eq
eu	eutrofiëring (vermesting)	4,34E-2	kg PO_4 eq

Uitputting

ab	abiotische grondstoffen	7,92E-5	kg Sb eq
en	energiedragers	3,51E-1	kg Sb eq

Landgebruik

Hinder ten gevolge van

BETON; GEWAPEND - GLASWOL - BETONSTEEN METSELWERK

Milieu-informatie

NIBE Milieuklasse:

2c

Schaduwkosten: € 12,27

Producteigenschappen:

Massa per FE	677,0	kg
Levensduur	75	jaar
Rc-waarde	4.500	m?K/W
Transportafstand naar fabriek	150	km

Afvalscenario:

Stort	7,1	%
Verbranding	1,3	%
Recycling	91,4	%
Hergebruik	0,1	%
Eigenprofiel	0,0	%

Omschrijving functionele eenheid

Dit systeem bevat de volgende hoeveelheden: 148,01 kg aan beton, 41,02 kg aan metselspecie, 3,97 kg aan hydrofobeermiddel, 3,94 kg aan glaswol, 0,098 kg aan RVS sppouwankers, 472,8 kg aan Beton C20/25 XC2, 0% puingranulaat, CEM I, 30,06 kg aan middelzwaar constructiestaal (o.a. geleiderails).

Opvallende milieu-eigenschappen

Dit product valt in milieuklasse 2c en is daarmee milieutechnisch een goede keuze. Het product is 8,2 keer zo zwaar als het lichtste product in deze functionele eenheid, dit heeft een nadelige invloed op de milieueffecten veroorzaakt door transport. Het basisprofiel 019 Insitu Betonmortel C20/25, 0% granulaat veroorzaakt met 43,4% het grootste deel van de schaduwkosten, daarop volgen het basisprofiel NM0660 - aanname beton gevelsteen met 17,1% en het basisprofiel 157 - metselspecie met 12,3% van de schaduwkosten.

De productiefase (A1-3) is verantwoordelijk voor 83,9% van de totale schaduwkosten gedurende de beschouwde periode van 75 jaar. Het transport naar de bouwplaats (A4) tijdens de constructiefase veroorzaakt 14,1% van de schaduwkosten. De constructie (A5) van het product veroorzaakt 0,8% van de schaduwkosten. In deze fase wordt het afval dat vrijkomt op de bouwplaats (o.a. verpakkingen en snijverlies) en processen die plaatsvinden bij constructie meegewogen. Er treden geen milieueffecten op die voortvloeien uit emissies naar lucht, bodem of water tijdens het gebruik (B1). Voor onderhoud (B2) treden geen milieueffecten op gedurende de beschouwde periode. Er vinden geen vervangingen (B3) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er vinden geen reparaties (B4) plaats in de gebruiksfase en derhalve zijn er geen schaduwkosten voor dit onderdeel. Er zijn geen schaduwkosten voor energieverbruik door het product (B6) om te kunnen functioneren in de beschouwde periode. Er zijn geen schaduwkosten voor waterverbruik door het product (B7) om te kunnen functioneren in de beschouwde periode. In de afvalfase van het product (C & D), exclusief het transport in deze fase (C2), worden -3,4% van de schaduwkosten veroorzaakt van wieg tot graf (bij recycling en re-use weer tot de wieg).Het transport in de afvalfase van het product (C2) veroorzaakt 4,6% van de schaduwkosten.

Milieucriteria

Emissies

br	broeikaseffect	1,33E+2	kg CO_2 eq
oz	ozonlaagaantasting	1,09E-5	kg CFC-11 eq
hu	humane toxiciteit	2,86E+1	kg 1,4 DB eq
aq	aquatische toxiciteit (zoet)	9,57E-1	kg 1,4 DB eq
aq	aquatische toxiciteit (zout)	3,92E+3	kg 1,4 DB eq
te	terrestische toxiciteit	1,96E-1	kg 1,4 DB eq
fo	fotochem. toxiciteit	4,90E-2	kg C_2H_4 eq
ve	verzuring	4,38E-1	kg SO_2 eq
eu	eutrofiëring (vermesting)	7,48E-2	kg PO_4 eq

Uitputting

ab	abiotische grondstoffen	2,37E-4	kg Sb eq
en	energiedragers	6,15E-1	kg Sb eq

Landgebruik

Hinder ten gevolge van

Royal HaskoningDHV
Enhancing Society Together

Notitie / Memo

HaskoningDHV Nederland B.V.
Industry & Buildings

Aan:	Royal Flora Holland
Van:	Quirine Henry
Datum:	22 juli 2019
Kopie:	Rudolf Scholtens
Ons kenmerk:	BF5124-RHD-ZZ-XX-NT-Z-0001
Classificatie:	Projectgerelateerd

Onderwerp: **Circulariteit inbouwpakket: uitgangspunten**

1 CO_2-besparing materialen

		Schaduwprijs	*CO2 emissies (LCA)*
BVO nieuwbouw:	1.937 m²	€1,04 / m² BVO	836.092 kg CO2 eq.
VO bestaand:	3.110 m²	€0,00 / m² BVO	0 kg CO2 eq.
Totaal:	**5.047 m²**	**€1,04 / m² BVO**	**836.092 kg CO2 eq.**
			165,66 kg CO2 eq / m² BVO
Volledige nieuwbouw:	5.047 m²	€1,04 / m² BVO	2.178.500 kg CO2 eq
			431,64 kg CO2 eq / m² BVO
			-1.342.408 kg CO2 eq besparing

110

Appendix 3: C# scripts

The codes that can be found in this appendix include only one class file of the whole project, namely CalculateValues.cs. This file is selected as an example to give the reader an idea about how the CECC tool works since the main buttons on the Revit ribbon is connected to this class file. However, the use of only this one class file will not be sufficient to replicate the CECC tool. The whole project package, related C# scripts and how to set it up on a user's computer can be found and downloaded via this link.

CalculateValues.cs

```csharp
using Autodesk.Revit.Attributes;
using Autodesk.Revit.DB;
using Autodesk.Revit.UI;
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using System.Threading.Tasks;
using Autodesk.Revit.ApplicationServices;
using Autodesk.Revit.UI.Selection;
using System.Diagnostics;
using System.Windows.Forms;
using System.Data;
using System.Collections;
using System.IO;
using CECC.Properties;


namespace CECC
{
    [Autodesk.Revit.Attributes.Transaction(Autodesk.Revit.Attributes.TransactionMode.
Manual)]
    [Autodesk.Revit.Attributes.Regeneration(Autodesk.Revit.Attributes.RegenerationOpt
ion.Manual)]


    public class CalculateValues : IExternalCommand
    {

        public Document m_doc;
        public IList<Element> m_wallsToProcess;
        public IList<Element> m_floorsToProcess;
        public FormViewModel formViewModel = new FormViewModel();
        public FormMain form = new FormMain();

        public IList<String> resultsCarbonWalls;
        public IList<String> resultsCarbonFloors;
        public IList<String> resultsCostsWalls;
        public IList<String> resultsCostsFloors;
```

```csharp
        public IList<String> landfillIncWalls;
        public IList<String> landfillIncFloors;
        public IList<String> recyclingWalls;
        public IList<String> recyclingFloors;
        public IList<String> reuseWalls;
        public IList<String> reuseFloors;


        public void CollectElements()
        {

            FilteredElementCollector collectorFloors = new FilteredElementCollector(m
_doc);
            m_floorsToProcess = collectorFloors.OfCategory(BuiltInCategory.OST_Floors
).WhereElementIsNotElementType().ToElements();


            FilteredElementCollector collectorWalls = new FilteredElementCollector(m_
doc, m_doc.ActiveView.Id);
            m_wallsToProcess = collectorWalls.OfCategory(BuiltInCategory.OST_Walls).W
hereElementIsNotElementType().ToElements();

        }


        static bool dataLoaded = false;

        public Result Execute(ExternalCommandData revit, ref string message, ElementS
et elements)
        {

        Autodesk.Revit.ApplicationServices.Application app = revit.Application.Ap
plication;
        m_doc = revit.Application.ActiveUIDocument.Document;


        //loadData starts here


        if (dataLoaded == false)
        {

            //change the path according to your file location
            string path = @"D:\Ece\Graduation\database.csv";

            try
            {
                using (StreamReader reader = new StreamReader(path))
                {
                    // this allows you to do one Read operation
                    string data = reader.ReadLine();
                    string[] read;
                    char[] seperators = { ',' };
```

```csharp
                    //loops through every row for each column
                    while ((data = reader.ReadLine()) != null)
                    {
                        //reads every column
                        read = data.Split(seperators, StringSplitOptions.RemoveEm
ptyEntries);

                        string value1 = read[0];
                        string value2 = read[1];
                        string value3 = read[2];
                        string value4 = read[3];
                        string value5 = read[4];
                        string value6 = read[5];
                        string value7 = read[6];
                        string value8 = read[7];
                        string value9 = read[8];
                        string value10 = read[9];
                        string value11 = read[10];
                        string value12 = read[11];
                        string value13 = read[12];
                        string value14 = read[13];
                        string value15 = read[14];
                        string value16 = read[15];

                        Indicator i = new Indicator();
                        i.assemblyCode = value1;
                        i.name = value2;
                        i.embodiedCarbon = float.Parse(value3);
                        i.functionalUnit = value4;
                        i.kgPerM2 = float.Parse(value5);
                        i.cost = float.Parse(value6);
                        i.newMaterialPercent = float.Parse(value7);
                        i.reusedMaterialPercent = float.Parse(value8);
                        i.recycledMaterialPercent = float.Parse(value9);
                        i.bioMaterialPercent = float.Parse(value10);
                        i.landfillPotentialPercent = float.Parse(value11);
                        i.incinerationPotentialPercent = float.Parse(value11);
                        i.landfillPotentialPercent = float.Parse(value12);
                        i.recyclingPotentialPercent = float.Parse(value13);
                        i.reusePotentialPercent = float.Parse(value14);
                        i.useFactor = float.Parse(value15);
                        i.mci = float.Parse(value16);

                    }
                }
            }

            catch (Exception e)
            {
                Console.WriteLine("The process failed: {0}", e.ToString());
            }

            dataLoaded = true;

        }
```

```
            //loadData ends here

            CollectElements();

            List<String> names = new List<String>();
            List<String> uniqeIDs = new List<String>();
            List<String> levelIDs = new List<String>();
            List<String> areas = new List<String>();
            List<String> volumes = new List<String>();
            List<String> weights = new List<String>();
            List<String> resultsCarbon = new List<String>();
            List<String> resultsCost = new List<String>();
            List<String> resultsCircularity = new List<String>();

            List<String> resultsCarbonWalls = new List<String>();
            List<String> resultsCarbonFloors = new List<String>();
            List<String> resultsCostsWalls = new List<String>();
            List<String> resultsCostsFloors = new List<String>();

            List<String> landfillIncWalls = new List<String>();
            List<String> landfillIncFloors = new List<String>();
            List<String> recyclingWalls = new List<String>();
            List<String> recyclingFloors = new List<String>();
            List<String> reuseWalls = new List<String>();
            List<String> reuseFloors = new List<String>();

            foreach (Element element in m_wallsToProcess)
            {

                ElementId materialId = element.GetTypeId();
                //if you want to retrieve local element ids use the following line (t
his is not unique id)
                //ElementId elementId = element.Id;

                ElementType type = m_doc.GetElement(materialId) as ElementType;

                string assemblyCodes = type.get_Parameter(BuiltInParameter.UNIFORMAT_
CODE).AsString();


                foreach (Indicator myIndicator in Indicator.myList)
                {

                    if (assemblyCodes == myIndicator.assemblyCode)
                    {

                        //looks through all the materials and takes the first one
                        ElementId material = element.GetMaterialIds(false).ElementAt(
0);

                        //gets the area value in square feet and converts it to meter
 squares by division operation
                        double area = element.GetMaterialArea(material, false) / 10.7
64;
```

```csharp
                        //gets the volume value in cubic feet and converts it to mete
r cubes by division operation
                        double volume = element.GetMaterialVolume(material) / 35.315;

                        //kilograms
                        double weight = myIndicator.kgPerM2 * ((float)area);

                        CalculateMaterialQuantitiesOfElement(element);

                        float result1 = myIndicator.embodiedCarbon * ((float)area);
                        float result2 = myIndicator.cost * ((float)area);

                        float result3 = myIndicator.kgPerM2 * ((float)area) * (myIndi
cator.landfillPotentialPercent + myIndicator.incinerationPotentialPercent);
                        float result4 = myIndicator.kgPerM2 * ((float)area) * myIndic
ator.recyclingPotentialPercent;
                        float result5 = myIndicator.kgPerM2 * ((float)area) * myIndic
ator.reusePotentialPercent;

                    resultsCarbon.Add(result1.ToString());
                    resultsCost.Add(result2.ToString());

                    uniqeIDs.Add(element.UniqueId.ToString());
                    //uniqeIDs.Add(elementId.ToString());
                    names.Add(element.Name.Replace(',', ':'));

                    levelIDs.Add(element.LevelId.ToString());
                    areas.Add(area.ToString());
                    volumes.Add(volume.ToString());
                    weights.Add(weight.ToString());

                    resultsCircularity.Add(myIndicator.mci.ToString());

                    resultsCarbonWalls.Add(result1.ToString());
                    resultsCostsWalls.Add(result2.ToString());

                    landfillIncWalls.Add(result3.ToString());
                    recyclingWalls.Add(result4.ToString());
                    reuseWalls.Add(result5.ToString());

                }

            }

        }

        foreach (Element element in m_floorsToProcess)
        {

            ElementId materialId = element.GetTypeId();
            //if you want to retrieve local element ids use the following line (t
his is not unique id)
            //ElementId elementId = element.Id;
```

```csharp
                ElementType type = m_doc.GetElement(materialId) as ElementType;

                string assemblyCodes = type.get_Parameter(BuiltInParameter.UNIFORMAT_
CODE).AsString();

                foreach (Indicator myIndicator in Indicator.myList)
                {

                    if (assemblyCodes == myIndicator.assemblyCode)
                    {

                        //looks through all the materials and takes the first one
                        ElementId material = element.GetMaterialIds(false).ElementAt(
0);

                        //gets the area value in square feet and converts it to meter
 squares by division operation
                        double area = element.GetMaterialArea(material, false) / 10.7
64;

                        //gets the volume value in cubic feet and converts it to mete
r cubes by division operation
                        double volume = element.GetMaterialVolume(material) / 35.315;

                        //kilograms
                        double weight = myIndicator.kgPerM2 * ((float)area);

                        CalculateMaterialQuantitiesOfElement(element);

                        float result1 = myIndicator.embodiedCarbon * ((float)area);
                        float result2 = myIndicator.cost * ((float)area);

                        float result3 = myIndicator.kgPerM2 * ((float)area) * (myIndi
cator.landfillPotentialPercent + myIndicator.incinerationPotentialPercent);
                        float result4 = myIndicator.kgPerM2 * ((float)area) * myIndic
ator.recyclingPotentialPercent;
                        float result5 = myIndicator.kgPerM2 * ((float)area) * myIndic
ator.reusePotentialPercent;

                        resultsCarbon.Add(result1.ToString());
                        resultsCost.Add(result2.ToString());

                        uniqeIDs.Add(element.UniqueId.ToString());
                        //uniqeIDs.Add(elementId.ToString());
                        names.Add(element.Name.Replace(',', ':'));

                        levelIDs.Add(element.LevelId.ToString());
                        areas.Add(area.ToString());
                        volumes.Add(volume.ToString());
                        weights.Add(weight.ToString());

                        resultsCircularity.Add(myIndicator.mci.ToString());

                        resultsCarbonFloors.Add(result1.ToString());
                        resultsCostsFloors.Add(result2.ToString());
```

```
                        landfillIncFloors.Add(result3.ToString());
                        recyclingFloors.Add(result4.ToString());
                        reuseFloors.Add(result5.ToString());


                    }
                }
            }

            //fills in the lists from FormViewModel with the acquired data from Revit
model
            formViewModel.resultCarbon = resultsCarbon;
            formViewModel.resultCost = resultsCost;
            formViewModel.resultCircular = resultsCircularity;
            formViewModel.name = names;
            formViewModel.uniqueID = uniqeIDs;
            formViewModel.levelID = levelIDs;
            formViewModel.area = areas;
            formViewModel.volume = volumes;
            formViewModel.weight = weights;

            formViewModel.resultsCarbonWalls = resultsCarbonWalls;
            formViewModel.resultsCarbonFloors = resultsCarbonFloors;
            formViewModel.resultsCostsWalls = resultsCostsWalls;
            formViewModel.resultsCostsFloors = resultsCostsFloors;

            formViewModel.landfillIncWalls = landfillIncWalls;
            formViewModel.landfillIncFloors = landfillIncFloors;
            formViewModel.recyclingWalls = recyclingWalls;
            formViewModel.recyclingFloors = recyclingFloors;
            formViewModel.reuseWalls = reuseWalls;
            formViewModel.reuseFloors = reuseFloors;


            PresentResults();
            return Result.Succeeded;

        }


        public void PresentResults()
        {
            using (form)
            {

                //cancel when user hits escape
                if (form.DialogResult == System.Windows.Forms.DialogResult.Cancel)
                    form.Close();

                form.dataGridView1.AutoGenerateColumns = true;

                DataTable dt = new DataTable();
                dt.Columns.Add("Names");
                dt.Columns.Add("Unique IDs");
                dt.Columns.Add("Associated Level IDs");
```

```csharp
            dt.Columns.Add("Areas (m2)");
            dt.Columns.Add("Volumes (m3)");
            dt.Columns.Add("Weight (kg)");
            dt.Columns.Add("Circularity (MCI)");
            dt.Columns.Add("Embodied Carbon (kgCO2eq)");
            dt.Columns.Add("Costs (EUR)");

            float totalCarbon = 0;
            float totalCarbonOut;

            //float totalCircularity = 0;
            //float totalCircularityOut;

            float totalCost = 0;
            float totalCostOut;

            float totalWeight = 0;
            float totalWeightOut;

            for (int i = 0; i < formViewModel.resultCarbon.Count; i++)
            {

                float.TryParse(formViewModel.resultCarbon[i], out totalCarbonOut)
;

                totalCarbon += totalCarbonOut;

            }

            for (int i = 0; i < formViewModel.weight.Count; i++)
            {

                float.TryParse(formViewModel.weight[i], out totalWeightOut);
                totalWeight += totalWeightOut;

            }

            for (int i = 0; i < formViewModel.resultCost.Count; i++)
            {

                float.TryParse(formViewModel.resultCost[i], out totalCostOut);
                totalCost += totalCostOut;

                dt.Rows.Add(formViewModel.name[i], formViewModel.uniqueID[i], for
mViewModel.levelID[i], formViewModel.area[i], formViewModel.volume[i], formViewModel.
weight[i], formViewModel.resultCircular[i], formViewModel.resultCarbon[i], formViewMo
del.resultCost[i]);
            }

            dt.Rows.Add("", "", "", "", "", "", "", "", "");
            dt.Rows.Add("Total", "", "", "", "", totalWeight.ToString(), "", tota
lCarbon.ToString(), totalCost.ToString());
            dt.Rows.Add("Walls total", "", "", "", "", "", "", calculateTotalsfor
Charts(formViewModel.resultsCarbonWalls).ToString(), calculateTotalsforCharts(formVie
wModel.resultsCostsWalls).ToString());
```

```csharp
                    dt.Rows.Add("Floors total", "", "", "", "", "", "", calculateTotalsfo
rCharts(formViewModel.resultsCarbonFloors).ToString(), calculateTotalsforCharts(formV
iewModel.resultsCostsFloors).ToString());

                    form.dataGridView1.DataSource = dt;

                    form.button4.Click += new System.EventHandler(this.allResults_Click);
                    form.button1.Click += new System.EventHandler(this.carbonFilter_Click
);

                    form.button2.Click += new System.EventHandler(this.circularityFilter_
Click);

                    form.button3.Click += new System.EventHandler(this.costFilter_Click);
                    convertChartCarbon();
                    convertChartCosts();
                    convertChartCircularity();
                    form.ShowDialog();

        }
    }

    private void allResults_Click(object sender, EventArgs e)
    {

        DataTable dt = new DataTable();
        dt.Columns.Add("Names");
        dt.Columns.Add("Unique IDs");
        dt.Columns.Add("Associated Level IDs");
        dt.Columns.Add("Areas (m2)");
        dt.Columns.Add("Volumes (m3)");
        dt.Columns.Add("Weight (kg)");
        dt.Columns.Add("Circularity (MCI)");
        dt.Columns.Add("Embodied Carbon (kgCO2eq)");
        dt.Columns.Add("Costs (EUR)");

        float totalCarbon = 0;
        float totalCarbonOut;


        float totalCost = 0;
        float totalCostOut;

        float totalWeight = 0;
        float totalWeightOut;

        for (int i = 0; i < formViewModel.resultCarbon.Count; i++)
        {

            float.TryParse(formViewModel.resultCarbon[i], out totalCarbonOut);
            totalCarbon += totalCarbonOut;

        }

        for (int i = 0; i < formViewModel.weight.Count; i++)
        {
```

```csharp
                float.TryParse(formViewModel.weight[i], out totalWeightOut);
                totalWeight += totalWeightOut;

            }

            for (int i = 0; i < formViewModel.resultCost.Count; i++)
            {

                float.TryParse(formViewModel.resultCost[i], out totalCostOut);
                totalCost += totalCostOut;

                dt.Rows.Add(formViewModel.name[i], formViewModel.uniqueID[i], formVie
wModel.levelID[i], formViewModel.area[i], formViewModel.volume[i], formViewModel.weig
ht[i], formViewModel.resultCircular[i], formViewModel.resultCarbon[i], formViewModel.
resultCost[i]);
            }

            dt.Rows.Add("", "", "", "", "", "", "", "", "");
            dt.Rows.Add("Total", "", "", "", "", totalWeight.ToString(), "", totalCar
bon.ToString(), totalCost.ToString());
            dt.Rows.Add("Walls total", "", "", "", "", "", "", calculateTotalsforChar
ts(formViewModel.resultsCarbonWalls).ToString(), calculateTotalsforCharts(formViewMod
el.resultsCostsWalls).ToString());
            dt.Rows.Add("Floors total", "", "", "", "", "", "", calculateTotalsforCha
rts(formViewModel.resultsCarbonFloors).ToString(), calculateTotalsforCharts(formViewM
odel.resultsCostsFloors).ToString());

            form.dataGridView1.DataSource = dt;
            form.dataGridView1.Update();
            form.dataGridView1.Refresh();

        }

        private void carbonFilter_Click(object sender, EventArgs e)
        {

            DataTable dt = new DataTable();
            dt.Columns.Add("Names");
            dt.Columns.Add("Unique IDs");
            dt.Columns.Add("Embodied Carbon (kgCO2eq)");

            float totalCarbon = 0;
            float totalCarbonOut;

            for (int i = 0; i < formViewModel.resultCarbon.Count; i++)
            {

                float.TryParse(formViewModel.resultCarbon[i], out totalCarbonOut);
                totalCarbon += totalCarbonOut;

                dt.Rows.Add(formViewModel.name[i], formViewModel.uniqueID[i], formVie
wModel.resultCarbon[i]);

            }
```

```csharp
            dt.Rows.Add("", "", "");
            dt.Rows.Add("Total", "", totalCarbon.ToString());
            dt.Rows.Add("Walls total", "", calculateTotalsforCharts(formViewModel.res
ultsCarbonWalls).ToString());
            dt.Rows.Add("Floors total", "", calculateTotalsforCharts(formViewModel.re
sultsCarbonFloors).ToString());

            form.dataGridView1.DataSource = dt;
            form.dataGridView1.Update();
            form.dataGridView1.Refresh();

        }

        private void circularityFilter_Click(object sender, EventArgs e)
        {

            DataTable dt = new DataTable();
            dt.Columns.Add("Names");
            dt.Columns.Add("Unique IDs");
            dt.Columns.Add("Circularity (MCI)");

            for (int i = 0; i < formViewModel.resultCarbon.Count; i++)
            {

                dt.Rows.Add(formViewModel.name[i], formViewModel.uniqueID[i], formVie
wModel.resultCircular[i]);

            }

            dt.Rows.Add("", "", "");
            dt.Rows.Add("Total", "", "");

            form.dataGridView1.DataSource = dt;
            form.dataGridView1.Update();
            form.dataGridView1.Refresh();

        }

        private void costFilter_Click(object sender, EventArgs e)
        {

            DataTable dt = new DataTable();
            dt.Columns.Add("Names");
            dt.Columns.Add("Unique IDs");
            dt.Columns.Add("Costs (EUR)");

            float totalCost = 0;
            float totalCostOut;

            for (int i = 0; i < formViewModel.resultCost.Count; i++)
            {

                float.TryParse(formViewModel.resultCost[i], out totalCostOut);
                totalCost += totalCostOut;
```

```csharp
                dt.Rows.Add(formViewModel.name[i], formViewModel.uniqueID[i], formVie
wModel.resultCost[i]);

            }

            dt.Rows.Add("", "", "");
            dt.Rows.Add("Total", "", totalCost.ToString());
            dt.Rows.Add("Walls total", "", calculateTotalsforCharts(formViewModel.res
ultsCostsWalls).ToString());
            dt.Rows.Add("Floors total", "", calculateTotalsforCharts(formViewModel.re
sultsCostsFloors).ToString());

            form.dataGridView1.DataSource = dt;
            form.dataGridView1.Update();
            form.dataGridView1.Refresh();

        }

        private void convertChartCarbon ()
        {

            form.chart1.Titles.Add("Embodied Carbon (kgCO2eq)");
            form.chart1.Series["series1"].IsValueShownAsLabel = true;

            form.chart1.Series["series1"].Points.AddXY("Walls", calculateTotalsforCha
rts(formViewModel.resultsCarbonWalls));
            form.chart1.Series["series1"].Points.AddXY("Floors", calculateTotalsforCh
arts(formViewModel.resultsCarbonFloors));

        }

        private void convertChartCosts ()
        {

            form.chart2.Titles.Add("Costs (EUR)");
            form.chart2.Series["series2"].IsValueShownAsLabel = true;

            form.chart2.Series["series2"].Points.AddXY("Walls", calculateTotalsforCha
rts(formViewModel.resultsCostsWalls));
            form.chart2.Series["series2"].Points.AddXY("Floors", calculateTotalsforCh
arts(formViewModel.resultsCostsFloors));

        }

        private void convertChartCircularity ()
        {

            form.chart3.Titles.Add("Future Scenario of Materials (kgs)");
            form.chart3.Series["series3"].IsValueShownAsLabel = true;

            form.chart3.Series["series3"].Points.AddXY("Walls - Waste", calculateTota
lsforCharts(formViewModel.landfillIncWalls));
            form.chart3.Series["series3"].Points.AddXY("Walls - Recycling", calculate
TotalsforCharts(formViewModel.recyclingWalls));
```

```csharp
            form.chart3.Series["series3"].Points.AddXY("Walls - Reuse", calculateTota
lsforCharts(formViewModel.reuseWalls));
            form.chart3.Series["series3"].Points.AddXY("Floors - Waste", calculateTot
alsforCharts(formViewModel.landfillIncFloors));
            form.chart3.Series["series3"].Points.AddXY("Floors - Recycling", calculat
eTotalsforCharts(formViewModel.recyclingFloors));
            form.chart3.Series["series3"].Points.AddXY("Floors - Reuse", calculateTot
alsforCharts(formViewModel.reuseFloors));

        }

        private float calculateTotalsforCharts(IList<String> list)
        {

            float total = 0;
            float totalOut;


            for (int i = 0; i < list.Count; i++)
            {

                float.TryParse(list[i], out totalOut);
                total += totalOut;

            }

            return total;

        }


        public void CalculateMaterialQuantitiesOfElement(Element e)
        {

        }
        public object UIapp { get; private set; }
    }
}
```

Appendix 4: List of interviewees for functional requirements

Name	Company	Expertise	Date	Location
Aditya Parulekar	RHDHV	Architecture, Parametric design, Sustainability	14/05/2021	Online meeting
Gijs Joosen	RHDHV	Architecture, Parametric design	17/05/2021	Online meeting
Janine van den Kerkhof	RHDHV	Sustainability, Green certifications	22/02/2021	Online meeting
Jerin Emmen	RHDHV	Architecture, Engineering, Revit plugin development	07/05/2021	Online meeting
Kristian van Herwijnen	RHDHV	Sustainability, Green certifications	25/02/2021	Online meeting
Quirine Henry	RHDHV	Architecture, Sustainability, Green certifications, Circularity	16/02/2021	Online meeting
Rudolf Scholtens	RHDHV	Circularity, Project management	16/02/2021	Online meeting

Appendix 5: Results obtained from CECC tool

Results for "kanaalplaatvloer"

Names	Unique IDs	Associated Level IDs	Areas (m2)	Volumes (m3)	Weight (kg)	Embodied Carbon (kgCO2eq)	Circularity (MCI)	Costs (EUR)
NLRS_28.21_WA_beton ihwg d=400_gen	74fd1bdd-7a74-478a-936e-3f834162edb3-0042330d	1463	37,60929	15,04369803	25461,49	5002,035	0,5122	3674,089
NLRS_28.21_WA_beton ihwg d=400_gen	74fd1bdd-7a74-478a-936e-3f834162edb3-0042341d	1463	25,42223	10,16888037	17210,85	3381,156	0,5122	2483,523
NLRS_28.21_WA_beton ihwg d=400_gen	775a39e6-e01e-487e-82ea-c7d7e9c75cc2-00423ea7	1463	11,31302	4,525201172	7658,912	1504,631	0,5122	1105,18
NLRS_28.21_WA_beton ihwg d=400_gen	272a77fd-070b-435d-8a50-c9cc05441c67-00426258	1463	25,16529	10,066105	17036,9	3346,984	0,5122	2458,422
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00426cad	4483	11,35866	4,543457122	7689,81	1510,701	0,5122	1109,638
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-004276fd	4483	11,35866	4,543457122	7689,81	1510,701	0,5122	1109,638

NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427703	4500	11,68365	4,673455895	7909,833	1553,926	0,5122	1141,388
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427705	4500	11,68365	4,673455895	7909,833	1553,926	0,5122	1141,388
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427709	1088979	11,68365	4,673455895	7909,833	1553,926	0,5122	1141,388
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-0042770b	1088979	11,68365	4,673455895	7909,833	1553,926	0,5122	1141,388
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-0042770f	4336075	10,39341	4,157360765	7036,341	1382,324	0,5122	1015,343
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427711	4336075	10,39341	4,157360765	7036,341	1382,324	0,5122	1015,343
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430511	1463	2,811986	0,558964201	1903,714	373,9941	0,5122	274,7057
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-	1463	2,834588	0,563453746	1919,016	377,0002	0,5122	276,9137

	d639727e4507-0043056c						
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004307a6	1463	2,834436	0,563423317	1918,913	376,98	0,5122	276,8989
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004307a8	1463	2,84308	0,565136362	1924,765	378,1296	0,5122	277,7433
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004307ac	1463	2,826261	0,56180432	1913,379	375,8927	0,5122	276,1003
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430829	1463	2,818708	0,560309546	1908,265	374,8881	0,5122	275,3624
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-0043082d	1463	2,861866	0,568877597	1937,483	380,6282	0,5122	279,5786
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-0043082f	1463	2,815365	0,559625118	1906,002	374,4435	0,5122	275,0358
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430872	1463	2,646696	0,525800067	1791,813	352,0106	0,5122	258,5584

NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430874	1463	2,775829	0,551761437	1879,236	369,1853	0,5122	271,1735
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004308d4	1463	0,970919	0,192869969	657,3124	129,1323	0,5122	94,85008
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004308d6	1463	2,829252	0,562386648	1915,404	376,2906	0,5122	276,3925
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004308da	1463	2,895265	0,575976255	1960,094	385,0703	0,5122	282,8413
NLRS_23.21_FL_kanaalplaat d=260_gen	22a743ab-a682-4e89-94de-4bc533754b80-004506c6	4483	33,93639	8,823451012	17911,63	3230,744	0,5338	1997,326
NLRS_23.21_FL_kanaalplaat d=260_gen	22a743ab-a682-4e89-94de-4bc533754b80-00450d3c	4483	33,93639	8,823451012	17911,63	3230,744	0,5338	1997,326
NLRS_23.21_FL_kanaalplaat d=260_gen	22a743ab-a682-4e89-94de-4bc533754b80-00450e77	4483	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	22a743ab-a682-4e89-94de-	4483	33,93639	8,823451012	17911,63	3230,744	0,5338	1997,326

	4bc533754b80-00450f5a							
NLRS_23.21_FL_kanaalplaat d=260_gen	22a743ab-a682-4e89-94de-4bc533754b80-0045106c	4483	33,93639	8,823451012	17911,63	3230,744	0,5338	1997,326
NLRS_23.21_FL_kanaalplaat d=260_gen	22a743ab-a682-4e89-94de-4bc533754b80-0045117b	4483	33,72185	8,767671752	17798,39	3210,32	0,5338	1984,7
NLRS_23.21_FL_beton ihwg d=300_gen	caec57bc-ebb5-41b0-831d-799342053003-00451321	4483	49,65679	14,2555787	36497,74	5412,59	0,54505	1015,481
NLRS_23.21_FL_kanaalplaat d=260_gen	caec57bc-ebb5-41b0-831d-799342053003-004516ae	4483	33,72185	8,767671543	17798,39	3210,32	0,5338	1984,7
NLRS_23.21_FL_beton ihwg d=300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00453f69	4500	50,02063	14,34862985	36765,16	5452,248	0,54505	1022,922
NLRS_23.21_FL_kanaalplaat d=260_gen	34220296-2f84-4a8f-8c81-341d277b91d9-004543f8	4500	33,72145	8,76756692	17798,18	3210,282	0,5338	1984,676
NLRS_23.21_FL_kanaalplaat d=260_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454429	4500	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454445	4500	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302

NLRS_23.21_FL_kanaalplaat d=260_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454460	4500	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	34220296-2f84-4a8f-8c81-341d277b91d9-0045447b	4500	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454498	4500	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	34220296-2f84-4a8f-8c81-341d277b91d9-004544b5	4500	33,72145	8,767567129	17798,18	3210,282	0,5338	1984,676
NLRS_23.21_FL_beton ihwg d=300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454976	1088979	50,02063	14,34862985	36765,16	5452,248	0,54505	1022,922
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ae8	1088979	33,72145	8,76756692	17798,18	3210,282	0,5338	1984,676
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454b3a	1088979	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454b55	1088979	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-	1088979	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302

	590fd66078ce-00454b70							
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454b8b	1088979	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ba6	1088979	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454bc1	1088979	33,72145	8,767567129	17798,18	3210,282	0,5338	1984,676
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454c39	4336075	33,72145	8,76756692	17798,18	3210,282	0,5338	1984,676
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454c82	4336075	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ca5	4336075	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454cc8	4336075	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302

NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ceb	4336075	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454d0e	4336075	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454d31	4336075	33,72145	8,767567129	17798,18	3210,282	0,5338	1984,676
NLRS_23.21_FL_beton ihwg d=300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454db2	4336075	50,02063	14,34862985	36765,16	5452,248	0,54505	1022,922
NLRS_23.21_FL_beton ihwg d=300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00454ec1	4336084	69,09154	20,72743836	50782,28	7530,978	0,54505	1412,922
NLRS_23.21_FL_kanaalplaat d=260_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00455012	4336084	33,72145	8,76756692	17798,18	3210,282	0,5338	1984,676
NLRS_23.21_FL_kanaalplaat d=260_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00455076	4336084	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00455091	4336084	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-004550ac	4336084	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302

NLRS_23.21_FL_kanaalplaat d=260_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-004550f2	4336084	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-0045510d	4336084	33,93599	8,823346388	17911,41	3230,706	0,5338	1997,302
NLRS_23.21_FL_kanaalplaat d=260_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-0045512e	4336084	33,72141	8,76755702	17798,16	3210,278	0,5338	1984,673
Total					975339.4	172031,2		97209,53
Walls total						29860,21		21932,88
Floors total						142171		75276,62

Results for "breedplaatvloer"

Names	Unique IDs	Associated Level IDs	Areas (m2)	Volumes (m3)	Weight (kg)	Embodied Carbon (kgCO2eq)	Circularity (MCI)	Costs (EUR)
NLRS_28.21_WA_beton ihwg d=400_gen	74fd1bdd-7a74-478a-936e-3f834162edb3-0042330d	1463	37,60929	15,0437	25461,49	5002,035	0,5122	3674,089
NLRS_28.21_WA_beton ihwg d=400_gen	74fd1bdd-7a74-478a-936e-3f834162edb3-0042341d	1463	25,42223	10,16888	17210,85	3381,156	0,5122	2483,523
NLRS_28.21_WA_beton ihwg d=400_gen	775a39e6-e01e-487e-82ea-c7d7e9c75cc2-00423ea7	1463	11,31302	4,525201	7658,912	1504,631	0,5122	1105,18
NLRS_28.21_WA_beton ihwg d=400_gen	272a77fd-070b-435d-8a50-c9cc05441c67-00426258	1463	25,16529	10,06611	17036,9	3346,984	0,5122	2458,422
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00426cad	4483	11,35866	4,543457	7689,81	1510,701	0,5122	1109,638
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-004276fd	4483	11,35866	4,543457	7689,81	1510,701	0,5122	1109,638
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427703	4500	11,68365	4,673456	7909,833	1553,926	0,5122	1141,388
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427705	4500	11,68365	4,673456	7909,833	1553,926	0,5122	1141,388

NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427709	1088979	11,68365	4,673456	7909,833	1553,926	0,5122	1141,388
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-0042770b	1088979	11,68365	4,673456	7909,833	1553,926	0,5122	1141,388
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-0042770f	4336075	10,39341	4,157361	7036,341	1382,324	0,5122	1015,343
NLRS_28.21_WA_beton ihwg d=400_gen	ce4972c7-d611-44ca-b177-712ea8cb58a9-00427711	4336075	10,39341	4,157361	7036,341	1382,324	0,5122	1015,343
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430511	1463	2,811986	0,558964	1903,714	373,9941	0,5122	274,7057
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-0043056c	1463	2,834588	0,563454	1919,016	377,0002	0,5122	276,9137
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004307a6	1463	2,834436	0,563423	1918,913	376,98	0,5122	276,8989
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004307a8	1463	2,84308	0,565136	1924,765	378,1296	0,5122	277,7433
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004307ac	1463	2,826261	0,561804	1913,379	375,8927	0,5122	276,1003
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430829	1463	2,818708	0,56031	1908,265	374,8881	0,5122	275,3624

NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-0043082d	1463	2,861866	0,568878	1937,483	380,6282	0,5122	279,5786
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-0043082f	1463	2,815365	0,559625	1906,002	374,4435	0,5122	275,0358
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430872	1463	2,646696	0,5258	1791,813	352,0106	0,5122	258,5584
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-00430874	1463	2,775829	0,551761	1879,236	369,1853	0,5122	271,1735
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004308d4	1463	0,970919	0,19287	657,3124	129,1323	0,5122	94,85008
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004308d6	1463	2,829252	0,562387	1915,404	376,2906	0,5122	276,3925
NLRS_21.21_WA_beton ihwg d=200_gen	25e72129-96b5-46f5-9982-d639727e4507-004308da	1463	2,895265	0,575976	1960,094	385,0703	0,5122	282,8413
NLRS_23.21_FL_breedplaat d=50/300_gen	22a743ab-a682-4e89-94de-4bc533754b80-004506c6	4483	33,93639	10,18091	19662,74	3597,257	0,5455	4078,051
NLRS_23.21_FL_breedplaat d=50/300_gen	22a743ab-a682-4e89-94de-4bc533754b80-00450d3c	4483	33,93639	10,18091	19662,74	3597,257	0,5455	4078,051
NLRS_23.21_FL_breedplaat d=50/300_gen	22a743ab-a682-4e89-94de-4bc533754b80-00450e77	4483	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003

NLRS_23.21_FL_breedplaat d=50/300_gen	22a743ab-a682-4e89-94de-4bc533754b80-00450f5a	4483	33,93639	10,18091	19662,74	3597,257	0,5455	4078,051
NLRS_23.21_FL_breedplaat d=50/300_gen	22a743ab-a682-4e89-94de-4bc533754b80-0045106c	4483	33,93639	10,18091	19662,74	3597,257	0,5455	4078,051
NLRS_23.21_FL_breedplaat d=50/300_gen	22a743ab-a682-4e89-94de-4bc533754b80-0045117b	4483	33,72185	10,11654	19538,44	3574,516	0,5455	4052,271
NLRS_23.21_FL_beton ihwg d=300_gen	caec57bc-ebb5-41b0-831d-799342053003-00451321	4483	49,65679	14,25558	36497,74	5412,59	0,54505	1015,481
NLRS_23.21_FL_breedplaat d=50/300_gen	caec57bc-ebb5-41b0-831d-799342053003-004516ae	4483	33,72185	10,11654	19538,44	3574,516	0,5455	4052,271
NLRS_23.21_FL_beton ihwg d=300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00453f69	4500	50,02063	14,34863	36765,16	5452,248	0,54505	1022,922
NLRS_23.21_FL_breedplaat d=50/300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-004543f8	4500	33,72145	10,11642	19538,21	3574,473	0,5455	4052,222
NLRS_23.21_FL_breedplaat d=50/300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454429	4500	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454445	4500	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454460	4500	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003

NLRS_23.21_FL_breedplaat d=50/300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-0045447b	4500	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-00454498	4500	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	34220296-2f84-4a8f-8c81-341d277b91d9-004544b5	4500	33,72145	10,11642	19538,21	3574,474	0,5455	4052,223
NLRS_23.21_FL_beton ihwg d=300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454976	1088979	50,02063	14,34863	36765,16	5452,248	0,54505	1022,922
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ae8	1088979	33,72145	10,11642	19538,21	3574,473	0,5455	4052,222
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454b3a	1088979	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454b55	1088979	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454b70	1088979	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-	1088979	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003

	590fd66078ce-00454b8b							
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ba6	1088979	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454bc1	1088979	33,72145	10,11642	19538,21	3574,474	0,5455	4052,223
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454c39	4336075	33,72145	10,11642	19538,21	3574,473	0,5455	4052,222
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454c82	4336075	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ca5	4336075	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454cc8	4336075	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454ceb	4336075	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003

NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454d0e	4336075	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454d31	4336075	33,72145	10,11642	19538,21	3574,474	0,5455	4052,223
NLRS_23.21_FL_beton ihwg d=300_gen	d454a6b5-28d7-4bdd-8850-590fd66078ce-00454db2	4336075	50,02063	14,34863	36765,16	5452,248	0,54505	1022,922
NLRS_23.21_FL_beton ihwg d=300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00454ec1	4336084	69,09154	20,72744	50782,28	7530,978	0,54505	1412,922
NLRS_23.21_FL_breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00455012	4336084	33,72145	10,11642	19538,21	3574,473	0,5455	4052,222
NLRS_23.21_FL_breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00455076	4336084	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-00455091	4336084	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-004550ac	4336084	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-004550f2	4336084	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003

NLRS_23.21_FL_breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-0045510d	4336084	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-0045512e	4336084	33,72141	10,11641	19538,19	3574,469	0,5455	4052,218
Total					1036517	184835,9		169902,6
Walls total						29860,21		21932,88
Floors total						154975,7		147969,7

Appendix 6: Example MCI calculations

To illustrate how MCI calculations work, two products from the previous appendix which share the same product type have been selected. These two products are the last two "breedplaatvloer" products on page 137.

Names	Unique IDs	Level IDs	Area (m2)	Volume (m3)	Weight (kg)	Embodied Carbon (kgCO2eq)	Circularity (MCI)	Cost (EUR)
NLRS_23.21_FL_ breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-0045510d	4336084	33,93599	10,18078	19662,51	3597,214	0,5455	4078,003
NLRS_23.21_FL_ breedplaat d=50/300_gen	a32eede9-45f7-4c21-a12e-cb26264c7992-0045512e	4336084	33,72141	10,11641	19538,19	3574,469	0,5455	4052,218

As can be seen, these two products have different area and volume values, which result in different embodied carbon (kgCO2eq) and cost (EUR) values. However, their MCIs are the same.

According to the database information, the virgin materials (V) used for the production for "breedplaatvloer" is 100%. For the future scenario, 1% goes to landfill, 98.5% goes to recycling and 0.5% goes to reuse. In order something to be considered as waste (W) it has to be either landfill or incineration. Use factor (X) for "breedplaatvloer" is 1.

Using the Equation X:

$$MCI = \left(1 - \left(\frac{(V + W)}{2M} \times \frac{0.9}{X}\right)\right)$$

For the first item, MCI is calculated as:

$$MCI = \left(1 - \left(\frac{(19662.51 + (19662.51 * 0.01))}{2(19662.51)} \times \frac{0.9}{1}\right)\right)$$

$$MCI = 0.5455$$

For the second item, MCI is calculated as:

$$MCI = \left(1 - \left(\frac{(19538.19 + (19538.19 * 0.01))}{2(19538.19)} \times \frac{0.9}{1}\right)\right)$$

$$MCI = 0.5455$$

Therefore, they yield the same MCI value, meaning their material circularity indicator depends on the product type and not the mass itself. The same logic applies to all other product types as well.

Appendix 7: List of interviewees for tool validation

Name	Company	Expertise	Date	Location
Christopher Hoeh	RHDHV	Architecture, Sustainability, Green certifications	23/08/2021	Online meeting
Kristian van Herwijnen	RHDHV	Sustainability, Green certifications	23/08/2021	Online meeting
Patrick de Baat	RHDHV	Sustainability, Green certifications	23/08/2021	Online meeting
Quirine Henry	RHDHV	Architecture, Sustainability, Green certifications, Circularity	12/08/2021	Online meeting
Ragna Clocquet	RHDHV	Building physics, Sustainability, Green certifications	23/08/2021	Online meeting