ReLifeCycle

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P. van Rijsbergen

A Parametric Design Space Exploration Tool for Enhancing Responsible Material Use in Early Building Design

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PREFACE

It's a strange feeling writing this, realising that this preface is the final page I'll write before completing my studies at the Eindhoven University of Technology (assuming that I pass of course, but by writing this I'm just going to manifest it ;)). All I can say is that it's been a hell of a ride from start to end. I cannot express enough how valuable this time was for me personally. I've had so many amazing, new experiences that leave memories that will always remain dear to me, from living on my own for the first time and experiencing 'zero responsibilities' to somehow making it through the entire first year with a hangover half the time, starting an amazing band, and even building a sustainable house with my student team VIRTUe. I can see why so many people call this period 'the best time of their lives', although I definitely believe it doesn't end here, as the connections, inspirations and passions I've gathered over the years are eternal and will continue to bring me happiness for the rest of my life.

This graduation project started with me struggling to find a topic and eventually simply trying to combine the two biggest interests I developed during my studies: parametric design and sustainability. During my bachelor end project I got the chance to explore Grasshopper for the first time and I immediately fell in love with its special way of designing. I've always been walking the fine line between creativity and the technical field, not really knowing what I wanted to do, and then there it was: a way to use fields like mathematics creatively to generate designs that go beyond what I even thought was possible! Even though most of the time it's just really frustrating, as you're realising at 3 AM in the morning you've been staring at blocks and lines for the past 10 hours trying to solve a seemingly simple issue, somehow I just keep getting drawn to it. The other main motivation for continuing my studies in the built environment was the desire to do something good for the planet. So at every chance I got, I focused on sustainability in my projects, this graduation project being no exception. In the end I'm really proud of *ReLifeCycle*, the love child that was born from these two passions. I could never have dreamed that I would make my own Grasshopper plugin one day, and even now, looking back, I still can't believe it actually works.

I would like to use the last paragraph of this preface to express my gratitude to all the amazing, beautiful people that have supported me during this project. First a big thank you to Pieter Pauwels, my first supervisor, for supporting me in my ideas, sharing my love for parametric design and finding a way to make it fit in my graduation project. Also thanks to Ekaterina Petrova and Cristina Nan for being part of my amazing graduation committee and giving me exactly the feedback and insights that brought this thesis to another level. Special shout-out to Julia Kaltenegger, who, despite not being part of the committee, helped me countless times out of pure enthusiasm for the project. I would also like to thank my company supervisor, Sander van Gemert, for all the support and his unique ability to lift the weight of my shoulders during the most stressful periods. Of course many, many thanks to all of my amazing colleagues at Alba Concepts for the immense enthusiasm in my project. You gave me a place where I could truly be myself, and I can easily say that you've made this project ten times more enjoyable than it would have been alone. To my friends, family and band, thank you for keeping me from isolating myself for half a year and for knowing exactly when to pull me away for much-needed distraction. And last, but most definitely not least, to my lovely girlfriend for being there in the worst moments no one else saw, for taking care of me, and, of course, for always making me coffee at just the right time. You mean the world to me.

And finally thank you, the reader, for your interest in this topic. I hope it offers valuable insights!

With much love,

Pim van Rijsbergen
Eindhoven, March 2025

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ABSTRACT

The built environment stands out as a major contributor to global environmental impact, accounting for 35% of CO_2 emissions and 50% of raw material consumption in the Netherlands. Responsible material use, defined as the integration of Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and circularity, is crucial for reducing this impact. However, integration between these aspects is rare, and responsible material use is often neglected due to limited knowledge among design-related decision-makers, as well as a predominant focus on form- and cost-driven design. When considered, LCA, LCC or circularity implementation usually happens in the technical design phase where design changes are difficult and expensive. Hence, there is a need for a comprehensive tool that enhances responsible material use already during the early building design stages. Parametric design is found to be a potential method for this end due to its flexibility and optimisation potential for supporting Design Space Exploration (DSE). However, after evaluation of existing research and digital tooling, a notable gap was identified regarding research on the use of parametric design for enhancing responsible material use. To address this gap, *ReLifeCycle* is introduced as a parametric DSE tool. This research adopts design science and systems engineering methods and begins by defining requirements through user interviews, which are then translated into the system design using Unified Modeling Language (UML) diagrams. An integrated framework of assessment methods is made for quantifying LCA, LCC and circularity, with data stored in a relational MySQL database model. These components are the foundation for developing the *ReLifeCycle* prototype, which includes a Grasshopper plugin for responsible material use assessment, a Human UI script for a user interface, integration with Galapagos for Single-Objective Optimisation (SOO) and Wallacei for Multi-Objective Optimisation (MOO). The prototype is validated through a case study and expert opinion. The findings demonstrate the significant potential of parametric design for enhancing responsible material use and supporting DSE in early-stage design, and emphasise the need for a paradigm shift towards responsible material-driven design. However, the tool's reliance on data accuracy, assessment methods and building simplification, limits its ability to provide accurate real-world calculations. MOO proved effective as a means for supporting DSE, but critical reflection on the results remains necessary. Recommendations for further research include improving the integration of reusability, incorporating the financial residual value of materials, establishing a Building Information Modeling (BIM) connection and including operational and energy impacts.

Keywords: Responsible Material Use, Life Cycle Assessment, Life Cycle Costing, Circularity, Parametric Design, Design Space Exploration

SUMMARY

Introduction

With the Paris Agreement in 2015, the world agreed to limit the global temperature rise to a maximum of 1.5°C (United Nations, 2015). To achieve this goal, the Netherlands committed to reducing carbon emissions by 55% and primary resource use by 50% in 2030, aiming for a circular and climate-neutral society by 2050 (Rijksoverheid, nd). The built environment is one of the largest contributors to climate change and therefore must take immediate action. While current measures focus on reducing impact during the usage stage, a significant impact can still be reduced during the production and construction process (NPCE, 2023). This requires the responsible use of materials, defined by the integration of environmental impact measured through Life Cycle Assessment (LCA), financial impact measured through Life Cycle Costing (LCC) and circularity defined by Circular Economy (CE) principles.

Research shows that responsible material use is often overlooked in building design due to a lack of knowledge among design-related decision-makers (Meex et al., 2018), with architects mainly focused on form and contractors on costs (Mohammed, 2022). This highlights the need for a comprehensive tool that integrates LCA, LCC and circularity, something existing tools lack, to encourage responsible material-driven design. Moreover, assessments typically occur during late design stages, making changes difficult, while early integration can lead to a more environmentally friendly and circular design (Hollberg and Ruth, 2016). Additionally, the complex multi-objective nature of responsible material use makes the Design Space Exploration (DSE) process time-consuming, emphasising the need for optimisation methods. This leads to the following research question:

How can the responsible use of materials in a building be enhanced in the early design stages through parametric design?

The literature review introduces parametric design as a notable method for supporting DSE due to its flexibility and optimisation potential. A significant gap is identified in the use of parametric design for integrating LCA, LCC and circularity. This research therefore addresses this gap by introducing *ReLifeCycle*: a parametric DSE tool for responsible material use assessment and enhancement, developed for Grasshopper (Figure 0.1).

Figure 0.1: *ReLifeCycle* schematic framework

Methodology

The research adopts the design science methodology (Wieringa, 2014) and systems engineering approach (Kossiakoff et al., 2011) to develop a prototype for *ReLifeCycle*. First, a system design is defined, followed by a framework for assessment methods and data management, after which the prototype is developed.

ReLifeCycle Design

ReLifeCycle's user profile targets design-related decision makers, including architects, engineers, consultants and contractors, with parametric design expertise in Grasshopper. Due to the niche field of parametric design, it focuses on innovators and early adopters. Unstructured interviews with experts on parametric design, circularity and sustainability provide insights that are translated to a set of functional and non-functional requirements. These are divided into four main packages: (1) Model Linking

& Material Mapping; (2) Responsible Material Use Assessment; (3) Responsible Material Use Enhancement and (4) Results Interface. The requirements are prioritised with the MoSCoW method and the most important ones are converted into twenty use cases that define the system's functionality.

Unified Modeling Language (UML) diagrams and a system architecture are created to design the system. A use case diagram shows for each package the interactions between the actors and the system. The "Model Linking & Material Mapping" package involves assigning a name, classification and material to a Grasshopper geometry. The "Responsible Material Use Assessment" package calculates environmental impact, financial impact and circularity using an external material database. The "Responsible Material Use Enhancement" package uses a third-party optimisation plugin to generate material-optimised variants. The "Results Interface" visualises the assessment results in a user-friendly interface and allows the variants from the optimisation process to be compared efficiently.

Additional diagrams include an activity diagram for the system's workflow and sequence diagrams for defining the interactions between system components. The system architecture outlines the overall structure of the system, following the Model-View-Controller (MVC) software pattern.

ReLifeCycle Framework

Building on the system design, the workflows of *ReLifeCycle* are shown in Figure 0.2. The core is the *ReLifeCycle* Grasshopper plugin, which is based on an integrated assessment framework for responsible material use and a relational database model. The assessment framework proposes several methods for each aspect: (1) the MilieuPrestatie Gebouw (MPG), Paris Proof (PP) indicator and Construction Stored Carbon (CSC) for environmental impact (LCA); (2) direct costs (material and labour costs) and the True Price for financial impact (LCC); (3) the Building Circularity Index (BCI) including the Disassembly Potential (DP) and material input and output flows for circularity.

After an evaluation of databases, one database is selected for each aspect. The NL/SfB classification system is used to categorise building elements. A relational database model is made with MySQL that links these material databases.

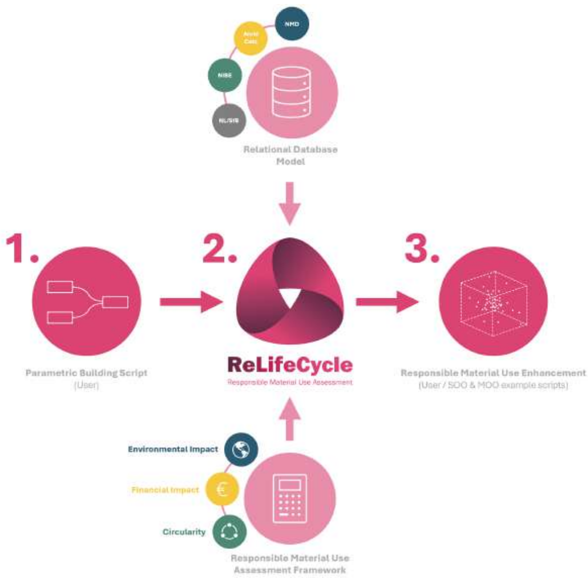

Figure 0.2: *ReLifeCycle* workflows

ReLifeCycle Prototype

The *ReLifeCycle* prototype consists of three main parts. The first part is a Grasshopper plugin, developed with C#, for the "Model Linking & Material Mapping" and "Responsible Material Use Assessment" packages. This plugin consists of custom Grasshopper components and establishes a connection with the MySQL server to retrieve material data. The second part considers the "Responsible Material Use Enhancement" package and uses the Galapagos plugin for Single-Objective Optimisation (SOO) and Wallacei for Multi-Objective Optimisation (MOO). The third part is the "Results Interface", which is made with a separate Grasshopper script, created with the Human UI plugin (Figure 0.3). All necessary code and resources for the *ReLifeCycle* prototype can be found on the GitHub repository, including demo videos.

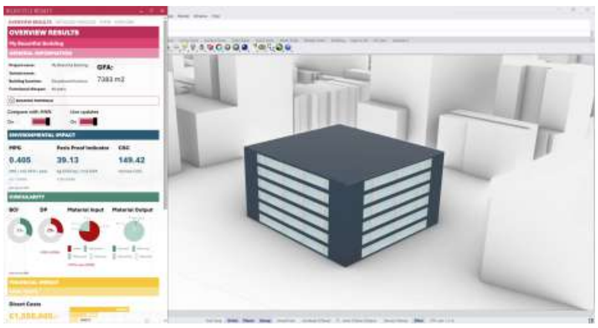

Figure 0.3: *ReLifeCycle* user interface

Validation

This research uses two validation methods: a real-life case study and expert opinion. The case study is "Het Schoolvoorbeeld", a school building concept initiated by the Innovation Partnership for School buildings (IPS) of the Municipality of Amsterdam. First, a parametric Grasshopper script is made for this case, after which the *ReLifeCycle* prototype is applied to assess its accuracy and potential to enhance responsible material use. Comparing the results to a benchmark shows minor deviations for the environmental and circularity assessments, and large deviations for the financial assessment, highlighting the dependence on data quality. After the benchmark, SOO and MOO algorithms are applied. SOO simulations for each assessment indicator show that environmental objectives favour mostly biobased materials, circularity objectives combine biobased and reusable materials like steel, and financial objectives prioritise traditional, cost-effective materials. To find the best solution for the case study requirements, two MOO simulations are performed. The first optimises one indicator per aspect simultaneously, while the second tries to minimise direct costs while setting the case study requirements as constraints. The second simulation provides the best solution, but requires some manual material adjustments to account for practical limitations not considered in the optimisation.

To gather expert opinion, a prototype test is conducted with three experts in parametric design. The participants found the *ReLifeCycle* workflow intuitive and valued the interface for providing clear results and multiple functions for finding high-impact areas. However, the test also highlighted the dependence on user input and understanding for accurate results, as well as the need for clearer documentation. In the end, *ReLifeCycle* successfully meets all MUST and most SHOULD requirements.

Conclusion

The main contribution of this research is the *ReLifeCycle* prototype, a parametric DSE tool for enhancing responsible material use in early building design. This tool consists of four contributions: (1) an integration between LCA, LCC and circularity for assessing responsible material use; (2) a relational database model for linking material data; (3) an integration with MOO for supporting DSE; and (4) a user-centred design for effective results visualisation.

A significant finding is the advancement of parametric design for responsible material use. *ReLifeCycle* is the first of its kind among state-of-the-art tools to integrate LCA, LCC and circularity with parametric design in one tool. Additionally, it pushes parametric design toward a more responsible material-driven design by incorporating material selection in the optimisation process, something that is not found in existing Grasshopper tools. This research therefore shows that parametric design has a high potential for enhancing responsible material use in the early design stages. Its ability to generate many design variants in a short time, in combination with MOO supports an intuitive, more efficient DSE process. However, this research also emphasises the need to be careful with relying on algorithmic optimisation due to its black-box nature, and suggests using it as a means rather than an end. Implementing *ReLifeCycle* into early-design workflows is expected to integrate responsible material use in early decision-making, but wider adoption of parametric design remains a challenge that requires initial implementation by early adopters. Finally, this research emphasises the need for a paradigm shift toward a more responsible material-driven approach in early design that goes beyond aesthetics and costs.

Limitations of this research include a high dependency on data quality, assessment methods and building model simplifications, making *ReLifeCycle* more suitable for comparison rather than accurate real-world calculations. Additionally, it does not yet support secondary material reuse, which is one of the most important circularity strategies. Furthermore, *ReLifeCycle* uses integer sliders to select materials for the optimisation plugins, which may skew results due to an assumed linear relationship between materials. Moreover, there is no direct, dynamic link with the source databases, reducing data accuracy and reliability.

For further research, it is recommended to integrate reused materials from urban mining hubs and material banks into the circularity assessment, incorporate financial residual value of materials, improve the design process with a BIM connection through Speckle and extend the tool's functionalities to include operational impact and energy aspects with plugins such as Ladybug.

SAMENVATTING

Introductie

Met het Klimaatakkoord van Parijs in 2015 is afgesproken om de wereldwijde temperatuurstijging te beperken tot maximaal 1,5°C (United Nations, 2015). Nederland streeft er daarom naar om de CO_2-uitstoot met 55% te verminderen en het primaire grondstoffengebruik met 50% in 2030, met als doel een circulaire en klimaatneutrale samenleving in 2050 (Rijksoverheid, nd). De bouwsector speelt hierin een cruciale rol. Huidige maatregelen richten zich vooral op de gebruiksfase, terwijl aanzienlijke milieuwinst te behalen is tijdens het productie- en bouwproces (NPCE, 2023). Dit vereist het verantwoord gebruik van materialen, gedefinieerd door de integratie van milieu-impact met Life Cycle Assessment (LCA), financiële impact met Life Cycle Costing (LCC), en circulariteit volgens de principes van de Circulaire Economie (CE).

Verantwoord materiaalgebruik wordt vaak over het hoofd gezien in gebouwontwerp door een gebrek aan kennis bij ontwerpgerelateerde besluitvormers (Meex et al., 2018), met architecten vooral gericht op esthetica en aannemers op kosten (Mohammed, 2022). Dit benadrukt de behoefte aan een tool die LCA, LCC en circulariteit integreert, iets wat bestaande tools missen, om verantwoord materiaalgedreven ontwerp aan te moedigen. Bovendien gebeuren evaluaties vaak laat in het ontwerpproces, waardoor wijzigingen moeilijk zijn, terwijl vroege integratie kan leiden tot duurzamere ontwerpen (Hollberg and Ruth, 2016). Daarnaast maakt de complexe multi-objectieve aard van verantwoord materiaalgebruik het proces van Design Space Exploration (DSE) tijdrovend, wat de noodzaak van optimalisatiemethoden benadrukt. Dit leidt tot de volgende onderzoeksvraag:

Hoe kan het verantwoord gebruik van materialen in een gebouw worden verbeterd in de vroege ontwerpfasen door middel van parametrisch ontwerpen?

De literatuurstudie introduceert parametrisch ontwerpen als een belangrijke methode om DSE te ondersteunen vanwege de flexibiliteit en optimalisatiemogelijkheden. Er ontbreekt echter onderzoek naar de toepassing van parametrisch ontwerpen voor de integratie van LCA, LCC en circulariteit. Dit onderzoek speelt hierop en introduceert *ReLifeCycle*: een parametrische DSE tool voor het evalueren en verbeteren van verantwoord materiaalgebruik, ontwikkeld voor Grasshopper (Figure 0.4).

Figure 0.4: *ReLifeCycle* schematisch framework

Methodologie

Het onderzoek past design science methodologie (Wieringa, 2014) en een systems engineering aanpak (Kossiakoff et al., 2011) toe om een prototype voor *ReLifeCycle* te ontwikkelen. Eerst wordt een systeemontwerp gedefinieerd, gevolgd door een framework voor evaluatiemethoden en data management, waarna het prototype wordt ontwikkeld.

ReLifeCycle Ontwerp

Het gebruikersprofiel van *ReLifeCycle* richt zich op ontwerpgerelateerde besluitvormers, waaronder ontwerpers, ingenieurs, adviseurs en aannemers, met expertise op het gebied van parametrisch ontwerpen in Grasshopper. Vanwege het nicheveld van parametrisch ontwerpen ligt de focus op innovators en early adopters. Ongestructureerde interviews met experts op het gebied van parametrisch ontwerp, circulariteit en duurzaamheid geven inzichten die worden vertaald naar een set functionele en niet-functionele eisen. Deze zijn onderverdeeld in vier hoofdmodules: (1) Modelkoppeling & Materiaaltoewijzing; (2) Evaluatie van Verantwoord Materiaalgebruik; (3) Verbetering van Verantwoord Materiaalgebruik en (4) Resultateninterface. De eisen worden geprioriteerd met de MoSCoW methode en de belangrijkste worden omgezet in twintig use cases die de functionaliteit van het systeem bepalen.

Unified Modeling Language (UML) diagrammen en een systeemarchitectuur ontwerpen het systeem. Een use case diagram toont de interacties tussen de actoren en het systeem. De module "Modelkoppeling & Materiaaltoewijzing" wijst materiaaldata toe aan geometrie. "Evaluatie van Verantwoord Materiaalgebruik" berekent milieu-impact, financiële impact en circulariteit met behulp van een externe materiaaldatabase. De module "Verbetering van Verantwoord Materiaalgebruik" gebruikt een externe optimalisatieplugin om materiaalgeoptimaliseerde varianten te genereren. De "Resultateninterface" visualiseert de resultaten in een gebruiksvriendelijke interface en maakt een efficiënte vergelijking van de optimalisatievarianten mogelijk.

Extra diagrammen omvatten een activiteitendiagram voor de workflow van het systeem en sequentiediagrammen voor de interacties tussen systeemcomponenten. De systeemarchitectuur schetst de algemene structuur van het systeem en volgt het Model-View-Controller (MVC) softwarepatroon.

ReLifeCycle Framework

De kern van het *ReLifeCycle* framework, bestaat uit de *ReLifeCycle* Grasshopper plugin, met een geïntegreerd evaluatieframework en een relationeel databasemodel (Figure 0.5). Het evaluatieframework omvat verschillende methoden voor elk aspect: (1) MilieuPrestatie Gebouw (MPG), Paris Proof (PP) indicator en Construction Stored Carbon (CSC) voor milieu-impact (LCA); (2) directe kosten en True Price voor financiële impact (LCC); (3) Building Circularity Index (BCI) inclusief Disassembly Potential (DP) en materiaalinput- en outputstromen voor circulariteit.

Na een evaluatie van databases is voor elk aspect één database geselecteerd. Het NL/SfB classificatiesysteem is gebruikt om bouwelementen te categoriseren. Het relationele databasemodel linkt deze databases met MySQL.

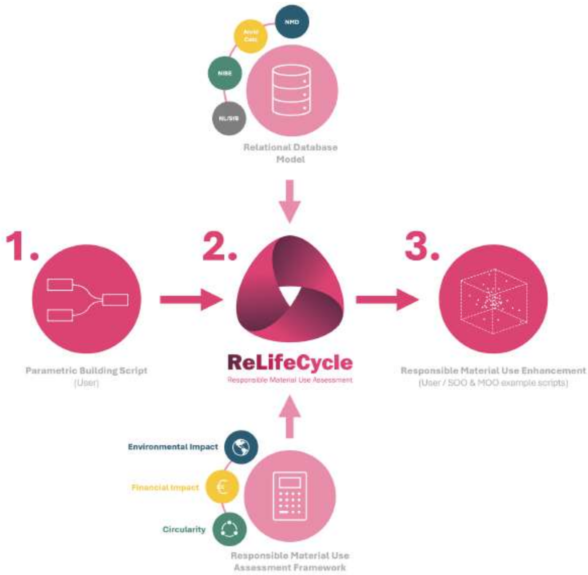

Figure 0.5: *ReLifeCycle* workflows

ReLifeCycle Prototype

Het *ReLifeCycle* prototype bestaat uit drie hoofdonderdelen. Het eerste onderdeel is een Grasshopper plugin, ontwikkeld in C#, voor de modules "Modelkoppeling & Materiaaltoewijzing" en "Evaluatie van Verantwoord Materiaalgebruik". Deze plugin bevat custom Grasshopper componenten en maakt verbinding met de MySQL server om materiaalgegevens op te halen. Het tweede onderdeel betreft de module "Verbetering van Verantwoord Materiaalgebruik" en maakt gebruik van de Galapagos plugin voor Single-Objective Optimisation (SOO) en Wallacei voor Multi-Objective Optimisation (MOO). Het derde onderdeel is de "Resultateninterface", die is gemaakt met een apart Grasshopper script, ontwikkeld met de Human UI plugin (Figure 0.6). Alle benodigde code en middelen voor het *ReLifeCycle* prototype zijn te vinden in de GitHub repository, inclusief demovideo's.

Figure 0.6: *ReLifeCycle* user interface

Validatie

Dit onderzoek maakt gebruik van twee validatiemethoden: een case study en expert feedback. De case study betreft "Het Schoolvoorbeeld", een schoolgebouwconcept geïnitieerd door het Innovatiepartnerschap Schoolgebouwen (IPS) van de Gemeente Amsterdam. Eerst wordt een parametrisch Grasshopper script gemaakt voor deze case, waarna het *ReLifeCycle* prototype wordt toegepast om de nauwkeurigheid en potentie voor het verbeteren van verantwoord materiaalgebruik te beoordelen. Vergelijking met een benchmark toont kleine afwijkingen in de milieu- en circulariteitsevaluatie, maar grote afwijkingen in de financiële evaluatie, wat de afhankelijkheid van datakwaliteit benadrukt. Na de benchmark worden SOO en MOO algoritmen toegepast. SOO simulaties per evaluatie-indicator laten zien dat milieudoelstellingen voornamelijk biobased materialen prefereren, circulariteitsdoelstellingen een combinatie van biobased en herbruikbare materialen zoals staal kiezen, en financiële doelstellingen traditionele, kosteneffectieve materialen prioriteren. Om de beste oplossing te vinden voor de casuseisen worden twee MOO simulaties uitgevoerd. De eerste optimaliseert één indicator per aspect tegelijk, terwijl de tweede directe kosten minimaliseert met de casuseisen als randvoorwaarden. De tweede simulatie levert de beste oplossing op, maar vereist enkele handmatige materiaalwijzigingen om praktische beperkingen die buiten de optimalisatie vallen te compenseren.

Voor de expert feedback methode is een prototype test uitgevoerd met drie experts in parametrisch ontwerpen. De deelnemers vonden de *ReLifeCycle* workflow intuïtief en waardeerden de interface vanwege de duidelijke resultaten en de verschillende functies om impactvolle elementen te identificeren. De test benadrukte echter ook de afhankelijkheid van gebruikersinput en -inzicht voor nauwkeurige resultaten, evenals de behoefte aan uitgebreidere documentatie. Uiteindelijk voldoet *ReLifeCycle* aan alle MUST en de meeste SHOULD eisen.

Conclusie

De belangrijkste bijdrage van dit onderzoek is het *ReLifeCycle* prototype, een parametrische DSE tool voor het verbeteren van verantwoord materiaalgebruik in de vroege ontwerpfasen van gebouwen. Deze tool levert vier bijdragen: (1) een integratie van LCA, LCC en circulariteit voor het evalueren van verantwoord materiaalgebruik; (2) een relationeel databasemodel voor het koppelen van materiaaldata; (3) integratie met MOO ter ondersteuning van DSE; en (4) een gebruikersgerichte ontwerpbenadering voor effectieve visualisatie van resultaten.

Een belangrijke bevinding is de vooruitgang van parametrisch ontwerpen voor verantwoord materiaalgebruik. *ReLifeCycle* is de eerste tool in de state-of-the-art die LCA, LCC en circulariteit integreert met parametrisch ontwerpen. Verder stimuleert het een materiaalgedreven aanpak door materiaalkeuze mee te nemen in het optimalisatieproces, iets wat niet gevonden is in bestaande Grasshopper tools. Dit onderzoek toont het potentieel van parametrisch ontwerpen voor het verbeteren van verantwoord materiaalgebruik en efficiëntere DSE in de vroege ontwerpfasen, maar benadrukt ook het risico van blind vertrouwen op algoritmische optimalisatie, en stelt voor om dit als middel te gebruiken in plaats van een doel op zich. Brede adoptie van parametrisch ontwerpen blijft echter een uitdaging die afhankelijk is van initiële implementatie door early adopters. Tot slot benadrukt dit onderzoek de noodzaak van een transitie naar een meer verantwoord materiaalgedreven ontwerp in de vroege ontwerpfasen, welke verder gaat dan alleen esthetiek en kosten.

Beperkingen van dit onderzoek zijn onder andere de sterke afhankelijkheid van datakwaliteit, evaluatiemethoden en gebouwmodel versimpelingen, waardoor *ReLifeCycle* geschikter is voor vergelijking dan voor nauwkeurige praktijkberekeningen. Daarnaast ondersteunt het nog geen secundair materiaalhergebruik, een van de belangrijkste circulariteitsstrategieën. Verder gebruikt *ReLifeCycle* integer sliders voor de materiaalkeuze in optimalisatieplugins, wat de resultaten kan vertekenen door een veronderstelde lineaire relatie tussen materialen. Bovendien is er geen directe koppeling met de originele databronnen, wat de nauwkeurigheid en betrouwbaarheid van de data vermindert.

Voor toekomstig onderzoek wordt aanbevolen om hergebruikte materialen uit urban mining hubs en materialenbanken te integreren in de circulariteitsevaluatie, restwaarde van materialen mee te nemen in de berekeningen, het ontwerpproces te verbeteren met een BIM-koppeling via Speckle, en de tool uit te breiden met operationele impact en energieaspecten via plugins zoals Ladybug.

LIST OF ACRONYMS

ADO	Architectural Design Optimisation
ADPE	Abiotic Depletion Potential for non-fossil resources
ADPF	Abiotic Depletion Potential for fossil resources
AI	Artificial Intelligence
AP	Acidification Potential
API	Application Programming Interface
BCI	Building Circularity Index
BIM	Building Information Modeling
BoQ	Bill of Quantity
Brep	Boundary Representation
CCC	Construction Consolidation Centre
CD	Construction Documents
CE	Circular Economy
CI	Circularity Indicator
cLCC	Conventional Life Cycle Costing
CLT	Cross-Laminated Timber
CSC	Construction Stored Carbon
DB	Database
DD	Design Development
DfA	Design for Adaptability
DfD	Design for Disassembly
DfRcy	Design for Recycling
DfRe	Design for Reuse
DP	Disassembly Potential
DSE	Design Space Exploration
ECI	Element Circularity Index
eLCC	Environmental Life Cycle Costing
EP	Eutrophication Potential
EPD	Environmental Product Declaration
ER	Entity Relationship
ETP	Eco Toxicity Potential
FAETP	Fresh Water Aquatic Ecotoxicity Potential
GA	Genetic Algorithm
GFA	Gross Floor Area
GH	Grasshopper
GUI	Graphical User Interface
GUID	Global Unique Identifier
GWP	Global Warming Potential
HNN	Het Nieuwe Normaal
HTP	Human Toxicity Potential
IFC	Industry Foundation Classes
IPS	Innovation Partnership for School buildings
IRP	Ionizing Radiation Potential
KPI	Key Performance Indicator
LCA	Life Cycle Assessment

LCC	Life Cycle Costing
LFI	Linear Flow Index
LI	LosmaakbaarheidsIndex
LP	Linear Programming
MAETP	Marine Aquatic Ecotoxicity Potential
MCI	Material Circularity Index
MKI	MilieuKostenIndicator
MOO	Multi-Objective Optimisation
MPG	MilieuPrestatie Gebouw
MVC	Model-View-Controller
NIBE	Nederlands Instituut voor Bouwbiologie en Ecologie
NLP	Non-Linear Programming
NMD	Nationale Milieu Database
NPV	Net Present Value
ODP	Ozone layer Depletion Potential
PCI	Product Circularity Index
PD	Pre-Design
PM	Particulate Matter emissions
POCP	Photochemical Ozone Creation Potential
PP	Paris Proof
SA	Simulated Annealing
SCI	System Circularity Indicator
SD	Schematic Design
SDK	Software Development Kit
S-LCA	Social Life Cycle Assessment
sLCC	Societal Life Cycle Costing
SOO	Single-Objective Optimisation
SQL	Structured Query Language
SQP	Soil Quality Potential
Std Dev	Standard Deviation
TCO	Total Cost of Ownership
TETP	Terrestrial Ecotoxicity Potential
UI	User Interface
UML	Unified Modeling Language
WDP	Water Deprivation Potential

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1. INTRODUCTION

1.1 Research Context

We live in a time where our world faces a global challenge: climate change. The major contributor to this issue is the emission of greenhouse gases such as carbon dioxide (CO_2), largely produced through energy production processes. All sectors contribute to this problem; however, the building and construction industry stands out, as it accounts for a staggering 40% of waste and 35% of CO_2 emissions in the Netherlands (Government of The Netherlands, 2016). It is also one of the highest material consuming sectors, especially of raw materials (Guerra and Leite, 2021; Zimmann et al., 2016) with an estimated account of 50% of raw material consumption of which 85% comes from primary resources and 15% from secondary resources (EIB, 2022). The Netherlands signed the Paris Agreement in 2015, agreeing to the goal of limiting the increase in global temperature to a maximum of 1.5°C to greatly reduce the impact of climate change (United Nations, 2015). To realise this objective, the Netherlands committed to reduce carbon emissions with at least 55% and primary resource use with 50% by 2030, aiming to be completely climate-neutral and circular in 2050 (Rijksoverheid, nd, 2019). We therefore have to rethink how we design and construct buildings and how we use materials in these processes to reduce environmental impact.

To address the problem of climate change, the concept of sustainability was called in life and famously defined by the Brundtland Report as "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland, 1987). Today, sustainability is often further described by three interconnected pillars for a holistic approach (Purvis et al., 2019): social, economic and environmental sustainability.

Complementary to sustainability, the concept of circularity in the form of the Circular Economy (CE), emerged. The CE is a model that opposes the concept of a linear economy and instead focuses on creating a closed-loop system by reusing, recycling, sharing, refurbishing, and other strategies to ensure that materials are never wasted. According to the Ellen MacArthur Foundation, a CE is based on three principles: (1) eliminate waste and pollution, (2) circulate products and materials and (3) regenerate nature (Ellen MacArthur Foundation, 2023). It has a strong relationship with sustainability since CE in general is seen as a beneficial condition for sustainability (Geissdoerfer et al., 2017). The Dutch 'National Circular Economy Program 2023-2030' (NCPE) states a clear ambition for the Netherlands: to be fully circular by 2050. For the built environment they define this as "meeting the socio-economic need for housing and infrastructure without exceeding the carrying capacity of the Earth" (NPCE, 2023).

To achieve this goal in the Netherlands, a large emphasis is placed on refurbishing existing buildings. However, it is estimated that one-third of the buildings that will exist in 2050, still have to be constructed and that the global building stock will even double by 2060 (Naimoli, 2020). It is therefore important to focus on both renovation and new construction. For new construction, the built environment has been making progress in reducing its environmental impact through sustainable developments mainly in the usage phase, such as the implementation of energy-saving solutions and PV panels. However, the NCPE emphasises that the following years should have a greater focus on reducing the impact of the construction process itself. This comes down to an important principle: the responsible use of materials and resources. If we become more conscious about the materials we use in our building designs, we can have a huge impact on reducing the global environmental impact to combat climate change.

Ansah et al. (2021) define 'responsible materials' as "products that have been certified as meeting sustainability standards". This can be viewed as considering the social, environmental, economic, and circular aspects of materials. Since social sustainability is an indirect effect of material use and therefore challenging to measure (Macombe et al., 2013; Siebert et al., 2018), it will be disregarded from the definition and this research will define responsible materials with the following aspects:

1. Environmental impact
2. Financial impact
3. Circularity

Design-related decision-makers in the built environment often have limited expertise on these aspects (Meex and Verbeeck, 2015; Meex et al., 2018). This asks for an assessment tool that reviews the responsible material use of a building design on these three aspects, so comparisons and optimisations can be made.

Many assessment frameworks already exist in current literature and practice for quantifying and measuring each aspect, however, a combination of all three seems to be uncommon. To assess the environmental impact of a building, Life Cycle Assessment (LCA) is often used. This is an internationally standardised method for assessing the environmental impact of a product or building during all stages of its life cycle (Ilgin and Gupta, 2010). However, some issues are identified with the current LCA methodology. In practice, LCA is rarely applied during the early stages of the design process. It is typically conducted in the fourth stage, known as the technical or construction design phase, where all necessary information is available to carry out an LCA without having to make assumptions (Hollberg and Ruth, 2016). Be that as it may, the first two stages, pre-design and schematic design, hold significant influence over design decisions and therefore have a large effect on the environmental impact of a building. For instance, if a concrete structure is chosen early on, switching this to a timber structure later to reduce environmental impact would require a major redesign of the grid layout and connections. This highlights the importance of including material-related performances in early design. This is also illustrated in the MacLeamy Curve (Davis, 2011) in Figure 1.1, which shows that the ability to impact the design decreases over time as costs of change increase.

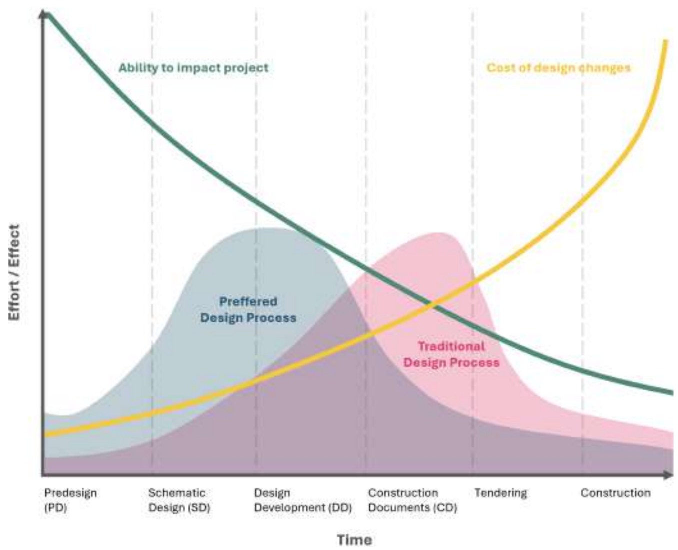


Figure 1.1: MacLeamy Curve (2004) (adapted from Davis (2011))

Additionally, LCA presents another challenge. According to van Gulck et al. (2022), conventional LCA methods follow a linear calculation approach that considers one life cycle of a building element but does not fully integrate circularity principles to design for a CE. In a CE, building elements can have multiple life cycles depending on their re-use and recycle potential (Eberhardt et al., 2019). For instance, in a linear LCA, a timber beam will always show a lower environmental impact compared to a steel beam.

However, the steel beam can be reused across multiple life cycles, potentially making it a more sustainable choice when reusing it. This reveals a broader perspective that goes beyond direct environmental impact. So to enlarge the perspective on the environmental impact of a building, we have to integrate circularity.

In terms of financial costs, Life Cycle Costing (LCC) is a calculation method that is often applied. It considers all costs during the lifetime of a product or service such as the construction, operation and end-of-life costs (Lu et al., 2021). Kambanou and Sakao (2020) state that financial costs are a major barrier for increasing circularity in businesses. They therefore highlight the importance of combining circularity with LCC into a combined framework so businesses can make well-considered circular decisions based on their budget.

Concerning circularity, there is no internationally standardised method as widely used as the LCA or LCC. However, a wide range of circularity indicators (C-indicators) exist like the Material Circularity Indicator (MCI) developed by the Ellen MacArthur Foundation (2015) and the Building Circularity Indicator (BCI) introduced by Verberne (2016), that have proven to be effective for measuring circularity (Cottafava and Ritzen, 2021; Elia et al., 2017; Khadim et al., 2022).

Digital tooling for LCA, LCC and circularity has mainly been developed in the field of Building Information Modeling (BIM) (Hollberg, 2016). However, in recent years, the use of parametric design methods for the built environment has gradually increased (Assasi, 2019). Nasir and Arif (2023) state that this method shows great promise to contribute to a sustainable built environment. This is mainly because of its computational power and optimisation possibilities, so more environmentally friendly and material-efficient building designs can be made. Parametric design is therefore a promising solution. However, there is a general lack of tools and research exploring the use of parametric design for responsible material use (Säwén et al., 2022; Dervishaj and Gudmundsson, 2024).

To use the advantages of parametric design, several studies conducted research into its use for supporting Design Space Exploration (DSE) and optimisation of building designs (Hollberg and Ruth, 2014; Reisinger et al., 2021; Wolbert, 2022; Zorn, 2023). Genetic Algorithms (GA's) are often applied for Multi-Objective Optimisation (MOO) processes, which are useful methods when a design has to be explored and optimised on multiple aspects.

1.2 Problem Definition

The research problem addresses four challenges. Firstly, responsible material use is often neglected in building design. This has three main reasons. First, design-related decision-makers often lack the required knowledge to make informed decisions on the use of responsible materials in their building designs (Meex et al., 2018; Meex and Verbeeck, 2015). Second, architects often prioritise form and spatial qualities over responsible material choices, where aesthetically pleasing materials are favoured (Mohammed, 2022). Third, there is general resistance among contractors to adopting sustainable and circular materials, with costs being a main driver in design decisions today (Lizarralde et al., 2015). It follows the principle of 'sustainability follows form, follows costs' where short-term savings are prioritised over long-term sustainability and circularity. Therefore, there is a need for a comprehensive tool that better informs the design-related decision-makers about the environmental, financial and circularity impacts of materials, looking beyond just costs and form.

Secondly, while tools already exist for measuring each aspect of responsible material use separately, a holistic approach is needed that integrates LCA with circularity to overcome its linearity (Eberhardt et al., 2019; Glogic et al., 2021; van Gulck et al., 2022; van Stijn et al., 2021) and includes LCC as a realistic constraint (Braakman et al., 2021; Kambanou and Sakao, 2020; Lavagna et al., 2021; Panjwani, 2022). Integration of all three aspects is rare in existing literature with only a few applications (Karabinar, 2021; Reisinger et al., 2022) and therefore requires more research.

Thirdly, if LCA, LCC and circularity assessments are actually performed, they usually happen in the technical or construction design stage (Hollberg and Ruth, 2016), which makes it difficult to change the design and materialisation. Therefore, it is important to consider these factors already early on, during the pre-design and schematic design phases, when more radical decisions on materials can be made.

Finally, finding the best design and material variants while considering the multiple objectives of responsible material use (LCA, LCC, circularity), is a time-consuming process. To make this process more efficient, there is a need for a tool that supports DSE with optimisation methods (Karabinar, 2021; Reisinger et al., 2021).

So based on the existing literature and the challenges mentioned, this study focuses on the need for a comprehensive tool that enhances responsible material use through an integrated assessment of LCA, LCC and circularity during early building design stages, to support design-related decision-makers in the design space exploration process and provide contractors with better insights into the long-term benefits of sustainable and circular materials.

1.3 Research Question and Objectives

This research specifically focuses on integrating responsible material use during the early design stages, as these stages have the most influence on design and material decisions. While existing studies and digital tools primarily examine LCA, LCC and circularity within the context of BIM, BIM software such as Revit is typically too advanced for the early design stages and is rarely used (Patsoumadakis, 2021). In contrast, parametric design is found to be better suited for early design due to its support in DSE (Dino, 2012), optimisation potential (Hollberg, 2016; Lobaccaro et al., 2018) and its ability to generate an infinite number of design variants (Nasir and Arif, 2023). However, parametric design is often associated with exploring design through form and space (Zarei, 2012), raising an interesting question: can it also be used to explore design with materials as a starting point? Given the limited research on the use of parametric design on responsible material use (Säwén et al., 2022; Dervishaj and Gudmundsson, 2024), the research question is formulated as follows:

"How can the responsible use of materials in a building be enhanced in the early design stages through parametric design?"

The objective of this research is to enhance responsible material use specifically during the early stages of building design. To bridge the gap in research on the potential of parametric design for this end, this research aims to develop *ReLifeCycle*, a parametric DSE tool explicitly designed to target users with influence on the design. This tool provides an integrated assessment framework for LCA, LCC and circularity. Here, a framework refers to a structured approach that organises and integrates calculation methods and data to assess responsible material use. *ReLifeCycle* builds upon the previous frameworks from Karabinar (2021) and Reisinger et al. (2022) and introduces a unique framework, as schematically illustrated in Figure 1.2. This framework is translated and developed into a user-friendly prototype tool that can be tested against its ability to enhance responsible material use in the early design stages.

The research has both practical and scientific objectives. Practically, *ReLifeCycle* aims to assist users in the DSE process by allowing them to evaluate, compare and optimise designs on the multiple objectives of responsible material use. A responsible material is defined by a low environmental impact and high circularity. As a result, the tool creates material variants that explore trade-offs, between the lowest environmental impact and highest circularity potential, while considering financial costs. In doing so, *ReLifeCyle* seeks to drive a shift among design-related decision-makers, transitioning from a traditional form- and cost-driven design to a more holistic, responsible material-driven approach. The societal impact of this potentially contributes to the overall reduction of environmental impact in the built environment.

Scientifically, the research seeks to develop a novel parametric approach to integrating LCA, LCC and circularity in the early design stages, addressing the gap in current practices that typically focus on BIM-based tools or fragmented assessments applied later in the design process.

Figure 1.2: *ReLifeCycle* schematic framework

1.4 Research Scope

To define a clear research scope, several limitations have been set for this study. First of all, the tool targets new construction, considering whole building designs at the meso (building) and micro (material) levels. Next, it will focus on the early design stages only, providing a so-called 'screening' assessment (Wittstock et al., 2012). These are the pre-design (PD) and schematic design (SD) phases. The design development (DD) and construction documents (CD) stages are out of scope for this research. While several parametric design software programs exist, the research will be limited to the Grasshopper and Rhino environment as these are the most commonly used programs in parametric architectural design, particularly during the early design stages (Gu et al., 2021). To further limit the scope of this research, the region is narrowed down to the Dutch construction industry. This means that material data and assessment methods will mainly be based on the Dutch standards. For the LCA aspect, only embodied environmental impact will be considered during a building's life cycle. The operational impact from energy consumption during the use stage will not be included in the assessment. Furthermore, only two of the three pillars of sustainability will be adopted in this research: environmental and economic sustainability. Social sustainability, often assessed with Social Life Cycle Assessment (S-LCA), is beyond the scope of this research.

Figure 1.3 outlines the scope of data sources, data attributes and assessment methods used in this research, following an input-process-output framework. For geometry data input, Grasshopper 3D building model geometry is used. In terms of material data, one database is selected for each aspect of responsible material use. For environmental impact (LCA), the Nationale MilieuDatabase (NMD) is employed, which contains data on environmental shadow costs (MilieuKostenIndicator (MKI)), Global Warming Potential (GWP) and Construction Stored Carbon (CSC). The NMD categorises data into three groups: (1) brand-specific; (2) brand-independent tested and (3) brand-independent untested. This research uses category 2, as brand-specific data is too detailed for the early design stages (Hollberg, 2016), and untested data carries a higher risk of inaccuracies. For financial impact (LCC), the ArchiCalc database provides data on material costs and labour costs and the Nederlands Instituut voor Bouwbiologie en Ecologie (NIBE) database offers circularity data related to material input and output flows, as well as disassembly factors. Elaboration on the selected databases is presented in Section 5.3. The material data is mapped to the geometry data and a responsible material use assessment is performed, consisting of an environmental impact, financial impact and circularity assessment. These assessments calculate multiple indicator results for each aspect, as illustrated in the diagram. A detailed explanation of the assessment methods is provided in Section 5.2.

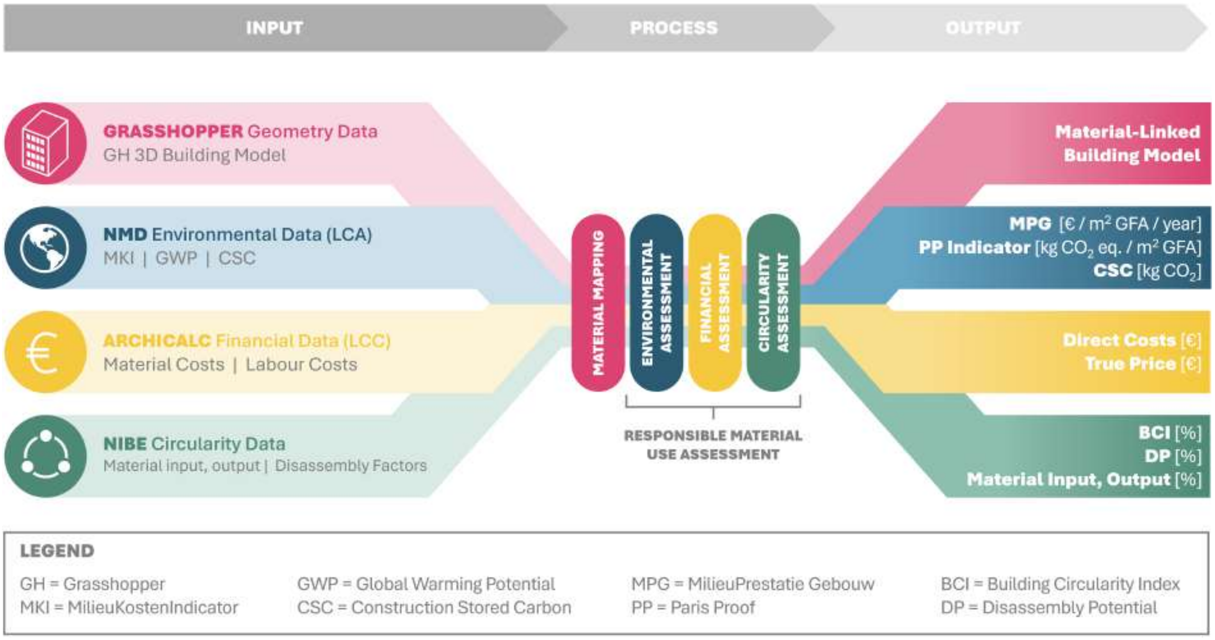


Figure 1.3: Input-process-output diagram explaining the scope of assessment methods and data

1.5 Reading Guide

Figure 1.4 provides an overview of the structure of this thesis. Section 1 gives an introduction into the research context. Section 2 provides an extensive literature review on responsible material use, related digital assessment tools and methods for supporting DSE. Section 3 outlines the research methodology, which is based on design science and systems engineering. Next, the system design of *ReLifeCycle* is elaborated in Section 4, including the definition of a user profile, requirements and system diagrams. Building on this, Section 5 introduces a framework for *ReLifeCycle*, which organises and integrates responsible material use assessment methods, data sources and the management of this data. Following the system design and framework, Section 6 describes the resulting prototype, which is validated in Section 7. The results are discussed in Section 8 and the thesis ends with a conclusion in Section 9, addressing the contributions, findings, limitations and recommendations of this research.

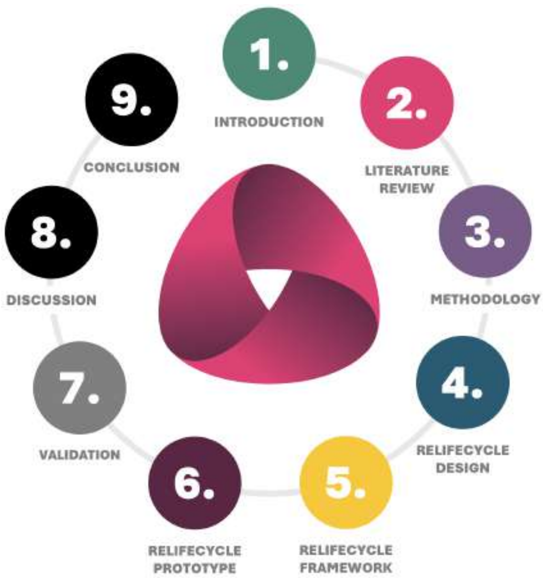


Figure 1.4: Reading Guide

2. LITERATURE REVIEW

2.1 Responsible Material Use

As addressed by the NPCE (2023), the built environment is responsible for a major part of raw material usage and should therefore place great focus on reducing the environmental impact of the construction process itself. Hence, it is essential to handle materials more responsibly. This research will therefore aim to find a method for aiding architects and decision-makers in enhancing the responsible material use of their building designs.

Responsible material use in this research is defined as the environmentally conscious management of materials. This includes: the minimisation of material use and waste and the maximisation of sustainable and circular material use (Figure 2.1). As stated in the Introduction, this is guided by three key principles: (1) environmental impact; (2) financial impact and (3) circularity.

To implement these principles, this research will explore the integration between them by investigating:

1. Life Cycle Assessment (LCA) for environmental impact
2. Life Cycle Costing (LCC) for financial impact
3. Circularity indicators for circularity

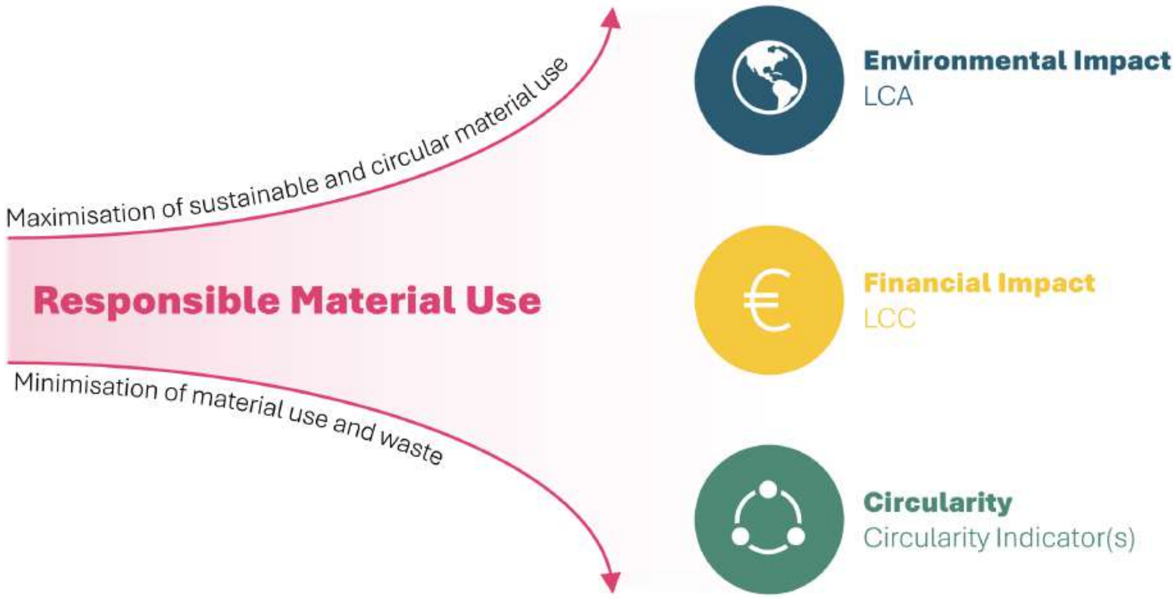


Figure 2.1: Explanatory visualisation of the responsible material use concept

2.1.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is an assessment method that is used to evaluate a product or a combination of products, like a building, through its entire life cycle. This encompasses everything from the extraction of raw materials to manufacturing, disposal and end-of-life scenarios (Ilgin and Gupta, 2010). The goal of an LCA is to evaluate environmental impact. LCA is a complex methodology that incorporates environmental data related to various products and materials. It considers environmental impact categories, which are specific effects of multiple emissions on the environment such as global warming, acidification and ozone depletion (Hauschild and Huijbregts, 2015). An impact category is measured in emission-equivalents, such as CO_2-equivalent for assessing global warming potential (GWP). In this context, the 'equivalent' means the combined impact of various greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O), converted into the equivalent amount of CO_2 required to produce the same impact on global warming. The standard European LCA methodology, EN15804+A1, originally encompassed 11 impact categories (Table 2.1). With the introduction of EN15804+A2, this has been updated to include several new indicators and sub-indicators, resulting in a total of 19 impact categories (Table 2.2).

Table 2.1: Environmental Impact Categories from EN 15804+A1 (set 1) (Stichting Nationale MilieuDatabase, 2022a)

Environmental Impact Category	Indicator	Unit
Global Warming Potential	GWP	kg CO_2-eq
Abiotic Depletion Potential for non-fossil resources	ADPE	kg Sb-eq
Abiotic Depletion Potential for fossil resources	ADPF	kg Sb-eq
Depletion potential of the stratospheric ozone layer	ODP	kg CFC-11-eq
Formation potential of tropospheric ozone photochemical oxidants	POCP	kg C2H4-eq
Acidification Potential of land and water	AP	kg SO2-eq
Eutrophication Potential	EP	kg $(PO4)^3$-eq
Human Toxicity Potential	HTP	kg 1.4-DCB-eq
Fresh water aquatic ecotoxicity potential	FAETP	kg 1.4-DCB-eq
Marine aquatic ecotoxicity potential	MAETP	kg 1.4-DCB-eq
Terrestrial ecotoxicity potential	TETP	kg 1.4-DCB-eq

Table 2.2: Environmental Impact Categories from EN 15804+A2 (set 2) (Stichting Nationale MilieuDatabase, 2022a)

Environmental Impact Category	Indicator	Unit
Climate change - total	Global Warming Potential total (GWP total)	kg CO_2-eq.
Climate change - fossil	Global Warming Potential fossil fuels (GWP fossil)	kg CO_2-eq.
Climate change - biogenic	Global Warming Potential biogenic (GWP biogenic)	kg CO_2-eq.
Climate change - land use	Global Warming Potential land use change (GWP – luluc)	kg CO_2-eq.
Ozone Depletion	Depletion potential of the stratospheric ozone layer (ODP)	kg CFC_{11}-eq.
Acidification	Acidification potential, Accumulated Exceedance (AP)	mol H^+-eq
Eutrophication aquatic freshwater	Eutrophication potential, nutrients reaching freshwater end compartment (EP freshwater)	kg P-eq.
Eutrophication aquatic marine	Eutrophication potential, nutrients reaching marine end compartment (EP marine)	kg N-eq.
Eutrophication terrestrial	Eutrophication potential, Accumulated Exceedance (EP terrestrial)	mol N-eq.
Photochemical ozone formation	Formation potential of tropospheric ozone (POCP)	kg NMVOC-eq.
Depletion of abiotic resources - minerals	Abiotic depletion potential for non-fossil resources (ADP minerals and metals)	kg Sb-eq.
Depletion of abiotic resources – fossil fuels	Abiotic depletion for fossil resources (ADP fossil)	MJ, net cal. val.
Water use	Water deprivation potential, deprivation-weighted consumption (WDP)	m^3 world eq. deprived
Particulate Matter emissions	Potential incidence of disease due to PM emissions	Health problems - incidence

Environmental Impact Category	Indicator	Unit
Ionizing radiation, human health	Potential human exposure efficiency relative to U_{235} (IRP)	kBq U_{235}-eq.
Eco-toxicity (freshwater)	Potential Comparative Toxic Unit for ecosystems (ETP fw)	CTUh
Human toxicity, cancer effects	Potential Comparative Toxic Unit for humans (HTP-c)	CTUh
Human toxicity, non-cancer effects	Potential Comparative Toxic Unit for humans (HTP-nc)	CTUh
Land use-related impacts / Soil quality	Potential soil quality index (SQP)	Dimensionless

An LCA calculates the environmental impact of a product's life cycle, which can be divided into five stages, each further subdivided into multiple modules (A1-A3, B1-B5, etc.) according to the EN15804 (Figure 2.2). The fifth module, Module D, is an optional module used to apply the benefits of using circular materials.

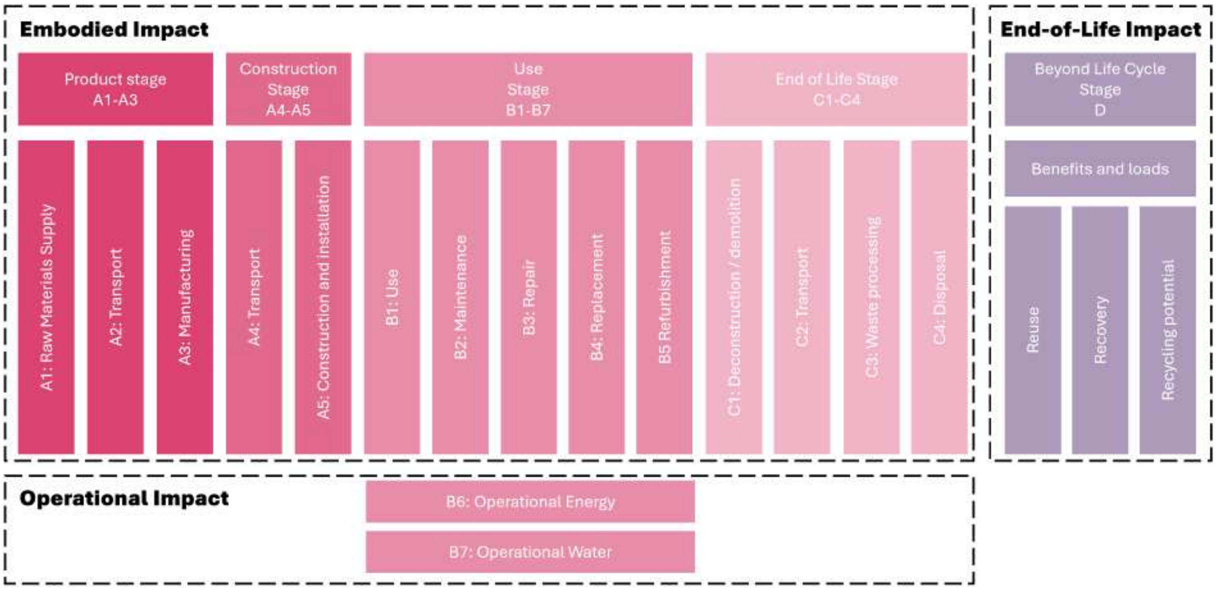


Figure 2.2: Life cycle stages (adapted from Building Enclosure (2021))

The conventional LCA methodology adopts a typical workflow that generally consists of four phases based on the ISO 14040 and 14041 international LCA standards (Ecochain, 2023):

1. Definition of goal and scope
2. Life Cycle Inventory (LCI)
3. Life Cycle Impact Assessment (LCIA)
4. Interpretation

In the goal and scope definition (1) an overview is made of the goal of the analysis and the elements to be included in the calculation. The latter is called the functional unit and consists of three parts for buildings: space (area, volume), lifespan and service (de Simone Souza et al., 2021).

Life Cycle Inventory (LCI) (2) involves data collection for the analysis and considers the environmental data of all used materials, as well as optional data on operational energy.

Life Cycle Impact Assessment (LCIA) (3) is a more complex phase in which the impact of the life cycle is calculated. It starts by determining which impact categories will be included. Afterwards, all effects on the environment are calculated by multiplying the product units with the emissions data from the LCI. Additional steps in this phase are characterisation, normalisation and weighting to place the results on a scale and convert them to a limited number of endpoints. Many different LCIA methods exist with different interpretations of how the emission results should be characterised to endpoints. Acero et al. (2015) provide a detailed overview of the most notable LCIA methods such as ReCiPe (Huijbregts et al., 2017), Eco-indicator 99 (Goedkoop and Spriensma, 2000) and ILCD (Chomkhamsri et al., 2011).

The final phase of the LCA process concerns the interpretation phase (4) which involves analysing the results to identify potential issues and make informed decisions.

Applying LCA for buildings can be difficult as not all necessary information and data are available to perform a complete LCA study during every stage of the design process, especially not in the early design stages (Wittstock et al., 2012), where specific material types and quantities are not fully defined yet. A building-specific LCA can furthermore be executed for different goals, such as a small LCA to check and minimise the environmental impact of a first design variant or a more advanced LCA near the end of the design process. To address this complexity, Wittstock et al. (2012) defined three types of LCA studies for buildings in the EeBGuide documents: (1) screening LCA; (2) simplified LCA and (3) complete LCA (Figure 2.3). These types can be seen as different levels of detail that are related to the goal and scope of a specific study. A screening LCA (1) contains the least detail and provides a brief, initial overview of the environmental impact of a building design so hotspots can be identified that require attention. This is usually done in the early design stages. It is important to note that a screening LCA is based on generic data (Meex et al., 2018), which is averaged material data that is not brand-specific, whereas specific data does relate to materials from particular brands and manufacturers. A screening LCA is therefore not officially representative and cannot be used to make comparisons with other buildings. A simplified LCA (2) adopts a similar method as the screening LCA but uses more precise data so a preliminary environmental assessment of a building can be performed. This type of study is often done in the design development stage where more information is available. According to Meex et al. (2018), a simplified LCA should use specific environmental data if this is available and otherwise generic data. Therefore, it still gives an estimation of environmental impact but with more accuracy than the screening LCA. Finally, the complete LCA (3) is the most comprehensive method and follows all guidelines in the ISO 14040 and 14044 LCA standards. This type is generally applied in the final stages of the design process when all information is available so product-specific data can be used. The results of a complete LCA are officially representative of the environmental impact of the building.

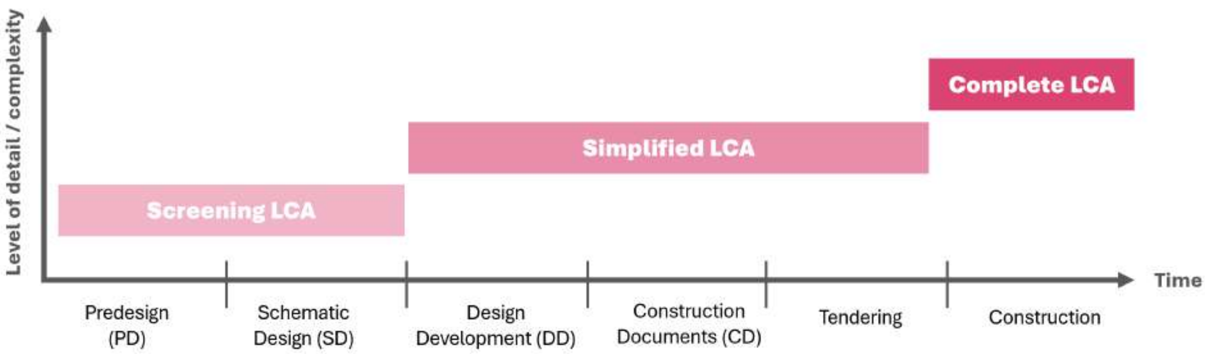


Figure 2.3: Relation between types of LCA and building design stages (adapted from Meex et al. (2018))

In the Netherlands, the MilieuPrestatieberekening Gebouw (MPG) is used as the general environmental impact assessment method for the built environment. This is a tool for calculating the shadow costs of a building. Shadow costs are defined as prevention costs, the theoretical costs of measures a government should take to prevent one unit of a specific environmental impact emission (Stichting Nationale Milieu-Database, 2022b). So for instance, this could involve an investment of a government in renewable energy, calculated as the cost of preventing one kilogram of CO_2. The higher the shadow costs, the greater the environmental impact on the planet, contributing to areas such as resource depletion, global warming and ecological degradation. The shadow costs are determined with the MilieuKostenIndicator (MKI), in English called the Environmental Cost Indicator (ECI), and are converted to a single-point score called the MPG score in Euros / m^2 GFA / year, which can be used to compare buildings.

2.1.2 Life Cycle Costing

Life Cycle Costing (LCC) is an assessment method that calculates the costs of an asset, or in the case of the construction industry, a building over all its life cycles (Woodward, 1997). It considers the economic pillar of sustainability and can have a diverse range of purposes such as planning, finding cost-saving opportunities, optimisation and investment evaluation (Rödger et al., 2017). White and Ostwald (1976) defined it as “the sum of all funds expended in support of the item from its conception and fabrication through its operation to the end of its useful life”. LCC therefore extends beyond initial purchase costs and provides a more complete perspective which is specifically useful for organisations to investigate the financial feasibility of a project in the long term. For example, when looking at the initial investment costs of high-performing materials or systems, these may seem high, but if this greatly reduces the costs during the maintenance and use stage, those might be more feasible than less expensive products. In general, two types of LCC costs can be identified: internal and external costs (Rödger et al., 2017). Internal costs, or private costs, are costs covered by actors directly involved in a product’s life cycle, such as manufacturers, contractors and consumers. External costs concern the indirect costs to society. For example, the construction of a new highway might lead to increased noise and air pollution, causing nearby housing prices to decrease. LCC can also include revenues which are defined as negative costs, however, in practice these are often ignored when multiple stakeholders are involved that sell and buy from each other (Panjwani, 2022). LCC can be applied to different objectives and scopes, aligning with the LCA goal and scope definition phase. To suit the needs of each objective, a working group of SETAC (Society of Environmental Toxicology and Chemistry) made a distinction between three types of LCC (Hunkeler et al., 2008; de Menna et al., 2016; Rödger et al., 2017) which are depicted in Figure 2.4:

1. **Conventional LCC (cLCC).** This type is also referred to as financial LCC and is the first adopted LCC method (White and Ostwald, 1976). cLCC is an economically motivated method and considers only the internal costs that have to be made by a single stakeholder such as a customer or a manufacturer. In the case of a building, this would include initial investment costs, such as costs for material, staff and equipment, as well as construction and maintenance costs for a contractor. The method for cLCC is adopted in various standards but is specifically targeted for the built environment in the ISO 15686 (van Oeveren, 2020).

2. **Environmental LCC (eLCC).** eLCC was developed by (Hunkeler et al., 2008) and extends upon cLCC by including the costs of a product for each phase of its whole life cycle. Where cLCC focuses on mainly one stakeholder, eLCC includes all stakeholders involved in the life cycle of a product and evaluates the entirety of internal costs that they have to cover. For a building, this includes both the costs of the contractor and the costs covered by other stakeholders such as the material factories. eLCC can also account for “to be internalised external costs” (Hunkeler et al., 2008) that compensate for the impact on the environment, for instance carbon taxes. There is no standardised method available yet for eLCC so currently the method developed by Hunkeler et al. (2008) is generally used which follows the international LCA standards: ISO 14040 and ISO 14044.

3. **Societal LCC (sLCC)**. The third and final LCC type, sLCC, includes all internal and external costs on a societal level and its main objective is governmental decision-making. If we compare this to the case of a building, this includes impacts on society, such as the impact on the neighbourhood level during construction and the long-term social effects of the construction of the building. These impacts are monetised to be able to assess the total societal costs. sLCC is currently in development (Rödger et al., 2017) and has no standardised or widely-adopted method.

Figure 2.4: Three types of LCC (adapted from Rödger et al. (2017))

When investigating the integration between LCC and LCA, eLCC seems to be most compatible compared to cLCC and sLCC (Heijungs et al., 2013; de Menna et al., 2016; Rödger et al., 2017), because of its lifecycle-based procedure as well as the potential inclusion of financial costs due to environmental impact, such as carbon taxes. It is therefore often conducted in combination with LCA.

The steps in an eLCC are therefore very similar to the steps of an LCA. Based on Rödger et al. (2017) and Lu et al. (2021) these are defined as:

1. Goal and scope definition
2. Collection of data for inventory analysis
3. Life Cycle Costing Assessment (LCCA)
4. Interpretation and sensitivity analysis

The goal and scope definition (1) follows the same procedure as in an LCA, determination of the goal, functional unit and limitations. The inventory analysis step (2) concerns the collection of the necessary internal and external financial data sources. LCCA (3) calculates the total costs of a product during its life cycle with LCC calculation methods. The interpretation phase (4) carries out an analysis of the LCCA results and can include net savings, savings-to-investment ratio, payback period and a sensitivity analysis (Lu et al., 2021). The LCA procedure follows a similar approach with goal and scope definition, inventory analysis, impact assessment, and interpretation. However, a key difference is that LCA requires the inventory data to be converted into impact categories that are weighted on importance during the LCIA, which is not necessary for LCC (Rödger et al., 2017). The costs can directly be used in calculating the total costs over a product's life cycle. Furthermore, an eLCC considers the time value of money (Lu et al., 2021), the change in costs over time due to factors like interest and discount rates. This also differs from standard LCA procedure.

For categorising the different costs within an eLCC, (de Menna et al., 2016) provide several frameworks such as (1) economic typology (budget, market, external); (2) life cycle stage (production, manufacturing, end-of-life); (3) activities (design, production, maintenance) and (4) other categories (staff, material, energy taxes). A categorisation based on life cycle stage seems to be most aligned with the LCA. This is also further supported by the ISO 15686 which divides LCC into construction, operation, occupancy, maintenance and end-of-life costs (Lu et al., 2021).

Many LCC calculation methods exist; however, for the built environment specifically, notable ones are the Net Present Value (NPV) and the Total Cost of Ownership (TCO) (Lu et al., 2021; Xie et al., 2022; Pearce et al., 2010). The NPV method is a conventional LCC method that takes into account cashflows (both revenues and costs) and uses discount and inflation rates to consider the time value of money. Its main purpose is to examine if an investment will yield a positive return. The TCO method is often used for comparing (sustainable) design variants on cost-savings and considers all direct and indirect costs during the entire life cycle of a product that an owner has to pay (Pearce et al., 2010). Revenues are excluded from this assessment.

Similarly to the LCA methodology, an LCC study can be performed at three levels of detail: (1) screening LCC; (2) simplified LCC and (3) complete LCC. The screening and simplified LCC studies use generic financial data, whereas the complete LCC uses product-specific data and adopts a more comprehensive approach.

2.1.3 Circularity

2.1.3.1 Definition of Circularity

Circularity is often referred to and considered the same as a Circular Economy (CE), which opposes the linear economy model, where products are created with raw material sources and disposed as waste at the end of their lives (Wautelet, 2023). A CE focuses on creating a closed-loop system by reusing, recycling, sharing, refurbishing and other strategies aimed to ensure materials will not be wasted (Ellen MacArthur Foundation, 2013). The concept of a CE has no clear origin or author, but it has been spoken about since the late 1970s (Ellen MacArthur Foundation, 2013) and gained real momentum through the report from the Ellen MacArthur Foundation and the McKinsey Company published during the World Economic Forum in 2012, in which they emphasised the importance of a transition to a CE (Wautelet, 2023).

According to the (Ellen MacArthur Foundation, 2013), the CE concept evolved through various schools of thought: (1) regenerative design; (2) performance economy; (3) Cradle to Cradle (C2C); (4) industrial ecology; (5) blue economy; (6) biomimicry and (7) permaculture.

Regenerative design (1) is a method of designing systems in such a way that they renew themselves, which means their consumption of materials and energy sources is regenerated constantly, similarly to natural ecosystems (Lyle, 1994).

The performance economy (2) is defined as an economy that “does the right things” by prioritising the environmentally conscious use of resources and focusing on selling services instead of products (Ellen MacArthur Foundation, 2013; Stahel, 2006; Wautelet, 2023).

C2C (3) is a framework developed by McDonough and Braungart (2002) and is based on the idea that all materials are nutrients and that product manufacturing and energy production should be a closed-loop system with three design principles: “waste equals food”, “use current solar income” and “celebrate diversity” (Ellen MacArthur Foundation, 2013; McDonough and Braungart, 2002). In this closed-loop system, two types of cycles are identified: the biological and technical cycle (Figure 2.5). The biological cycle considers the circulation of products for human consumption, which should always be bio-degradable to be used as nutrients again. The technical cycle, on the other hand, is about the circulation of service products that should never go to disposal (McDonough and Braungart, 2002).

Industrial Ecology (4) is the study of ecological principles in industrial systems and revolves around the idea of viewing the industrial society as a separate ecosystem on the planet (Wautelet, 2023). Similarly to C2C, this principle focuses on creating closed-loop systems with no waste (Ellen MacArthur Foundation, 2013).

The Blue Economy (5) is an economic school of thought and aims to tackle resource scarcity by focusing on everything that is locally available such as materials and energy sources, therefore creating more value through innovative business models and competitiveness (Ellen MacArthur Foundation, 2013; Pauli, 2016; Wautelet, 2023).

Biomimicry (6) was introduced by Benyus (1997). It investigates natural processes and ideas and

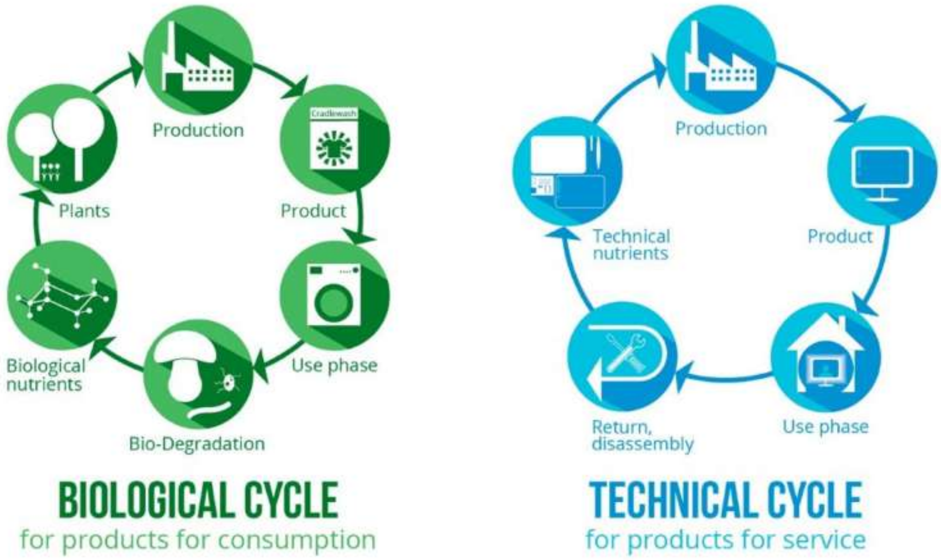


Figure 2.5: The biological and technical cycles in the C2C framework (EPEA, 2017)

tries to imitate these to solve environmental problems, as everything in nature has already evolved to fit perfectly within its ecosystem (Wautelet, 2023). The three main principles of biomimicry are: "nature as model", "nature as measure" and "nature as mentor" (Benyus, 1997).

The final school of thought, permaculture (7), is a concept that implements the diversity, stability and resilience of natural ecosystems into agricultural landscapes to create more sustainable farming (Ellen MacArthur Foundation, 2013) and is defined by the founders of the term, Mollison and Holmgren (1978), as "an integrated, evolving system of perennial or self-perpetuating plant and animal species useful to man" (Mollison and Holmgren, 1978).

The schools of thought previously mentioned, form the roots of the CE concept, however, the exact definition of CE has been a topic of discussion for many years among scholars and practitioners (Lieder and Rashid, 2016). To provide a clarification on this topic, Kirchherr et al. (2017) investigated 114 definitions of CE found in existing literature. After a thorough analysis, they formulated the following overarching definition that encompasses all the key aspects of CE:

> *"An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations"*
>
> (Kirchherr et al., 2017)

They do add that it should be acknowledged that CE is not limited to a definition and its understanding has multiple dimensions. It will be, however, the definition of CE that this research will adopt.

The Ellen MacArthur Foundation has translated the original schools of thought and definition of CE to three main principles: (1) "eliminate waste and pollution"; (2) "circulate products and materials" and (3) "regenerate nature" (Ellen MacArthur Foundation, 2023). To go beyond a definition and principles, the Ellen MacArthur Foundation visualised the CE concept with the widely known butterfly diagram (Figure 2.6), which extends upon the C2C model from McDonough and Braungart (2002) (Figure 2.5).

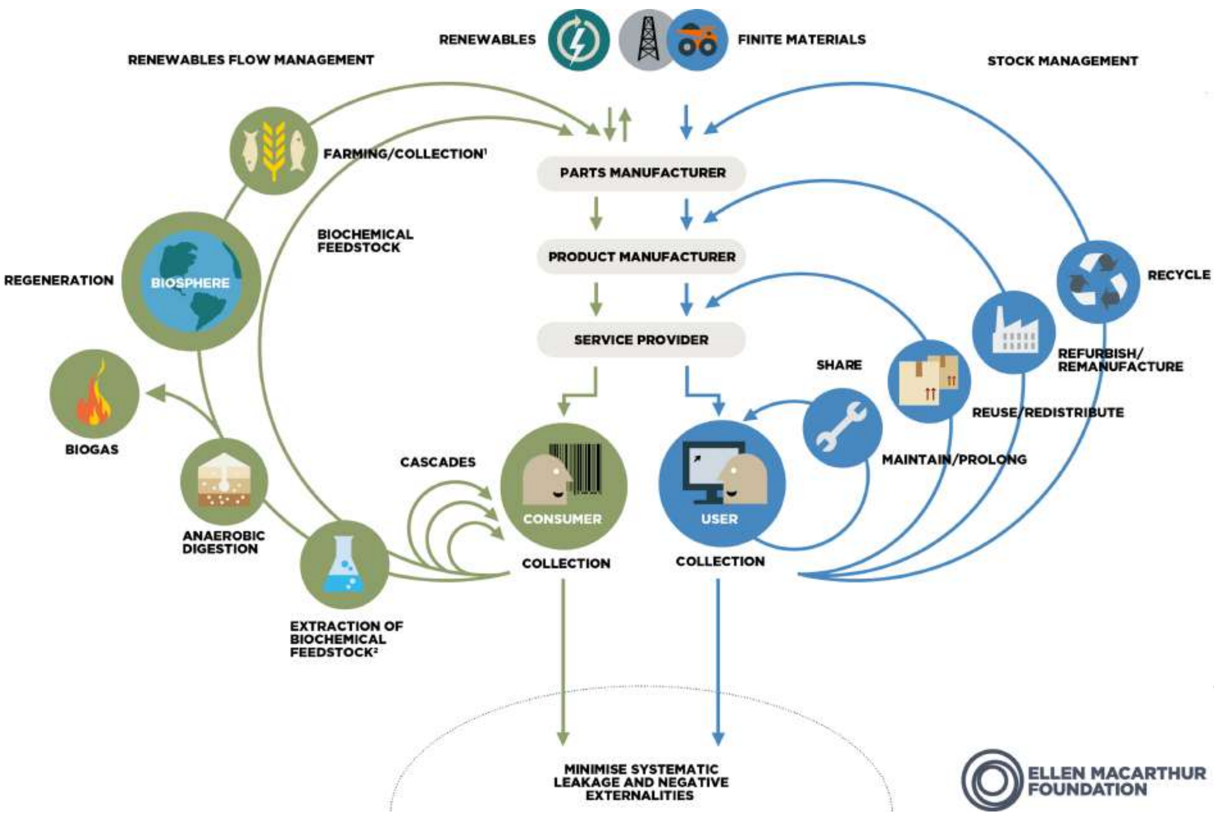


Figure 2.6: Circular Economy butterfly diagram (Ellen MacArthur Foundation, 2019)

The middle of the butterfly diagram represents the production process, which starts with raw resources, either renewable or finite, after which they are extracted by the parts manufacturer, made into products by the product manufacturer and distributed to the consumers and users by the service provider.

The left wing of the diagram represents the biological cycle which considers only biodegradable materials such as food and timber (Ellen MacArthur Foundation, 2022a). The main concept of this cycle is the regeneration of nature by returning nutrients from biological products back to the biosphere instead of wasting them. In this way they can be farmed or collected again when regenerated. A different concept within the biological cycle is cascading. Cascading means aiming to get the maximum possible value out of a material by (re)using biological resources as much as possible before they are returned to Earth. An example of this would be making stock from vegetable scraps instead of wasting them. According to the CE, materials should always circulate in cascading loops first before going to the outer loops where they are used to create biogas or compost that is returned to the earth to be regenerated.

The right wing represents the technical cycle, that covers products that are used rather than consumed. This cycle consists of non-biodegradable materials such as metals (Ellen MacArthur Foundation, 2022b). The smaller the loop in the technical cycle, the more effectively the maximum value can be taken out of a product. The smallest cycle, for example, considers the concept of product sharing. By sharing products with different users, the intensity of the use of those products increases, which ensures that more value is generated before the products start to degrade. Another cycle is the maintenance of products to prolong their lifetime. This also increases the value of a product during its lifetime. Reusing is the concept of designing products in such a way that they do not go to waste, like reusable bags or demountable concrete floor slabs. The last resort option in the technical cycle is recycling, which happens when a product cannot be reused or refurbished in any way anymore. In this step, the product is converted back to its basic materials so its value is preserved. However, the energy used to initially manufacture the product is lost through this process.

Both cycles eventually aim to "minimise systematic leakage and negative externalities" (Ellen MacArthur Foundation, 2019) which is indicated at the bottom of the diagram.

2.1.3.2 Circularity in the Built Environment

The built environment is one of the main contributors to climate change (Government of The Netherlands, 2016) so it is highly beneficial to move towards a CE in this sector. This is why, through the 2015 Paris Agreement, the Netherlands agreed to reduce the usage of primary resources by at least 50% by 2030 and ultimately achieve a fully circular economy in 2050 (Rijksoverheid, 2019).

Just as with the concept of CE itself, the meaning of CE in the built environment is a topic of discussion in current literature and a clear definition is lacking (Ossio et al., 2023). The Dutch Circular Construction Economy, the organisation responsible for developing the agenda for the transition to a CE in the Netherlands, define circularity in the built environment (circular construction) as follows:

> *"Circular construction is defined as the development, use and reuse of buildings, areas and infrastructure without unnecessarily exhausting natural resources, polluting the living environment, and affecting ecosystems. Construction in a way that is economically sound and contributes to the well-being of humans and animals. Here and there, now and later."*
>
> (Economy, 2018)

Another angle is given by Ossio et al. (2023) who reviewed 316 publications to introduce the following definition of circularity in the built environment:

> *"Circular Construction is a multidimensional and dynamic economic system for construction based on the application of Economy principles. It aims to achieve buildings and infrastructure designs considering different systemic levels (micro, meso, and macro) to achieve a built environment that targets zero waste and pollution. It allows construction materials and products to remain in use, retaining their maximum value by following biological or technical looping strategies through and within the whole life cycle of construction projects. This approach operates in a sustainable, clean, and renewable way, allowing for the regeneration of natural systems. It is enabled by a context defined by technology, management systems, government policies and regulations, business models, and social and stakeholder behaviour that enable construction needs to be met sustainably."*
>
> (Ossio et al., 2023)

This definition is considered to be more complete in comparison to the one from the Circular Construction Economy and will therefore be adopted by this research as the definition of CE in the built environment.

As mentioned in the definition from Ossio et al. (2023), circularity in the built environment can be further decomposed into circularity at macro, meso and micro levels (Pomponi and Moncaster, 2017). The micro level is the least complex and focuses on individual building elements and materials. The meso level considers a building as a whole that consists of multiple elements and materials, increasing complexity and interdisciplinarity. The macro level is the most complex and encompasses cities and areas, which brings many more dimensions such as social, ecological and technical aspects (Rios et al., 2022). In this research, the focus will be on the meso and micro levels that consider circular building design and circular use of materials.

A way to decompose circularity at the meso (building) level further is the concept of the building shearing layers, originally developed by Frank Duffy (1990) and elaborated by Stewart Brand (1994). This concept divides a building into several layers of components, each with a different lifetime (Figure 2.7). They state that during the lifetime of a building, changes happen for each of these layers separately, rather than for the whole building as a single object (Moffatt and Russel, 2001). Looking at a building from this perspective, we get a better view of which circularity strategies can be implemented for each layer based on their lifetime and material composition.

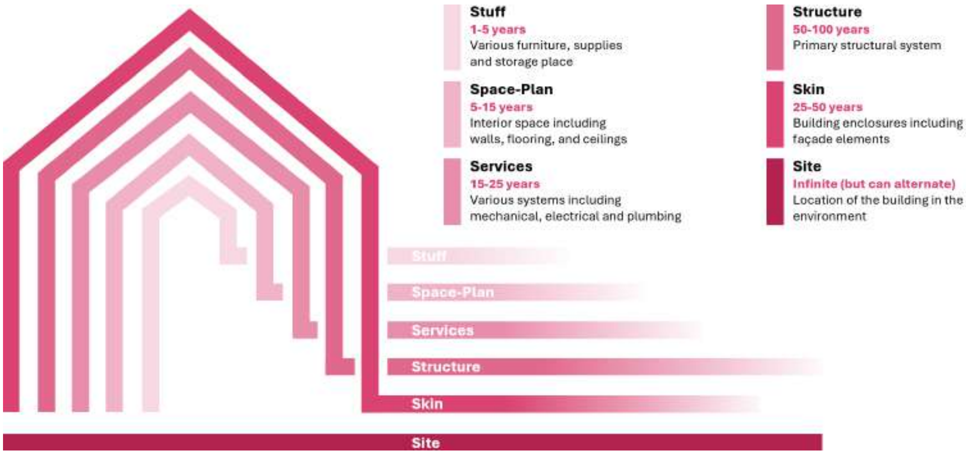


Figure 2.7: Building shearing layers from Brand (1994) (adapted from Building Enclosure (2022))

The way to transition to a CE in the built environment is through circularity strategies. To provide a clear basis for these strategies from a business perspective, Bocken et al. (2016) developed a framework for the transition from a linear to a circular economy. They introduce three resource cycles: slowing, closing and narrowing the loop (Figure 2.8) which all work towards reducing resource use. Slowing the loop is done by extending the lifetime of a resource through reuse, maintenance, refurbishment, etc. Closing the loop considers recycling resources at the end of their life to ensure a circular production process, and narrowing the loop is about using as few materials as possible for a product.

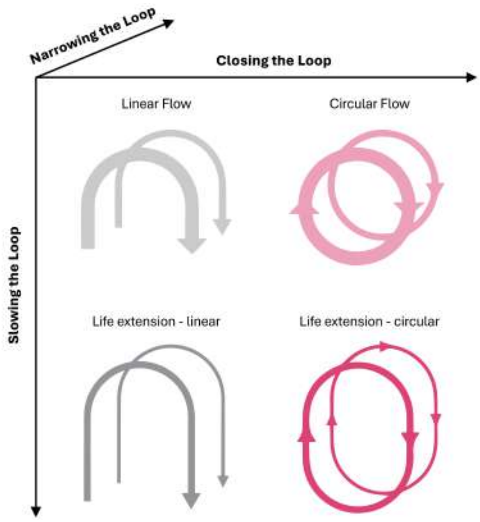


Figure 2.8: Linear and circular flows and the effect of different resource cycles to reduce resource use (adapted from Bocken et al. (2016))

The NPCE (2023) adds a fourth element to the framework from Bocken et al. (2016) and introduces "substitution", which considers replacing primary resources with secondary resources where possible. Based on these four measures, the NPCE provides a set of circularity strategies for the built environment which can be seen in Table 2.3.

Table 2.3: Circularity strategies for the built environment (NPCE, 2023)

Type of measure	Circularity strategies
Slowing the loop	■ Maintaining buildings in a way that extends their lifetime ■ Designing and constructing buildings in a way that extends their lifetime ■ Design for adaptability so a building can adapt to suit the needs of different end-users ■ Reuse reclaimed building components as much as possible ■ Design buildings so that their components are demountable and can be reused
Closing the loop	■ Recycle reclaimed building components in a high-grade manner when they cannot be reused
Narrowing the loop	■ Constructing more efficiently with limited waste ■ Use as few primary materials as possible
Substitution	■ Developing and using materials with a lower environmental impact, such as environmentally friendly, secondary, and renewable materials

For this research, which focuses on early building design, the "design" strategies from the NPCE are most interesting to explore. These strategies include a broad spectrum of methods such as Design for Disassembly (DfD), Design for Adaptability (DfA), Design for Reuse (DfRe) and Design for Recycling (DfRcy) (Charef et al., 2022; Ossio et al., 2023). Among these, DfD and DfA stand out as the most important strategies for the built environment's transition to a CE and should be integrated into the early design phases (Askar et al., 2022; Dams et al., 2021).

Design for Disassembly (DfD) is a method for designing buildings in such a way that they can be disassembled during their lifetime to accommodate future changes or, at the end of their life when they are demounted, to efficiently recover building components so they can be reused for other applications (Guy and Ciarimboli, 2005), acting as a "material bank" (Ottenhaus et al., 2023). In this way the value of each building component increases and the environmental impact decreases. Guy and Ciarimboli (2005) made a manual for designers to integrate DfD and set up ten main principles of the approach. Some highlighted principles include (1) documentation of materials and disassembly methods; (2) design of accessible and demountable connections with minimisation of chemical connections such as glue; (3) separation of MEP systems and (4) simplicity of structure and building design through standardisation. Important to note is that DfD at the same time considers multiple other circularity strategies such as maintenance and repair during a building's lifetime, which is made more efficient through detachable components (Ottenhaus et al., 2023).

Design for Adaptability (DfA) is a circular building strategy that takes into account future changes in users' needs, environmental effects or contextual conditions, to increase the lifetime of a building and gain more value (Ottenhaus et al., 2023). So, where DfD considers buildings mainly as a material bank, DfA adds the perspective of prolonging the lifespan of a building before reusing it. Moffatt and Russel (2001) set up eight key principles and strategies for an adaptable building: (1) durability; (2) versatility; (3) access to services; (4) redundancy; (5) simplicity; (6) upgradability; (7) independence and (8) building information. The implementation of the DfA approach is also strongly related to the shearing layers principle from Brand (1994) (Figure 2.7), since adaptations happen at different building layers with different lifetimes (Askar et al., 2022) and therefore different adaptability strategies apply for each layer (Verberne, 2016).

The circularity strategies above can be related to the Ellen MacArthur Foundation butterfly diagram (Figure 2.6). Figure 2.9 shows this diagram adapted specifically for the built environment. It considers renewable materials for the biological cycle and finite materials for the technical cycle. The production process in the middle starts with the processing of raw materials into building materials. In a CE this includes a loop for recycling construction waste and finite materials that have reached the end of their life. Afterwards, the construction materials are made into building parts and components. When certain parts of a building begin to degrade, they can be refurbished to prolong the lifetime and prevent demolition. Finally, the building parts are transported to the construction site and assembled. When building parts are reused, they are demounted from their original building and used in the assembly of a new building. DfD is strongly related to this reuse loop, both for the technical and biological cycle, as timber for example is a biological product that can be reused just as much as other materials. The end product is a building that remains functional for as long as possible with the upkeep and maintenance loop, the smallest loop in the technical cycle. This relates to the DfA approach that aims to increase the lifetime of a building as much as possible before moving to the larger cycles in the diagram. DfD is also implemented in this loop, since designing detachable components allows for the replacement of those parts when necessary to maintain a building. The biological cycle contains loops similar to those in the technical cycle, but with additional processes such as cascading building parts and, as a circular alternative to incineration at the end of their life, creating biogas from renewable materials and regenerating nature to harvest new materials.

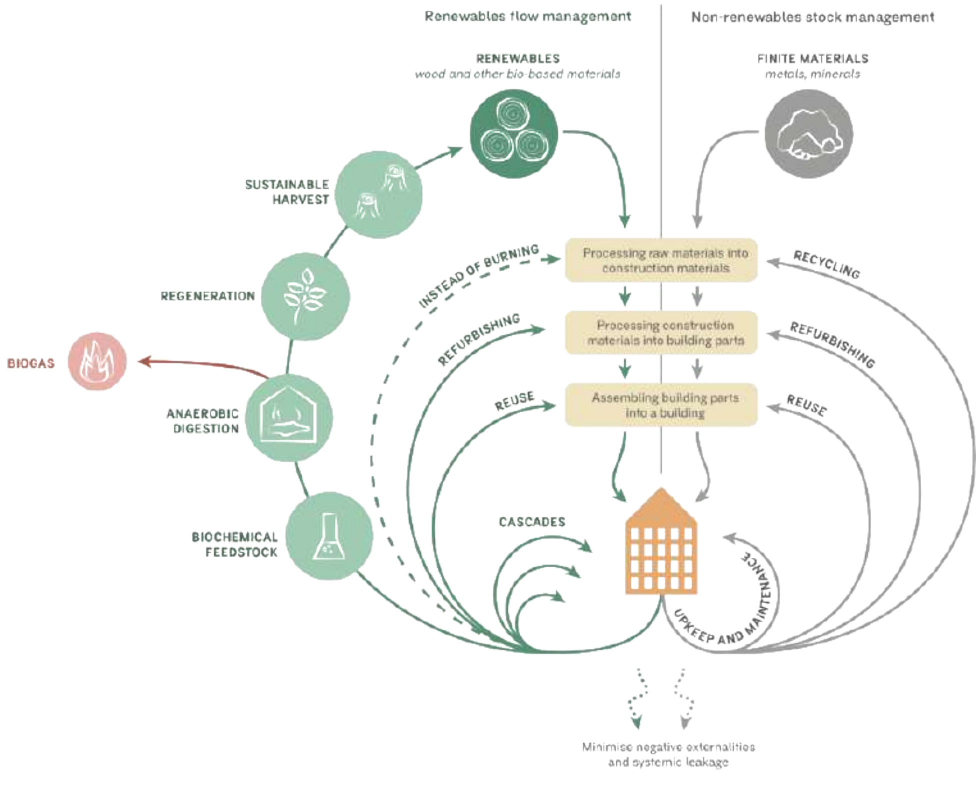


Figure 2.9: Butterfly diagram for a Circular Economy in the built environment (adapted from INARO (2021))

Also important to consider in a CE built environment is the perspective of logistics. Traditionally, construction materials are transported separately to the construction site, which decreases the efficiency of logistics, causing unnecessary carbon emissions. To solve this problem, construction hubs were introduced (Guisson et al., 2023), also referred to as material hubs (Köhrer, 2024) or Construction

Consolidation Centres (CCCs) (Muerza and Guerlain, 2021). These are centralised logistic facilities that collect construction materials and distribute them to construction sites to optimise transportation logistics (Muerza and Guerlain, 2021). To transition towards a CE, current developments are being made into implementing circular CCCs that facilitate logistics for reusing construction materials and recycling construction waste (Köhrer, 2024). This places them in the reuse, redistribute and recycling loops of the butterfly diagram. Tsui et al. (2024) identified four types of circular CCCs: urban mining hubs, industry hubs, local material banks and craft centres. Urban mining hubs collect separate building components and sort them first, after which they are stored and eventually distributed again. Industry hubs do the same but on a larger scale, concentrating more on bulk construction materials such as steel and concrete, and less so on building components. A local material bank takes the remaining building components and materials left by the industry and urban mining hubs and sells them locally. They often collaborate with craft centres, communal places that use the remaining components from demolition to make small new products such as furniture, which relates to the re-manufacture cycle in the butterfly diagram.

An example of a circular CCC in practice is the Dutch company BNext, an urban mining hub. They collect building parts and materials from demolition or demounting activities, inspect and categorise each item and then repair or recycle them before redistribution to other construction sites or material factories (Bnext.nl, nd).

Another advancement in a CE for the built environment is the concept of material passports. A material passport is a digital set of information that is given to a building element (Hoosain et al., 2020). This includes information about building element properties such as dimensions, location in the building, material strength class, material density, fire safety, recyclability, reusability, if the material is renewable or finite, embodied emissions, embodied energy, demountability, etc. (Heinrich and Lang, 2019). The benefit of a material passport is that it provides insight into the properties of all materials within a building, allowing companies to redistribute, reuse and recycle materials more efficiently with strategies such as urban mining and CCCs.

An example of the implementation of a material passport in the Netherlands is the Madaster platform. This platform uses 3D scans and BIM to give all materials in a building a digital passport, which is done by linking data from the Madaster material database to the Industry Foundation Classes (IFC) format of a 3D BIM model (Madaster, nd). The platform collects and stores all this data to create an online registry of materials and building components.

2.1.3.3 Building Circularity Assessment Methods

Similar to the LCA method for measuring environmental impact and the LCC method for measuring life cycle costs, there exist several assessment methods for measuring circularity as well. This section explores the circularity assessment methods that are specifically applicable to the built environment.

Circularity assessment methods are also referred to as circularity indicators or C-indicators (Khadim et al., 2022) and aim to quantify circularity strategies to make the performance of a building on circularity measurable (Blomsma and Brennan, 2017; Khadim et al., 2022). They are considered to be an important measure for the transition towards a CE (Elia et al., 2017) and can operate on the macro (cities), meso (buildings) and micro (materials and components) level. Since this research focuses on the micro and meso level, only C-indicators that assess on these levels are reviewed.

C-indicators can be further decomposed into Key Performance Indicators (KPIs) for the different dimensions of CE. Based on research by Khadim et al. (2022), Shivakumar (2021) and Zhai (2020) most circularity KPIs for the built environment are identified in Table 2.4, categorised for three life cycle stages: (1) production and construction stage together; (2) use stage and (3) end-of-life stage. Quantification of the KPIs differs among C-indicators.

Table 2.4: Circularity KPIs per life cycle stage (based on Khadim et al. (2022), Shivakumar (2021) and Zhai (2020)

Life Cycle Stage	Circularity KPI	Description
Production and Construction Stage (A1-A5)	1. Input of primary material	The amount of primary materials used, expressed in kilograms or a percentage of the total mass.
	2. Input of secondary material	The amount of secondary materials (reused or recycled) used, expressed in kilograms or a percentage of the total mass.
	3. Input of renewable material	The amount of renewable materials used, expressed in kilograms or a percentage of the total mass. Refers to the "regenerate nature" concept in the butterfly diagram.
	4. Use of non-renewable energy	The amount of non-renewable energy used to produce and construct.
	5. Use of renewable energy	The amount of renewable energy used to produce and construct.
Use Stage (B1-B7)	6. Functional lifetime	The functional lifetime of a product and if it has potential to surpass the industry average lifetime of that product. Refers to the maintain, refurbish, and remanufacture cycles in the butterfly diagram.
End of Life Stage (C1-C4)	7. Disassembly potential	The degree of implementation of the DfD principle to maximise the amount of components suitable for reuse.
	8. Adaptability potential	The degree of implementation of the DfA principle, the adaptability of a product to take on different functions.
	9. Recycling efficiency	The efficiency of the recycling process, measuring quality and quantity of the material output, including material loss.
	10. Output of components for reuse	The amount of components suitable for reuse, expressed in kilograms or a percentage of the total mass.
	11. Output of materials for recycling	The amount of materials suitable for recycling, expressed in kilograms or a percentage of the total mass.
	12. Output of materials for unrecoverable waste	The amount of materials that cannot be reused or recycled and will go to waste, which can be hazardous or non-hazardous. Waste will go to a landfill or incinerator for energy recovery. This step should be avoided in a CE.

The range of available C-indicators that incorporate the KPIs from Table 2.4, is extensive and there is no universally standardised method (Verberne, 2016). In an attempt to gather and review all C-indicators, Elia et al. (2017) conducted a critical review of general C-indicators at macro, meso and micro levels such as Material Flow Analysis (MFA) for macro level, Resource Productivity (RP) for meso and Material Circularity Indicator (MCI) for micro. Khadim et al. (2022) focused on C-indicators for the built environment specifically and performed a systematic literature review in which they identified 24 distinct indicators for buildings with 35 versions. They concluded that the majority of indicators follow a quantitative approach and vary widely in their scope, accuracy, data type and KPIs.

In this research, the focus is laid on C-indicators that are most applied in the Dutch construction industry, both because of the scope of this research and the leading position of the Netherlands in the development of building circularity indicators (Khadim et al., 2022). These C-indicators are elaborated in the next paragraphs.

Material Circularity Indicator

The Material Circularity Indicator (MCI) is a C-indicator on the micro (material, product) level, developed by the Ellen Macarthur Foundation and is one of the most universally applied circularity assessment methods in general and in the built environment (Cottafava and Ritzen, 2021). The MCI considers mainly the technical cycle of the butterfly diagram and measures the minimisation of linear flows and the maximisation of circular flows during the lifespan of a product (Ellen MacArthur Foundation, 2015). It generates a score between 0 and 1, with 0 indicating a completely linear system and 1 indicating a fully circular system. This score is calculated by integrating the mass of virgin raw material input, the mass of unrecoverable waste output and a utility factor, the functional lifetime of the product. These refer to KPIs (1), (6) and (12) of Table 2.4. The larger the amount of primary material and unrecoverable waste, the more linear the product. If a product consists only of secondary material and there is no waste, this product is considered fully circular.

Figure 2.10 shows the material flows in the technical cycle together with the corresponding formulas for calculating the virgin feedstock and unrecoverable waste. Virgin feedstock is calculated as the total product mass, minus the fractions of recycled, reused and renewable materials. Unrecoverable waste is the total product mass, minus the fractions of waste going to recycling, reusing, composting or energy recovery processes.

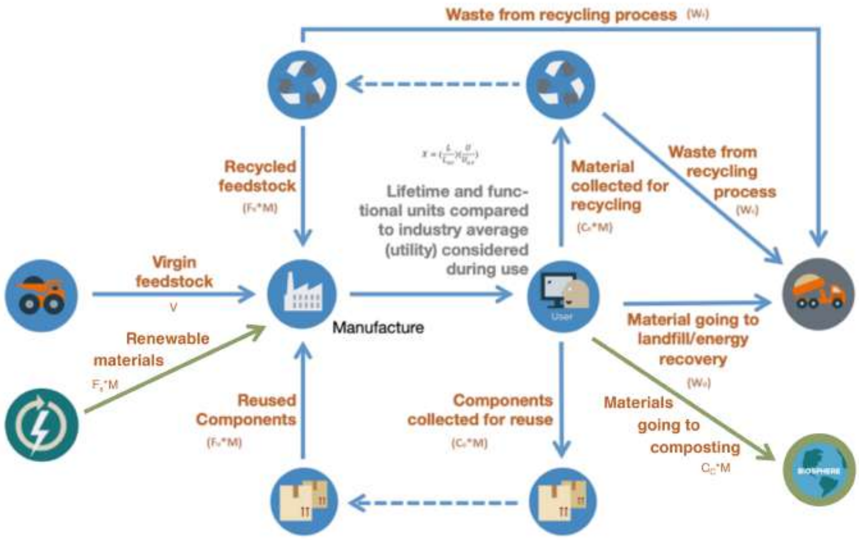


Figure 2.10: Material flows and formulas of the MCI method (adapted from Ellen MacArthur Foundation (2015) and Rocchi et al. (2021))

Virgin feedstock and unrecoverable waste are then used to calculate the Linear Flow Index (LFI) which also gives a value between 1 and 0, however in this case 1 means a completely linear flow and 0 a completely circular flow. The MCI is finally calculated by multiplying the LFI with the utility factor of the product and reversing it.

Building Circularity Indicator

The Building Circularity Indicator (BCI) is considered to be an improvement on the MCI through it being more specifically applied to the built environment itself (Cottafava and Ritzen, 2021). It has been developed since 2016 by Alba Concepts and the Technical University Eindhoven. The BCI was first introduced by Verberne (2016) who expanded the concept of the MCI together with the concept of material level hierarchy by Durmisevic and Brouwer (2006) and the DfD transformation capacity model from Durmisevic et al. (2006). Durmisevic & Brouwer classify a building into four levels: (1) building; (2) system; (3) component and (4) element level. Verberne adopted this classification and distinguished four specific circularity indicators for each level in the first conceptual framework for the BCI:

1. **Material Circularity Indicator (MCIp):** The indicator at the element level, which is the MCI calculated for each product in a building (MCIp). This is calculated similarly as the MCI from the

Ellen MacArthur Foundation.

2. **Product Circularity Indicator (PCI):** The indicator at the component level that extends upon the MCI by including the DfD principles for connections and interfaces of a product to measure its practical value. It does so by multiplying each MCIp with seven disassembly factors that were taken from Durmisevic et al. (2006).

3. **System Circularity Indicator (SCI):** The indicator at the system level which includes all products of one system by normalising them as a fraction of the total mass. A 'system' in this case is identified as one of the shearing layers from the framework of Brand (1994).

4. **Building Circularity Indicator (BCI):** The indicator at the building level and the final indicator in the BCI assessment method. The BCI is calculated by multiplying each SCI with the factor of system dependency. These factors are fuzzy variables, determined by Durmisevic et al. (2006), ranging from 0 to 1 and used to give a level of importance to each shearing layer from Brand (1994), as the circularity of products with a shorter lifespan is considered to be more important than circularity of products with a long lifespan (Verberne, 2016).

All indicators will result in a score between 0 and 1. A score of 0 means a fully linear material, product, system or building with only virgin feedstock input, unrecoverable waste output and no disassembly potential, whereas a score of 1 means they are completely circular.

The original BCI methodology from Verberne has undergone several adaptations since then. Zhai (2020) investigated these developments in detail in a thesis. van Vliet (2018) developed a revised version of the BCI that uses a redeveloped method for the DfD assessment and replaces the shearing layers from Brand (1994) with a system classification based on disassembly and reusability potential.

Alba Concepts (2018) developed the BCI further by commercialising it into the Building Circularity Index (BCIX). They reduced the assessment to three indicators: (1) Product Circularity Index (PCIX); (2) Element Circularity Index (ECIX) and (3) Building Circularity Index (BCIX). The PCIX here is a combination of the MCI and the so-called Disassembly Potential (DP), which considers two of the originally seven disassembly factors from Durmisevic et al. (2006): type of connection and accessibility to connection. The SCI is replaced with the ECIX which assesses the level of circularity of an element, which is defined as an interconnected group of products that have a fixed connection with each other and cannot be disassembled. The ECIX is calculated in a similar way as the PCIX with the MCI and DP. Finally, the BCIX is calculated by weighting the ECIX scores for each element based on their weight in relation to the total building mass.

In 2021, the official circularity assessment method BCI Gebouw was launched in collaboration with Alba Concepts. BCI Gebouw builds upon the BCIX from Alba Concepts (2018) and is the latest version of the BCI. A conceptual model of the assessment method can be seen in Figure 2.11 (BCI Gebouw, 2022). It follows a similar approach as the BCIX but reintroduces the Material Circularity Index (MCI) again as the first step before the PCI. It still uses the categorisation of building components into products and elements and DfD principles are considered with the DP, which is expressed in Dutch as "losmaakbaarheidsindex" (LI). The DP combined with the MCI gives the calculation for the PCI and ECI scores. The final BCI score is the sum of all PCI and ECIs of a building and results in a score between 10% (fully linear) and 100% (fully circular). Another difference with the previous BCI versions is that BCI Gebouw calculates the final BCI score by weighting the ECI scores for each element based on the MilieuKostenIndicator (MKI): an indicator from the Dutch MPG method that assigns shadow costs to materials to account for their environmental impact. This is a significant difference from the previous methods, which used a building element's volume or mass as a weighting factor. According to Verberne (2016), volume and mass are not ideal variables to weigh the circularity of products for a building. For instance, materials like aluminium, which have a high environmental impact but are lightweight, would have less influence on the final BCI score, while they contribute heavily to environmental impact. Using the MKI instead prevents this but simultaneously brings a new challenge: products with a high MKI and high DP score but low reusability potential, such as PV panels, can distort the BCI score (BCI Gebouw, 2022). Additionally, BCI Gebouw (2022) highlights several other limitations and opportunities of their method. For instance, a detachable product is not necessarily always reusable, which can give a wrong positive PCI score to a product. The reusability is furthermore taken into account by both the MCI and DP already, making it count double in a sense. Finally, they recognise that the BCI method does not consider all aspects of circularity and that it is difficult to include all aspects in a single score.

The BCI is considered to be one of the most popular building circularity assessment methods both by academia and companies (Cambier et al., 2020; Khadim et al., 2022).

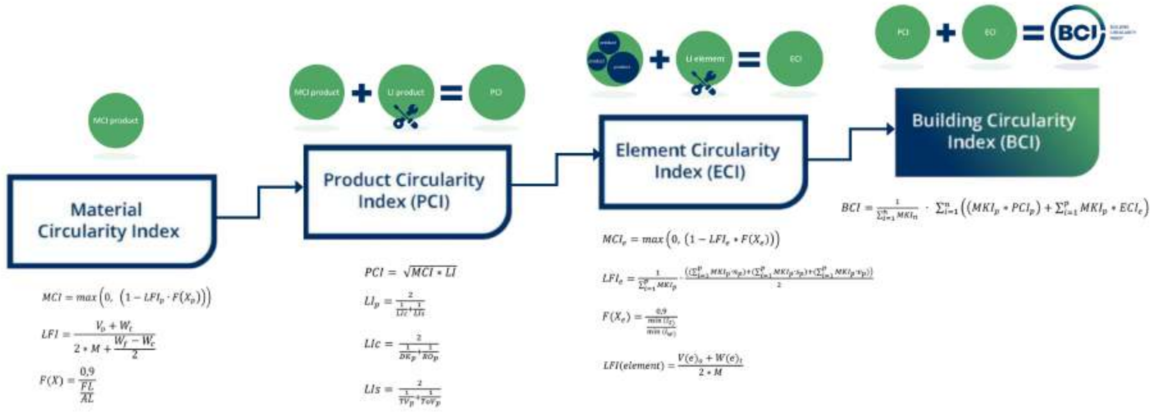


Figure 2.11: Stepwise assessment method of the BCI score (adapted from BCI Gebouw (2022))

Since the first introduction of the BCI by Verberne (2016), several modifications have been investigated in the literature as well. Zhai (2020) developed the BIM Based Building Circularity Assessment (BBCA) which suggests a combination of several elements from both Verberne (2016) and Alba Concepts (2018) to create a novel circularity assessment method. van Schaik (2019) developed the Modified Alba Concept For Foundation (MAC), a variation on the BCI, made specifically for foundations by using the adaptability potential instead of disassembly factors. Braakman et al. (2021) highlighted the limitation of the BCI that material necessary during the use and maintenance stage is not considered and therefore suggested the Modified BCI (MBCI), that adapts the calculations so that products with a longer functional lifespan use more material in their lifetime. Finally, Cottafava and Ritzen (2021) developed the Predictive BCI (PBCI) which uses Embodied Energy (EE) and Embodied Carbon (EC) as factors for weighting the ECI scores for a whole building, similar to BCI Gebouw that uses the MKI factor for this.

Madaster Circularity Indicator

Madaster, a Dutch platform supporting the transition to a CE in the built environment, developed the Madaster Circularity Indicator (CI) based on the MCI from the Ellen MacArthur Foundation (2015). Their platform uses the Madaster material database to perform circularity calculations for a building. These calculations measure circularity during three different life cycle stages of a building: (1) construction stage; (2) use stage and (3) end-of-life stage (Madaster, 2021). The CI is embedded in the online Madaster platform and connected to the Madaster material passport database to perform a circularity assessment similar to the MCI method. The final CI score is calculated for both the complete building and the shearing layers from Brand (1994) by using the mass of products as a weighting factor (Figure 2.12). The CI ranges from 0% to 100%, where 0-10% defines a linear building made only from virgin materials with a short functional lifespan and wasteful end-of-life scenarios. A score of 100% indicates a fully circular building made only from reusable products. To consider incorrect data entries into the Madaster material passport database, the CI is adjusted at the end with two correction factors to prevent misinformation.

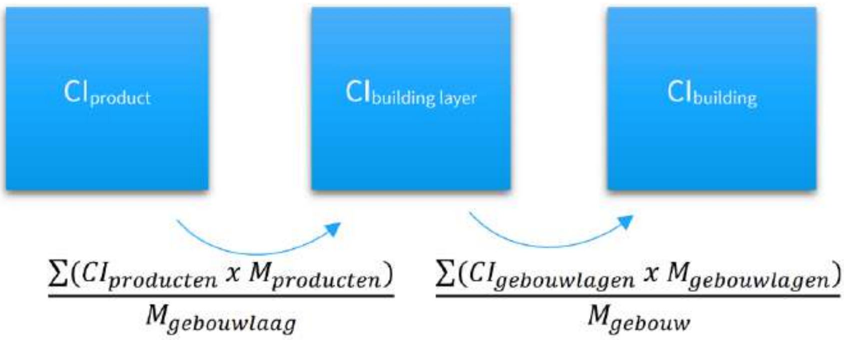


Figure 2.12: Overview of the Madaster Circularity Indicator calculation method (Madaster, 2021)

Platform CB'23

Platform CB'23 (Platform Circulair Bouwen 2023) is a Dutch platform that focuses on stepping up the transition to a circular built environment by facilitating agreements and connecting parties across the construction industry (CB'23, 2022). Platform CB'23 is also currently developing a circularity measurement method that looks at three goals of circular construction: (1) protecting stocks of materials; (2) environmental protection and (3) value retention. They recognised that methods such as the MCI and MPG focus only on one or two of these goals and often do not provide the details necessary to make informed decisions on circularity. The suggested measurement method from Platform CB'23 provides six indicators to measure the circular construction goals. For protecting stocks of materials, these are (1) input material quantity for producing, repairing or refurbishing an object; (2) output material quantity for reusing or recycling; (3) output material quantity that is lost and gone to waste. Environmental protection is measured with (4) the MilieuPrestatieberekening Gebouw (MPG). Finally, value retention is covered with (5) functional value at the end of the life cycle and (6) economic value at the end of the life cycle. Each main indicator is further divided into sub-indicators used for the calculations. Figure 2.13 shows a schematic overview of the Platform CB'23 circularity assessment method, highlighting the three main goals. Unlike the MCI, BCI or CI, the assessment method from Platform CB'23 does not calculate a single endpoint score yet. This is currently still under development.

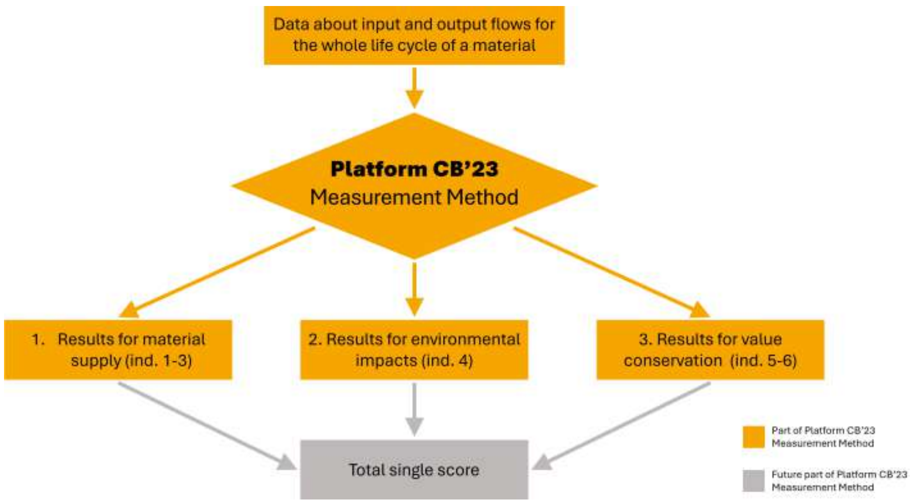


Figure 2.13: Overview of the Platform CB'23 circularity measurement method (CB'23, 2022)

Level(s)

Level(s) is a European framework for measuring and applying CE principles in the built environment by using the life cycle perspective (Commission, nd). It is a comprehensive framework that considers sustainability by implementing LCA, financial impact through LCC, circularity with the KPIs from Table 2.4, DfD and DfA principles, and health and comfort using several building physical indicators. Together this leads to six macro-objectives that are measured with sixteen additional indicators (Figure 2.14). The Level(s) framework can be implemented at each stage of the design process: (1) the conceptual design stage; (2) the detailed design and construction stage, and (3) the as-built and in-use stage. Similarly to Platform CB'23, Level(s) does not calculate a single endpoint score but rather provides results on different aspects of sustainability and circularity to support informed decision-making.

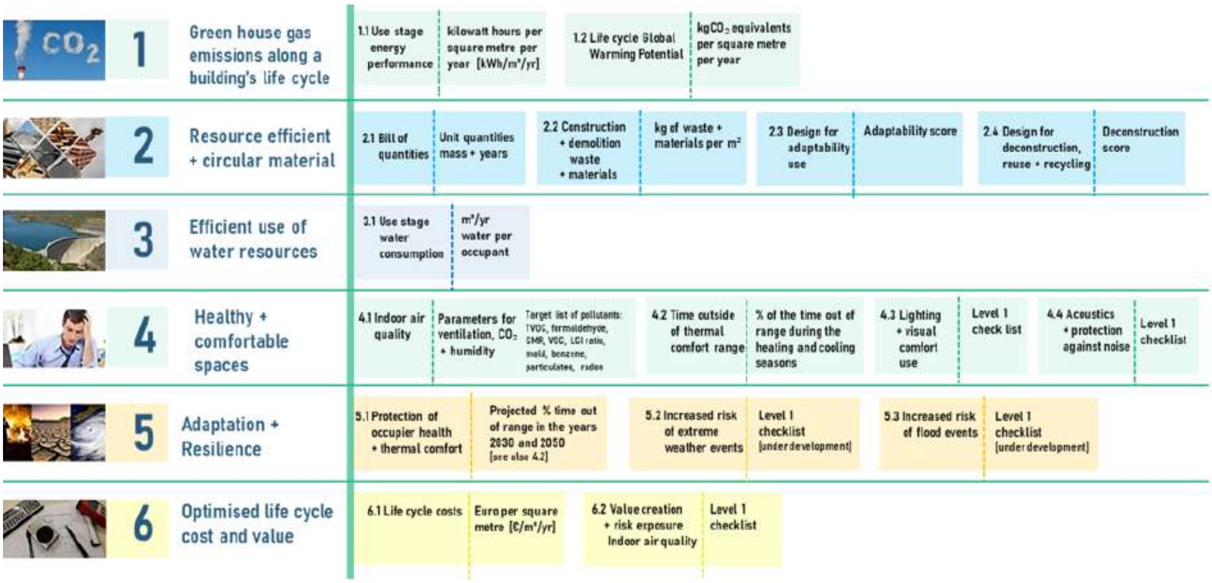


Figure 2.14: Level(s)' 6 macro objectives and corresponding indicators (Dodd et al., 2020)

Transformation Capacity Model

The Transformation Capacity (TC) model by Durmisevic et al. (2006) is one of the core methods for measuring the disassembly potential of buildings, on which the BCI is built upon. They divide the disassembly potential into seven aspects and multiple sub-aspects. For instance, one aspect is "connections" with "type of connection", "accessibility", "tolerance" and "morphology of joint" as sub-aspects (Durmisevic et al., 2006). To each sub-aspect, a fuzzy variable is assigned ranging from zero to one where zero means the worst impact on disassembly and one the best. Finally, a single score for the TC is calculated, called the adaptability potential.

Flex 4.0

FLEX 4.0 is a circularity assessment method developed by Geraedts (2016) to integrate the DfA principles and assess the adaptive capacity of buildings. FLEX 4.0 is the fourth instalment of the method and is currently still in the development and testing phase. It consists of an assessment framework that divides a building according to the shearing layers from Brand (1994) and assesses the building's adaptability with 32 performance indicators. Each indicator is given a range between 1-4 to indicate the level of adaptive capacity. The total sum of the scores gives the flexibility score, which is translated to one of five flexibility classes, ranging from "not flexible at all" to "excellent flexibility" (Geraedts, 2016).

2.1.4 Integration Between LCA, LCC and Circularity

This research investigates the evaluation of responsible material use through the integration of LCA, LCC and circularity. Following the detailed exploration of the concepts and assessment methods behind each aspect in the previous sections, this section focuses on the existing literature on their integration.

Nicholson et al. (2009) explored how different end-of-life allocation methods influence material selection and the assessment of environmental impact across multiple life cycles. They analysed five different methods for allocating environmental impact: the cut-off, losses of quality, closed loop, 50/50 and substitution methods. Their research shows that the cut-off, 50/50 and substitution methods generally discourage the use of materials with significant recycling burdens, such as high energy use and large amounts of recycling waste. The closed loop and loss of quality methods are less sensitive to those burdens. They conclude their study by emphasising the large influence of different allocation methods on the environmental impact of materials over multiple life cycles and call for future research into this topic.

In their study on circular LCA, van Gulck et al. (2022) highlight that the standard LCA study for buildings adopts a linear approach that does not include circularity aspects. It generally evaluates the environmental impact of one life cycle, not taking into account the possibility of multiple other life cycles of building components and materials. To tackle this problem, they introduced the concept of 'multi-cycling', which suggests that a circular product has multiple use cycles within its life cycle due to its potential to be reused. End-of-life scenarios such as reuse and recycling potential are included in Module D from the life cycle stages, but this stage lacks detail and mostly favours materials with a high reuse or recycle potential, which is not always realistic (Wastiels et al., 2013). Instead, they mainly implement the 'multi-cycling' concept by adding multiple use cycles in module B5 "Refurbishment". This resulted in a more comprehensive and circular LCA method.

In another study, conducted by Eberhardt et al. (2019), LCA and circularity are combined in a demonstration that visualises the difference in results between the LCA of linear building components and the LCA of circular building components. As a case study, they calculated the embodied carbon during two life cycles of a traditional, linear concrete column and a Design for Disassembly (DfD), circular concrete column, by using standard LCA methodology. The study findings revealed that the total embodied carbon of the traditional column exceeds that of the circular column, as the traditional column must be produced twice, whereas the circular column only has to be transported at the end of its first life cycle. They therefore emphasise the importance of combining LCA with circularity and highlight the current lack of readily applicable tools designed for this purpose.

Another approach was investigated by Glogic et al. (2021) who tackled the problem of linearity in LCA by adding circularity with the Material Circularity Indicator (MCI) to assess alkaline batteries on their environmental impact and circularity. They furthermore used the ReCiPe LCIA method to convert the LCA impact scores to three endpoints: human health, ecosystems and resources. By normalising these LCA scores with the most impactful scenarios and presenting the results in waterfall charts, a joint analysis is performed from which they observed that an increased MCI will generally result in lower LCA scores and is therefore useful to integrate into a combined assessment.

van Stijn et al. (2021) developed an extensive model for integrating circularity principles with LCA, called "Circular Economy Life Cycle Assessment" (CE-LCA). This model considers building components as a composite of different materials, each with its unique use cycle and lifespan, and assesses the environmental impacts associated with each material. To test the model, van Stijn et al. compared three different kitchen units to see the differences in circularity. The adopted method gives us a way of determining an 'ideal' circular system, but is complex as it requires much calculation input and extensive data of the materials, which is not always available in standard databases. Van Stijn et al. also added that it remains difficult to determine the exact life cycles of all materials in practice, increasing uncertainty.

Kambanou and Sakao (2020) conducted research into the integration of LCC and circularity and recognised that the implementation of circularity measures by businesses is hindered by the lack of insight into the financial consequences. They suggest that circularity measures and LCC should go hand-in-hand and investigate an approach that evaluates the costs and profits for different circular and non-circular measures. This LCC-based guideline was applied to three case companies and proved to be successful in providing them with both information on circularity aspects and financial consequences.

The importance of integrating LCC and circularity is further supported by Braakman et al. (2021) who state that the majority of companies are under the impression that circular measures are more expensive and will therefore not invest in these. In their research, they applied an LCC together with the Level of Circularity (LoC) to a single-family house case study. The LoC in this case is measured with the BCI from Verberne (2016). The results from their case study indicate that a single-family house constructed with circular materials, compared to one with traditional materials, doubles the BCI score without increasing the costs. Although a higher initial investment of 8% is generally required, Braakman et al. predict that this will reduce future costs by 25%. They therefore conclude that LCC is an important measure to encourage circularity as it can prove the financial benefits of circular measures.

State of the art on the integration of LCA, LCC and circularity altogether can be found in the research from Karabinar (2021), who highlights the importance of their integration to provide a comprehensive approach that prevents complicated and scattered, separate assessments. Lavagna et al. (2021) further support the importance of this integration and state that economic and environmental LCAs should be used to measure the sustainability of circularity strategies. Finally Panjwani (2022) concluded a thesis about building asset valuation in circular ecosystems with the finding that sustainability and circularity aspects produce more value when combined with financial assessment than when applied alone.

2.2 Digital Tooling Related to Responsible Material Use

The previous section introduced the three defined aspects of responsible material use: LCA, LCC and circularity. As previously highlighted, it is important to integrate these aspects to accurately evaluate and optimise responsible material use in building designs. This starts by conducting a literature review of the state-of-the-art digital assessment tools that contribute to this integration. A large variety of tools already exist for LCA, while there are significantly fewer known to be applied for LCC and circularity (Dervishaj and Gudmundsson, 2024). Most of the existing tools are based on spreadsheets and thus considered static, since the user has to manually input quantities of a building design (Hollberg and Ruth, 2016). However, in recent years there has been a gradual increase in tools developed for digital 3D Building Information Models (BIM) (Hollberg and Ruth, 2016). The 3D geometry of the models is used as input for assessment methods such as LCA, to increase the efficiency and accuracy of the workflow. This section provides an analysis of existing BIM tools for integrating LCA, LCC and circularity and divides the investigated tools into two categories.

1. General BIM tools
2. Parametric Design tools

Since the scope of this research is the field of parametric design, this section will conclude with an evaluative comparison table specifically for parametric design tools in order to support the research gap.

2.2.1 General BIM Tools

Akanbi et al. (2017) investigated the integration of circular end-of-life scenarios with BIM by developing a tool called BIM-based Whole-life Performance Estimator (BWPE), that evaluates the salvage performance of structural building materials to reduce waste and preserve embodied energy. To measure the salvage performance, they created a mathematical model that uses factors for material recoverability through recycling and reusing, and product reliability distribution with a hazard function and failure rate. With the use of C# programming language, Akanbi implemented BWPE as a plugin for Revit to link circularity data to building components. Finally, they evaluated the tool with a case study for a building's structural system and concluded that their research would provide architects with a valuable tool to support circular decisions.

Röck et al. (2018) developed a proof of concept for the implementation of LCA in the early design stages by using BIM. They did this by linking a BIM model in Revit to an Excel database with embodied impact data about the Global Warming Potential (GWP). This was established with Dynamo for Revit by automatically generating a Bill of Quantities (BoQ) from the BIM model and mapping those building elements to materials from the database. The results are presented in a boxplot diagram with impact per Gross Floor Area (GFA) together with a colour-graded 3D view of the model.

van Gemert (2019) focused on the integration between BIM and LCA in the early design stages as well, but by developing a user-friendly application called MPG-ENVIE that utilises the IFC schema for linking data, and the MPG method for performing an LCA. By using the Python programming language, the application extracts a BoQ from all elements of an IFC model and links these to an external Excel database by using the NL-SfB classification system. This database holds data on the emission equivalent units and shadow costs of eleven impact categories. After calculating the results, they are visualised in a user interface. MPG-ENVIE was tested with a case study for a Revit and SketchUp BIM model and was proven to be useful for improving building designs on environmental impact.

van Oeveren (2020) further build upon the research from Van Gemert by adding LCC to the LCA-BIM workflow in a tool called LEICAS. Comparable with MPG-ENVIE, LEICAS uses Python to link an IFC model to an Excel database, however, now containing data about both LCA impact categories and material costs. The data is processed by calculating environmental and economic impact scores and is presented in a user interface to provide visual feedback based on the preferences of a user.

Zhai (2020) brought a different perspective and developed a BIM-Based assessment framework and tool for automated analysis of a building's circularity during the early design stages. Zhai conducted an extensive literature review of six existing circularity assessment methods and proposed an assessment model that combines the most useful elements of each method. The final framework is mostly derived from the Building Circularity Indicator (BCI) developed by Verberne (2016). The tool, called BCAS, uses Dynamo for Revit to assess a BIM model on four different levels of circularity: material, product, system and building. The tool presents its results in a Revit pop-up interface with charts and coloured 3D model elements. By validating BCAS with a real case, Zhai concluded that assessing building circularity with BIM is possible and shows promise for making environmentally conscious decisions in the early design stages.

Research into the integration of LCA and circularity with BIM can be found in the work of Shivakumar (2021), who used the MCI together with the Detachability Index, to measure circularity and include Design for Disassembly principles (DfD). The proposed framework was developed into a tool for Revit by using Dynamo. The system architecture is comparable to some of the previously mentioned tools (van Gemert, 2019; van Oeveren, 2020; Röck et al., 2018; Zhai, 2020) and consists of linking an Excel database, calculating the circularity and LCA impacts and visualising the results in a user-interface for a case study. Interesting is that Shivakumar applied the TOPSIS method to apply Multi-Criteria Decision Making (MCDM) into the tool. TOPSIS (For the Ideal Solution) is based on the principle that a chosen variant should be closest to the ideal solution and farthest from the negative-ideal solution (Opricovic and Tzeng, 2004). Finally, Shivakumar concludes with the recommendation to add LCC to the framework and to develop an SQL database for linking the data.

Kaltenegger (2021) developed ROTUNDORO, a web-based decision-support tool for aiding engineers in choosing sustainable alternatives for building refurbishment. This tool combines an LCA for both embodied and operational energy, and a cost analysis for the total investment costs per building element. Through the Linked Building Data (LBD) method, an external MySQL material database is linked to material components of a BIM model by using IFC as a classification system. A market potential study was performed as well with a stated choice experiment between 500 Dutch homeowners to find the preference of various insulation types for homeowners. This provided ROTUNDORO with an additional result, the probability of acceptance of a refurbishment package, expressed in percentage. Kaltenegger combined all of this in an online prototype platform in which a user can upload an as-is BIM model and see the influence of different refurbishment packages on environmental impact, energy performance, costs and market potential. ROTUNDORO was applied to the use case of a Dutch terraced house and proved to be successful in web-based decision-support for environmentally conscious refurbishment.

Karabinar (2021) continued all of the previous work by integrating the three aspects of responsible material use: LCA, LCC and circularity. Karabinar developed a holistic framework that adopts the MCI to measure circularity, the Global Warming Potential LCA indicator for environmental impact and building costs for LCC (Figure 2.15).

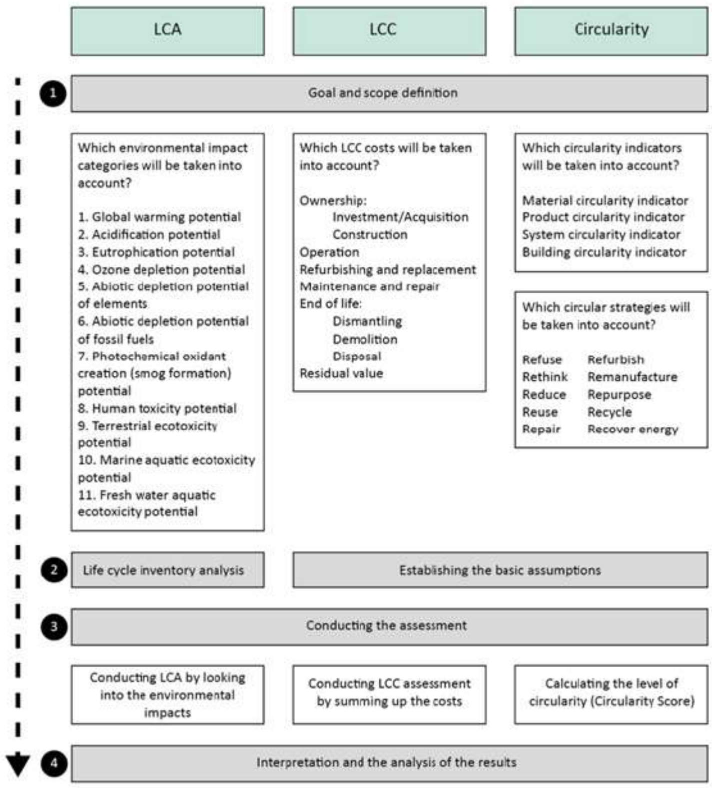


Figure 2.15: CECC framework (Karabinar, 2021)

Interesting is that the framework was developed for the detailed design stage, which deviates from the scope of most aforementioned literature. Through the use of the C# programming language, Karabinar's framework was translated into a Revit plugin named CECC. All material data is combined in an Excel database that is linked to Revit with NL-SfB coding. The results are displayed in a user interface through the use of tables and graphs. Karabinar acknowledges several limitations. One of these is that the used database is static and requires manual input. She therefore recommends research into linking a dynamic web database to such a tool so data is automatically updated when a change in data occurs. A second limitation is the lack of provided suggestions to a user to enhance the decision-making process. Karabinar therefore emphasises the need for a functionality that automatically does recommendations or optimisations.

Atta et al. (2021) integrated LCA methods and circularity aspects to develop a tool for digitising material passports with BIM. The goal of the tool was to aid stakeholders in handling materials during the construction stage, and how to use their circularity potential at the end of their life. Their research highlights the limitation of existing material passport tools to one life cycle, and proposes a new tool that covers all life cycle stages. This tool is created in Dynamo for Revit and evaluates a building on three indicators: (1) a deconstructability score and (2) recovery score for assessing circularity aspects; and (3) an environmental impact score for life cycle impact. The resulting tool enhances building elements from a Revit model with a material passport containing these scores, which proves useful for guiding stakeholders on disassembly and circularity strategies. For further research, they recommend including indicators for financial impact with dynamic cost databases.

A similar approach to that of Kaltenegger (2021) was taken by van den Biggelaar (2022) who developed two web-based tools for refurbishment decision support: CNET-DA and BEE. CNET-DA uses a semi-structured interview method to evaluate and identify the preferences of decision-makers on refurbishment options. This is achieved with a web-based interview application that guides users through a set of different choice alternatives for which they can give a ranking score. The main purpose of this tool is to aid the Multi Criteria Decision Making (MCDM) process. BEE is a BIM-based tool that performs an LCA, expressed with the MilieuKostenIndicator (MKI). BEE was developed as a web-based tool as well and allows users to upload an IFC file of an as-is BIM model, which can be explored in 3D. A user can then assign materials to each of the building components and see the influence on the environmental impact immediately. Both tools were tested with a case study of an office refurbishment project. The results showed good usability for BEE but revealed incompatibility with large IFC files. Van den Biggelaar finally recommends further research into the integration between CNET-DA and BEE.

2.2.2 Parametric Design

Parametric design refers to the use of algorithmic thinking to achieve an adaptable design based on parameters (Assasi, 2019). Parameters can be seen as a constraint for a design and by changing them, the design solution adapts accordingly (Jones, 2022). In the built environment, it is used to generate parametric 3D models for architectural designs. Because the design is generated through algorithmic thinking, a change in a parameter like building height will immediately adapt the whole building model to this change. Parametric design in the built environment is often linked with computational modelling software with programs such as Grasshopper (GH) for Rhino and Dynamo for Revit. However, its use dates back much earlier to one of the most well-known examples: the architecture of Antonio Gaudí, who used hanging chain models to optimise and adapt his designs, specifically that of the Sagrada Família (Ghaffar et al., 2022). Parametric design is considered to have many advantages such as:

1. **Flexibility.** Parametric design has the ability to investigate endless possibilities of design choices in an efficient manner (Nasir and Arif, 2023). This provides architects with the flexibility to quickly change a building design, or find a solution for a design problem without having to manually draw or model the effects of a change, increasing time-efficiency. Parametric design therefore offers significant advantages for the early design stages, due to its ability to explore many design variants (Schnabel, 2007).

2. **Compatibility with complex designs.** Parametric design is known for its ability to generate complex, organic designs which opens up the possibility for architects to explore more creative shapes and designs (Zarei, 2012).

3. **Optimisation potential.** Another advantage of the parametric approach is the possibility of algorithmic optimisation to find optimal solutions for design problems such as the best PV panel angle for energy production maximisation (Hollberg, 2016; Lobaccaro et al., 2018). This can be facilitated through generative design, an iterative process that automatically generates design variants (Zhang et al., 2021).

2.2.3 Parametric Design Tools

In Section 2.2.1 we have seen a variety of BIM-based tools used for integrating LCA, LCC and circularity for assessing responsible material use. This paragraph discusses the state of the art surrounding the parametric approach for this integration.

In literature, some work exists in the development of LCA tools for parametric design. Hollberg (2016) for example, has developed a parametric tool with Grasshopper, CAALA, that calculates embodied and operational impacts of different categories for a building design in the early design stages. It further focuses on the optimisation of insulation thickness, window layout and generic geometry with the Goat plugin. Hollberg accomplished a tool that was proven to be effective after application to two cases. However, recommendations for further development are the necessity of a single indicator score to increase the comprehensibility of the results, daylight simulation and the addition of LCC. Furthermore, the workflow of CAALA is set up as such that Grasshopper is only used to export a BoQ to external CAALA software which limits the usability of the tool (Apellániz et al., 2021).

Lobaccaro et al. (2018) adopted a similar approach as Hollberg but focused more on the optimisation of building orientation for global solar radiation. Their tool was developed in Grasshopper and considers both embodied and operational carbon. It was applied to a Zero Emission Building (ZEB) case for validation. They used Galapagos and Octopus for evolutionary algorithm optimisation to derive an optimal shape for the ZEB case.

In practice, the widely known LCA software One Click LCA also offers a plugin for Grasshopper, which has been developed by Apellániz et al. (2021). Their plugin provides results on the GWP of a Grasshopper model. They tested the plugin with a case study to compare different design variants and found that the approach seems to have potential for implementing LCA in the early design stages. They also experimented with generative optimisation processes through the use of the existing Galapagos, Octopus and Karamba3D Grasshopper plugins and by using GWP, building costs and structural integrity as objectives. They highlight the promise of these optimisation methods for the decision-making process. Recommendations include incorporating Design for Disassembly (DfD) and for Adaptability (DfA) to integrate circularity into the assessment.

So, from the previously mentioned studies, it can be stated that parametric design is a method with high potential for implementing LCA in the early design stages and that there is a need for further integration with LCC and circularity methods. Among the state of the art, several other parametric methods, tools and plugins have been developed. Säwén et al. (2022) made an overview of thirteen parametric LCA tools and developed a characterisation framework based on their software approach and a set of nine characterisation categories like required user knowledge, data source and LCA modules. Säwén et al. identified three approaches for parametric LCA tools as seen in Figure 2.16: (1) from Grasshopper geometry to a BoQ that is sent to an external LCA tool; (2) all functionalities conducted within the Grasshopper environment and (3) from Grasshopper geometry directly to an external LCA tool. The framework was successfully applied to the thirteen tools of which four were investigated in detail.

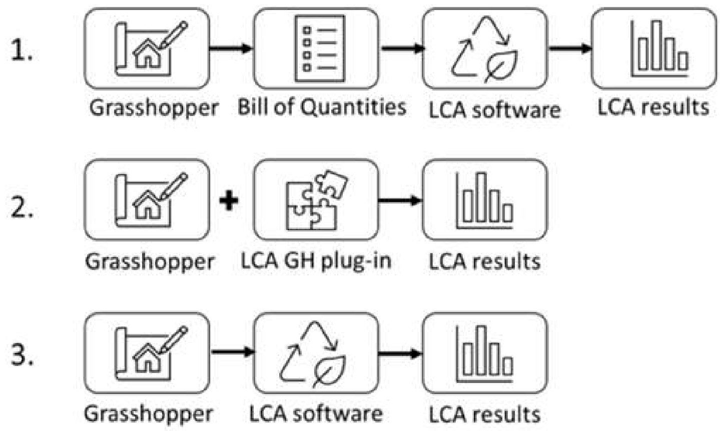


Figure 2.16: Classification of parametric LCA tool approaches (Säwén et al., 2022)

Dervishaj and Gudmundsson (2024) built upon the research from Säwén et al. and conducted a comparative study of digital assessment tools for LCA and circularity in the built environment. In their study, they successfully compared fourteen BIM, CAD and parametric tools with an elaborate framework of thirteen criteria. Of all tools, the parametric category seemed to offer more in terms of flexibility, number of workflows and optimisation potential.

The comparative studies and frameworks from Säwén et al. (2022) and Dervishaj and Gudmundsson (2024) are combined to provide an overview of existing parametric LCA, LCC and circularity tools in Table 2.5. Looking at the table, it becomes clear that integration between these aspects is rare, and that no tool exists that covers all three aspects. Dervishaj and Gudmundsson confirm this gap as well in the discussion of their study, and state that a combination with C-indicators is lacking in most current tools, with only RhinoCircular and Phoenix 3D taking this into account. Additionally, they highlight a lack in the inclusion of LCC, which is also reflected in the table, where the Carbon Cost Tracker is the only parametric LCA tool with integrated costs. Most tools such as One Click LCA, Cardinal LCA and EPiC, focus only on the GWP. Among these tools, One Click LCA stands out because of its large number of accessible environmental databases. Other tools such as Bombyx, CAALA and Tortuga offer fewer databases, but do include life cycle categories other than the GWP, providing a more complete LCA.

While there is no fully developed parametric tool that covers LCA, LCC and circularity, Reisinger et al. (2022) developed a framework named the Parametric Optimisation and Decision support (POD) model to address this gap (Figure 2.17). In this framework, they include a concurrent calculation of LCA, LCC, recycling potential and flexibility assessment for the case of flexible industrial building structures in early design. They used four environmental indicators to calculate the LCA, the recycling rate to assess circularity and four indicators for assessing flexibility, such as retrofit-ability and expandability. They add an automated structural analysis to the POD model to maintain the structural integrity of the building structure. A proof of concept was developed in Grasshopper with Karamba3D for structural analysis and was tested through a variant study test. After evaluation, Reisinger et al. recommend using the proposed POD model to develop a user-friendly tool and to integrate a multi-objective genetic optimisation algorithm to make the decision-making process more efficient. Finally, their framework focuses on structural design only, whereas a whole building assessment would be more complete.

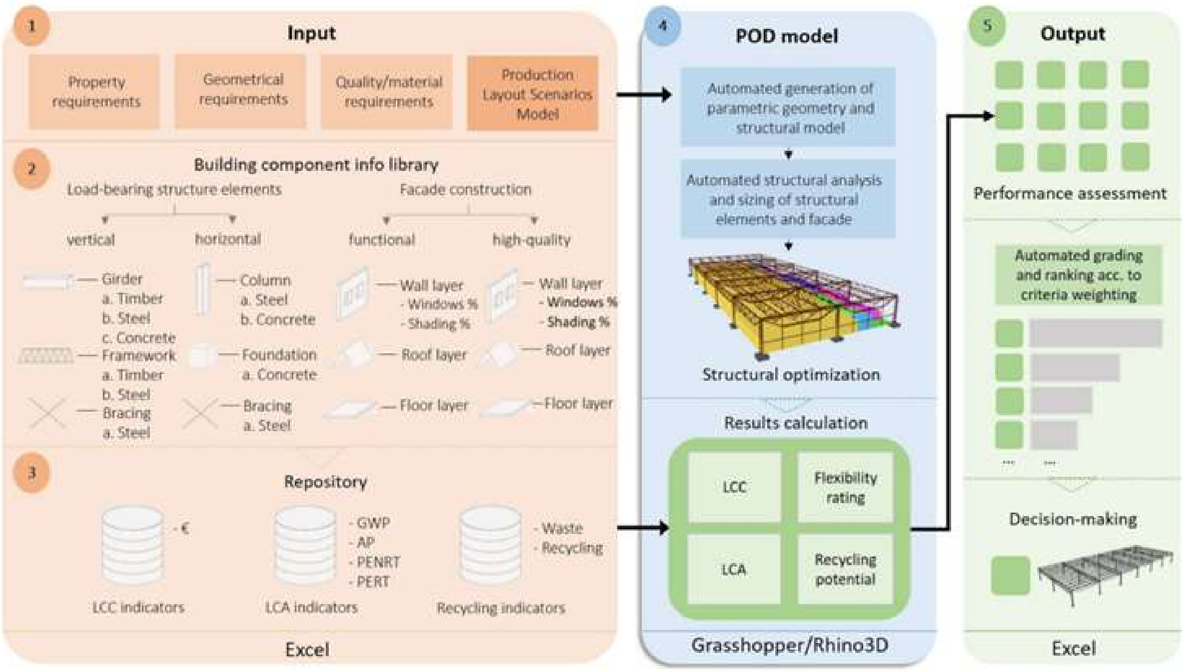


Figure 2.17: The POD model framework (Reisinger et al., 2022)

Table 2.5: Overview of existing parametric design tools for LCA, LCC and circularity in the built environment (combination from Dervishaj and Gudmundsson (2024), Säwén et al. (2022) and own research)

Name	Author	Year	Country	Type	Open access	Approach[1]	Database	Embodied Carbon (GWP)	Operational Carbon	LCA (other categories than GWP)	LCC	Circularity indicators	Optimisation integration
BHoM LCA toolkit	Fisher, A. May, R.	2020	UK	GH, Dynamo, Excel	✓	2	ICE, EC3, Boverket, ÖKOBAUDAT, Quartz	✓	✗	✗	✗	✗	✗
Bombyx	ETH Zürich	2021	Switzerland	GH plugin	✓	2	KBOB, EcoKomposit, Bauteilkatalog	✓	✓ (With Hive plugin)	✓	✗	✗	✗
Brimstone	Toivo Säwén	2023	Sweden	GH plugin	✓	2	Boverket	✓	✗	✗	✗	✗	✗
CAALA	Hollberg, A.	2021	Germany	Rhino plugin	✓	3	ÖKOBAUDAT	✓	✓	✓	✗	✗	✓ (Goat plugin)
Carbon Cost Checker	LEVS architecten	2023	Netherlands	GH tool	✗	2	Witteveen+Bos (CO_2), VGG (costs)	✓	✗	✗	✓	✗	✗
Cardinal LCA	Pathways	2021	USA	GH plugin	✓	2	EC3, ICE	✓	✗	✗	✗	✗	✓ (Ladybug, Karamba3D, Galapagos)
COVE	cove.tools	2021	USA	External tool	✓ (Paid)	3	EC3	✓	✓	✗	✗	✗	✗
EPiC	Stephan, A.	2022	Belgium	GH plugin	✓	2	EPiC database	✓	✗	✗	✗	✗	✗
IDGB	Negendahl, K Jensen, L.	2016	Denmark	Rhino tool	✗	2	EnergyPlus	✓	✓	✗	✗	✗	✗
One Click LCA	Apellániz, D.	2022	Finland	GH plugin	✓ (Paid)	2	Global generic and EPD databases	✓	✗	✗	✗	✗	✓ (Galapagos, Octopus)
Phoenix 3D	Structural Exploration LAb	-	Switzerlan	GH plugin	✓	2	Swiss LCA Database	✓ (For truss structures)	✗	✗	✗	✓ (ratio new / reused)	✓ (Karamba3D)
Rhino Circular	Heisel, F. Nelson, C.	2020	USA	GH plugin	✓	2	Custom database (Circular Construction Lab)	✗	✗	✗	✗	✓ (CI)	✗
Tortuga	Thumfart, M.	2016	Germany	GH plugin	✓	2	ÖKOBAUDAT, Quartz	✓	✗	✓	✗	✗	✗
ZEB-tool	Norwegian ZEB Research Centre	2019	Norway	GH workflow	✗	1	Ecoinvent	✓	✓	✗	✗	✗	✓ (Galapagos, Octopus)

[1] (Säwén et al., 2022): 1 = From GH geometry to bill of quantities to external LCA tool; 2 = Everything conducted within GH environment; 3 = From GH geometry to external LCA tool

2.3 Support in Design Space Exploration

2.3.1 Design Space Exploration

Design Space Exploration (DSE) is an engineering and design process that involves investigating a wide range of possible design configurations to find optimal solutions based on specified criteria and constraints, such as costs and performance (Kang et al., 2011). In this research, DSE is explained in the context of architectural building design. Here, a design space is a conceptual space that can be seen as all possible design configurations within the boundaries of a set of input parameters, for example the maximum width, height and length of a three-dimensional box (Nagy et al., 2022). The input parameters are called the genotype and the resulting box geometry the phenotype (Nagy, 2017). The design space in this case represents a scope: all unique boxes that can be generated with the input values for each parameter, as shown in Figure 2.18. Finding the best possible solutions within this design space is called the design space exploration process. An additional 'space' next to the design space, is the objective space, which adds criteria on a design's performance such as energy performance, environmental impact or financial impact (Brown et al., 2020).

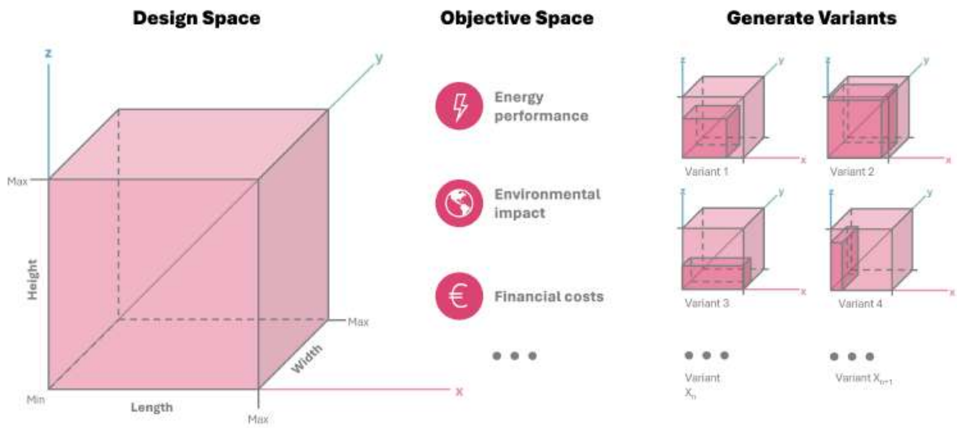


Figure 2.18: Explanation of design space exploration with the example of a 3D box

DSE in architectural design is closely linked to parametric design, as this approach explores the design and objective space by generating design variants based on a parametric script (Reisinger et al., 2021). This script uses input parameters to influence the design output, which is generated through a computational 'black box' since it has no knowledge about the inner workings of the model (Nagy et al., 2022) as shown in Figure 2.19. According to Dino (2012), parametric design can serve DSE as both a generative and analytical tool and highlights that the computational nature, flexibility and responsiveness of parametric design make it an ideal method for DSE.

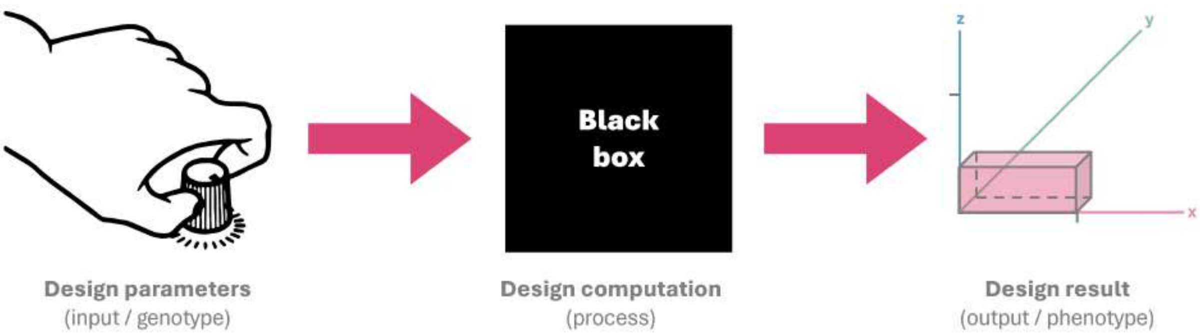


Figure 2.19: Parametric design space exploration process with the example of a 3D box (adapted from Nagy (2017))

In terms of applications of DSE, Kang et al. (2011) underscore three main uses: (1) rapid prototyping, (2) system integration and (3) optimisation. Rapid prototyping (1) involves the generation of a series of design variants to give insights on the impact of different decisions on the design result. This is especially useful for buildings, which are complex systems with numerous relations between different building components. System integration (2) is about the incorporation of a building design within a larger system, such as the surroundings of its location. DSE can be implemented to find design configurations that fit the constraints of that larger system. Finally, optimisation (3) is the process of finding the most effective solutions to a problem based on user criteria and constraints. With DSE, optimisation can be applied to generate a limited set of final variants that can be explored. The term optimisation refers to an extremely wide range of applied mathematics. In the context of building designs, it is often referred to as Architectural Design Optimisation (ADO) (Wortmann and Nannicini, 2017) and is, mainly through the integration of parametric design, considered to be an efficient application of DSE in building design (Geyer and Schlüter, 2014). The following section elaborates on the concept of ADO.

2.3.2 Architectural Design Optimisation

Architectural Design Optimisation (ADO) addresses optimisation problems related to finding the best building design variants in accordance with defined performance criteria (Wortmann and Nannicini, 2017). An optimisation problem always consists of three main components: (1) the objective function(s); (2) decision variables and (3) constraints (Boyles, 2015). The objective function (1) is the value or values that should be optimised, which means either a minimisation or maximisation of the value, for example, the minimisation of costs or maximisation of daylight entrance. Decision variables (2) are the key drivers of an optimisation process. They can be controlled to explore different configurations with the aim to eventually find the optimal solution(s) that satisfy the objective function. Examples of decision variables could be window size, insulation thickness and roof angle for a building's energy efficiency. Constraints (3) are limitations on the decision variables' values and set boundaries for the optimisation problem. An example of a constraint would be a financial budget for the costs of a building.

There exist many branches of mathematical optimisation, but according to Wortmann and Nannicini (2017), black-box optimisation is considered to be a particularly well-suited optimisation branch for ADO. This type of optimisation is also referred to as derivative-free optimisation and aims to solve optimisation problems that contain objectives or constraints for which their mathematical structure is too complex, unknown or not accessible (Alarie et al., 2021). The 'black box' in this case represents the optimisation process, which cannot be observed and understood except for its inputs and outputs, which is often the case with ADO problems (Wortmann and Nannicini, 2017).

The many existing optimisation methods are generally characterised by two variations: single and multi-objective optimisation (Nelissen, 2022). Single-objective optimisation (SOO) considers only one objective function and can generally be expressed with the following formula (Wortmann and Nannicini, 2017):

$$\min\left\{f(x) : x \in \left[x^L, x^U\right] \subseteq R^n, x_i \in Z \forall i \in I\right\} \tag{2.1}$$

Where $f(x)$ is the objective function and $\left[x^L, x^U\right]$ the lower and upper bounds of the decision variables that form the design space. $\subseteq R^n, x_i \in Z \forall i \in I$ represents a point in the design space that contains a set of decision variables constrained to integer values or otherwise real values. This point represents a solution to the SOO problem, which is finding the global minimum of the objective function $f(x)$. For SOO there is usually only one global optimal solution (Nelissen, 2022).

While SOO focuses on one objective function, multi-objective optimisation (MOO) deals with the optimisation of multiple objectives simultaneously that potentially conflict with each other, such as material costs that increase when environmental impact decreases (Wortmann and Nannicini, 2017). Because of this, an MOO problem is likely to have multiple solutions as the optimisation of one objective function might conflict with another objective. In general, MOO can be defined as optimising the vector of multiple single-objective functions (Wortmann and Nannicini, 2017), explained by the formula:

$$\min \{F(x) = [f_1(x), f_2(x), \ldots, f_k(x)]\} \tag{2.2}$$

There are two main methods for MOO (Evins, 2013). The first one is the weighted-sum approach where multiple objective functions are treated separately as single objectives. Each objective is multiplied with a weighting factor to combine them all in one single objective function (Kim and Weck, 2006). Penalty terms can be given to this objective function when a solution exceeds a constraint. Basically, the weighted-sum approach involves converting an MOO problem to an SOO problem.

The more elaborate approach for MOO is based on Pareto optimisation, which investigates trade-offs between objectives and consequently results in a set of different optimal solutions to the optimisation problem (Villa and Labayrade, 2011). Pareto optimisation works according to the Pareto dominance concept, which states that for a non-dominated solution, the optimisation of an objective value will be at the expense of one or multiple other objectives. Generally, this is defined as follows: "a solution x_1 is said to dominate the solution x_2 if x_1 is at least as good as x_2 on all objective functions and x_1 is better than x_2 on at least one objective function" (Kala, 2024). All solutions that are not dominated by another solution are called the Pareto optimal set and their resultant objective functions in the design space are called the Pareto front, which can have an infinite size (Selvi et al., 2018; Wortmann and Nannicini, 2017). Figure 2.20 explains the Pareto front as a two-dimensional curve for the optimisation of two objective functions f_1 and f_2. In this case solution C is dominated by solutions A and B and is therefore not included in the Pareto front. A and B are both non-dominated and considered optimal solutions of the Pareto front.

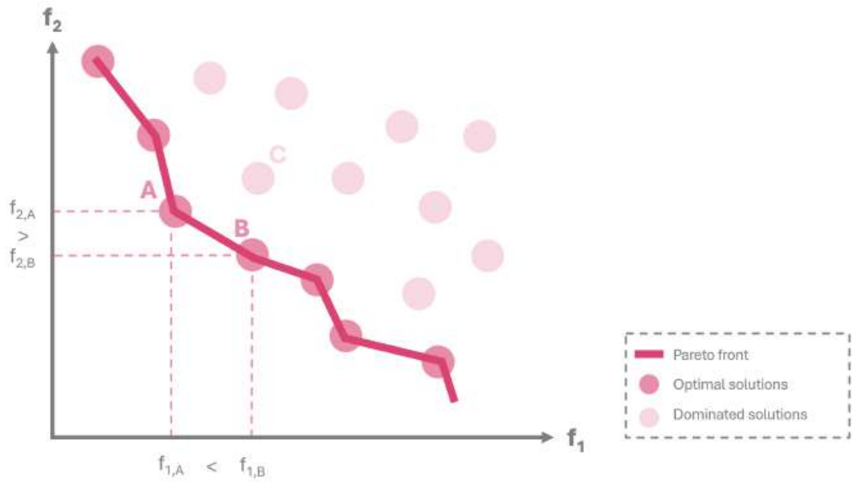


Figure 2.20: Pareto front example for two objectives (adapted from Villa and Labayrade (2011))

Compared to the weighted-sum approach, the Pareto optimisation method results in a wider range of solutions that also consider the trade-offs between objectives more accurately, whereas the solutions of a weighted-sum approach cover only specific parts of the Pareto front.

Wortmann and Nannicini (2017) introduce three main classes of black-box optimisation algorithms applied for ADO: (1) metaheuristics; (2) direct search and (3) model-based methods. Evins (2013) conducted an extensive review of existing optimisation methods in the field of sustainable building design. Figure 2.21 shows the optimisation classes together with identified methods retrieved from research by both Evins (2013) and Wortmann and Nannicini (2017).

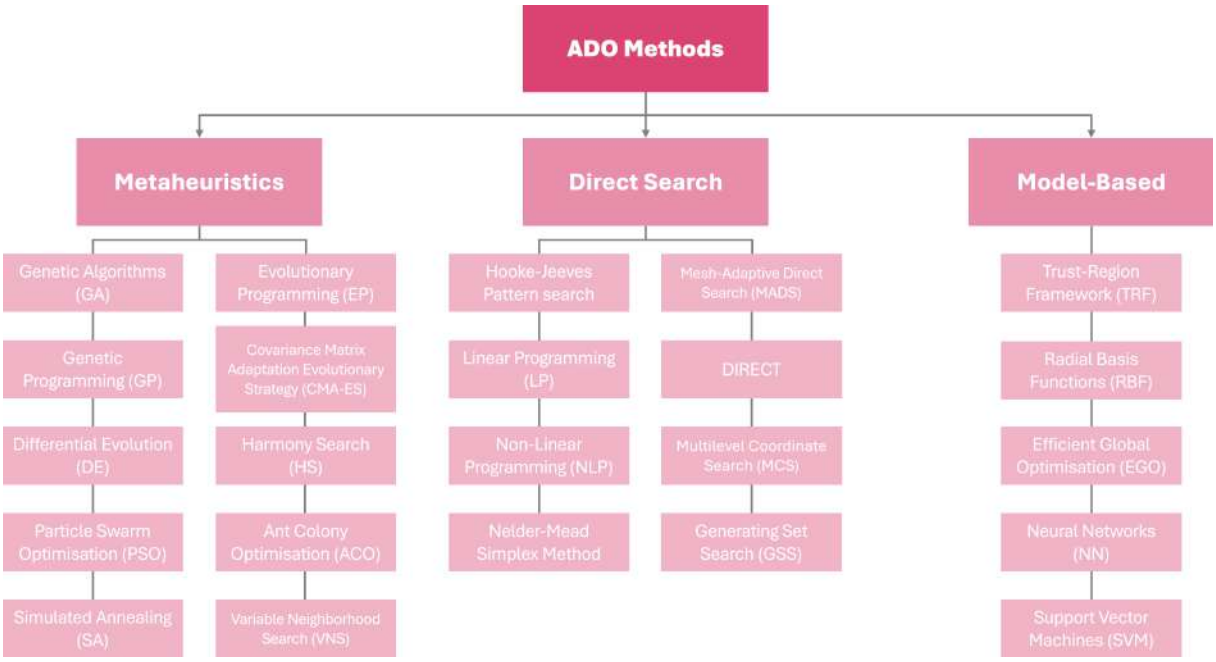


Figure 2.21: Architectural Design Optimisation Methods (Evins, 2013; Wortmann and Nannicini, 2017)

Metaheuristics (1) are stochastic algorithms, meaning they use random variables to solve complex optimisation problems. They iteratively evaluate random design solutions against defined performance criteria and continuously change the decision variables based on this information to achieve the most optimal solutions (Nagy et al., 2022). In ADO, metaheuristics are most commonly based on generative design (Nagy et al., 2022). One of the most popular methods of metaheuristics in ADO lies in the field of Artificial Intelligence (AI) with the utilisation of Evolutionary Algorithms (EAs), specifically Genetic Algorithms (GAs) (Wortmann and Nannicini, 2017). Evolutionary algorithms are inspired by nature through adopting the concept of survival of the fittest: eliminating the worst-performing solutions in a population. A user generally requires little expertise and knowledge for using evolutionary algorithms, making them a popular choice in practice (Hollberg and Ruth, 2014). GA's are a subset of evolutionary algorithms and use operations inspired by genetic reproduction such as the generation of new solutions through mutation (adding random changes) and crossovers (changing elements between solutions to create 'children') (Evins, 2013). A GA always starts with the generation of random solutions, which are then 'set loose' in the ecosystem, evaluated on their performance, and iteratively improved until an optimum (SOO) or set of optimal Pareto solutions (MOO) is acquired (Nagy et al., 2022; Villa and Labayrade, 2011). One of the most famous GAs is NSGA-II (Deb et al., 2002). Other well-known subsets of evolutionary algorithms include, among others (Evins, 2013): Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES), which uses probability distributions that are updated for each generation to create new solutions; Particle Swarm Optimisation (PSO), that mimics the movement of bird and fish 'swarms' by moving each solution around the design space based on its position and the position of neighbouring solutions; and Simulated Annealing (SA), a method inspired by metallurgy that progressively reduces the probability of accepting worse solutions. The main strengths of metaheuristics lie in their simplicity, straightforward implementation and wide applicability, particularly in the field of MOO, yet their dependence on random variables, time-consuming computation and uncertainty surrounding the quality of the optimal solutions are often seen as weaknesses (Wortmann and Nannicini, 2017).

Direct search methods (2) use iterative, deterministic algorithms by evaluating the objective function at subsequent points and comparing it to its predecessors to find the optimal solution (Evins, 2013). Wortmann and Nannicini (2017) define two types of direct search methods: local direct search and global direct search. Local direct search is designed for SOO and explores only a limited part of the design space, starting with evaluating the objective function from an initial point and moving towards neighbouring points to find a local optimum. It is often used when the design space is too large to explore in its entirety. Examples are the method of pattern search by Hooke and Jeeves (1961); Linear Programming (LP) in combination with the simplex method from Nelder and Mead (1965), a variant on the pattern search method; and non-linear programming (Evins, 2013). While local direct search only explores a part of the design space, global direct search navigates the entire design space to find global optima. It therefore concerns mainly MOO problems and tries to solve these by continuously subdividing the design space into boxes until an optimum is found. Examples of algorithms that use this method are DIRECT and Multilevel Coordinate Search (MCS). Compared to metaheuristics, the direct search method is less computationally intensive and provides more reliable results as it does not depend on random variables (Wortmann and Nannicini, 2017). However, they have a lower availability and are therefore less applied in ADO (Wortmann and Nannicini, 2016).

Model-based methods (3) aim to create a surrogate model of the system being optimised. This surrogate model is a mathematical approximation of the objective function and the inner workings of the black-box process of the system (Wortmann and Nannicini, 2016). It does so by interpolating known function values, which give an estimate of the unknown design space, that in turn can be used to quickly evaluate the performance of different solutions. Similarly to direct search methods, model-based methods can operate on local and global scales as well. Known methods of model-based optimisation are the Trust-Region Framework (TRF) and Radial Basis Functions (RBF) for local optimisation; and Efficient Global Optimisation (EGO), Neural Networks (NN) and Support Vector Machines for global optimisation (Wortmann and Nannicini, 2017). Due to their analytical nature, model-based methods are generally faster and more efficient than other methods, however, the quality of the optimal design solutions relies heavily on the accuracy of the surrogate model.

Wortmann and Nannicini (2017) finally investigated different criteria for choosing optimisation algorithms and concluded that SOO algorithms generally yield better optimal values for the objective function and MOO algorithms can best be used for understanding trade-offs between conflicting objective functions in complex systems. Additionally, for time-efficient optimisation they recommend using either direct-search or model-based methods, while suggesting the use of metaheuristics when time efficiency is less important due to their ease of implementation.

2.3.3 DSE and ADO Tools

Many tools for applying DSE and ADO exist and are widely implemented in parametric design software. The most common programs include Grasshopper (GH) for Rhino, Dynamo for Revit and PARAM-O for Graphisoft ArchiCAD (Shumilov and Guryeva, 2022). These platforms are based on visual programming, enabling users to create a parametric script without requiring extensive programming skills. The scope of this research is limited to Grasshopper for Rhino, the most popular parametric software program available (Gu et al., 2021). Table 2.6 provides an overview of existing DSE and ADO tools specifically designed for Grasshopper. The next paragraphs provide an elaboration on these tools.

In terms of SOO, Galapagos is the most commonly used GH plugin and is built-in with the standard GH installation. It uses metaheuristics and features a genetic and simulated annealing algorithm that requires two inputs: a genome, which should be linked to the decision variables and a fitness, which is the objective function that should be optimised. Optimus and Silvereye are other metaheuristics-based optimisation plugins. Optimus uses a so-called "self-adaptive differential evolution algorithm with ensemble of mutation strategies (jEDE)" (Cubukcuoglu et al., 2019) and Silvereye a Particle Swarm Optimisation (PSO) algorithm. Goat is the first SOO plugin to use a direct-search optimisation approach and uses non-linear programming (NLP) and the DIRECT algorithm while the Nelder-Mead Optimisation plugin was introduced later and adopted a different direct-search approach by using the Nelder-Mead Simplex method. Dodo is the only plugin that combines all three ADO classes and offers optimisation through metaheuristics with PSO, direct-search with NLP and model-based with AI Neural Networks.

Table 2.6: Overview of existing DSE and ADO tools for Grasshopper

Tool	Logo	Author	Year	Type	Open access	Optimisation class & method
Biomorpher		John Harding Cecilie Brandt-Olsen	2018	GH plugin	✓	SOO (GA)
Design Explorer	DesignExplorer	Thornton Tomasetti	2016	Web-based	✓	SOO / MOO (GA)
Design Space Exploration		MIT Digital Structures	2017	GH plugin	✓	SOO / MOO (GA)
Dodo		Lorenzo Greco	2015	GH plugin	✓	SOO Metaheuristics (PSO), direct-search (NLP), model-based (NN)
Galapagos		David Rutten	2010	Built-in GH plugin	✓	SOO (GA, SA)
Goat		Rechenraum	2010	GH plugin	✓	SOO Direct-search (NLP, DIRECT)
Nelder-Mead Optimisation		Eckersley O'Callaghan's Digital Design Group	2013	GH plugin	✓	SOO Direct-search (Nelder-Mead Simplex)
Octopus		Robert Vierlinger	2012	GH plugin	✓	MOO Metaheuristics (GA)
Opossum		Thomas Wortmann	2017	GH plugin	✓	SOO / MOO Model-based (RBFOpt, RBFMOpt) Metaheuristics (GA, Ant Colony, Particle Swarm)
Optimus		Cubukcuoglu et al.	2019	GH plugin	✓	SOO Metaheuristics (jEDE)
Silvereye		Chichocka et al.	2015	GH plugin	✓	SOO Metaheuristics (PSO)
Wallacei		Mohammed Makki	2019	GH plugin	✓	MOO Metaheuristics (GA)

For MOO, three main optimisation plugins exist for GH: Octopus, Wallacei and Opossum. Octopus and Wallacei are both Pareto-based optimisation tools that use metaheuristics through GAs. They work in a similar way as Galapagos, requiring as input variables: a genotype of decision variables and multiple objective functions. Their output is a dataset of Pareto-optimal solutions and resulting geometry phenotypes that are visualised through Pareto graphs (2D for two objectives, 3D for three), 2D parallel coordinate plots and diamond fitness charts. Opossum, on the other hand, is able to perform both single- and multi-objective optimisation. For MOO, it includes a model-based RBFMOpt, and a metaheuristic GA, Ant Colony Optimisation (ACO) and Particle Swarm Optimisation (PSO) algorithm. Opossum is therefore the most extensive MOO plugin in terms of the variety of optimisation methods it offers.

A tool designed especially for DSE and not only optimisation is Design Explorer. This is a web-based tool in which a user can upload a design space from a GH project to a server by providing a data.csv file of the script and a series of images of different model configurations based on the influence of the decision variables (Hristov, 2017). It uses GAs such as Galapagos or Octopus to facilitate the optimisation process and visualises the resulting design space through a 2D parallel coordinate plot containing the performance of the objective functions, in combination with corresponding images of the phenotype model (Figure 2.22). The lines of the coordinate plot can be moved to explore the effect of different performance values for each objective. Each resulting 3D model in the design space can be explored individually through the set of images.

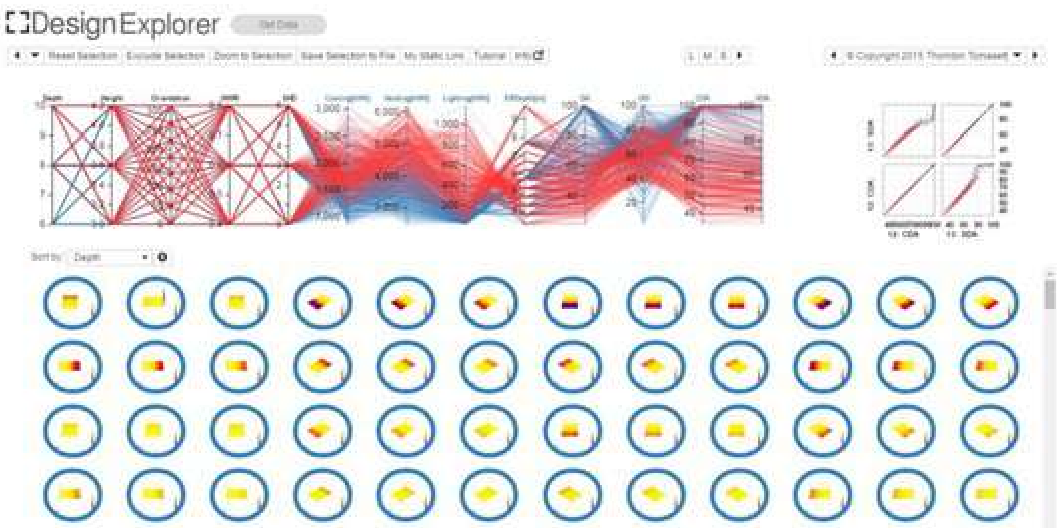


Figure 2.22: UI of Design Explorer (Design Explorer, 2016)

The Design Space Exploration plugin is similar to Design Explorer, but is a GH plugin that uses Stormcloud, an additional interactive evolutionary optimisation framework to perform an MOO that results in a visualised design space within GH.

2.3.4 Applications of DSE and ADO

In the context of this research, applications of DSE and ADO in the field of LCA, LCC and circularity in the built environment are examined in the next paragraphs.

Hollberg and Ruth (2014) for example investigated the necessary factors for the optimisation of façade insulation thickness by analysing both embodied and operational environmental impact with LCA. To realise this, they developed a parametric tool in Grasshopper with the help of the Galapagos optimisation plugin. This was applied to the case study of a typical German single-family house from the 1960s that has to be retrofitted with new insulation material. Their tool uses environmental data on eight insulation materials and a chosen heating system, together with energy demand data from EnergyPlus, an external energy simulation engine that is linked to Grasshopper with the Archsim plugin. The objective function of the optimisation is the minimisation of environmental impact, which is influenced by the insulation material and thickness of the walls, slabs, roof and ceiling. In the end, the tool proved to be an effective measure for minimising the environmental impact of retrofitting insulation measures, especially in the early design stages.

Next to LCA, Hester et al. (2018) also introduce building costs as an objective in their study about building design space exploration. They investigated the combination of an existing parametric LCA model called Building Attribute to Impact Algorithm (BAIA) with two different black-box optimisation methods: sequential specification and genetic optimisation. By applying this framework to a case study, they found that the genetic optimisation method performed better than the sequential specification method, as it resulted in solutions with lower environmental impacts and costs. At the same time, they highlight the limitation of the use of random variables by the GA, which causes results to differ slightly each time an optimisation is performed.

Reisinger et al. (2021) introduced a parametric design process for DSE considering the flexibility assessment of industrial buildings to optimise their circularity. They developed the framework in a Grasshopper script that models the design space for the use case of a flexible industrial building. The structural system of this building is then automatically optimised with Karamba3D and a flexibility assessment is performed, created by the authors. Finally, for each design variant the parameters and assessment results are exported to an Excel database to sort the data and explore trade-offs between variants. The proposed method allowed for efficient design space exploration but lacked the inclusion of other objectives such as costs and environmental impact. Reisinger therefore recommends using evolutionary MOO algorithms to create a more holistic approach.

A synthetic review of the application of MOO models for climate-responsive building design was carried out by Manni and Nicolini (2022). They analysed about 140 articles between 2014 and 2021 and concluded that MOO is mainly used to identify trade-offs between a building's energy efficiency, thermal and visual comfort, and additionally construction costs and operation impact. Optimised phenotypes usually include a building's envelope, windows and shading systems. They highlight the lack of MOO models that include environmental impact and expect improvement in that area in the years after their review.

Nelissen (2022) dedicated a thesis to the development of a decision-support tool that aids residents of housing clusters and municipalities in their transition from gas towards sustainable heating methods. This tool therefore aimed to optimise the implementation of heating techniques, while considering comfort (comfort level), environmental (kg CO_2) and financial (investment, maintenance, replacement and energy costs) aspects, which introduced a MOO problem. First, a Limited Cost-Benefit Analysis (LCBA) was done to evaluate different heating techniques based on costs and benefits. The optimisation model was then developed with the use of Mixed-Integer Linear Programming (MILP) coding in Python. R shiny was finally used to develop an interactive user interface that combines the results of the LCBA and optimisation. The end goal of the resulting decision-support tool is to inform the affected residents and municipalities about the effects of energy transition measures, for which the tool proves to be successful.

Baden and Taghizadeh (2023) did an evaluation study for the effectiveness of three Grasshopper MOO plugins in finding optimal renovation solutions when balancing environmental impact, energy use and costs for Swedish buildings. The considered plugins were Octopus, Wallacei and Opossum. For evaluating environmental impact, they calculated the GWP with the Swedish Brimstone plugin. Energy use and cost estimates were determined manually based on external studies and resources. They found that all three MOO plugins proved efficient in generating accurate, optimal solutions when using a generation size of 1260 iterations. Opossum was the most effective in reducing the simulation time, and Wallace excelled in its data analysis methods and ability to post-process the optimisation results. Baden and Taghizadeh conclude their study by recommending the inclusion of additional objectives, such as daylight entrance, thermal comfort and air quality, to further demonstrate the effectiveness of MOO plugins in reducing environmental impact,

In another thesis by Wolbert (2022), shadow cost optimisation for the case study of the load-bearing structure of construction halls in early design is investigated using parametric and generative design. Wolbert adapted the original Environmental Cost Indicator (ECI) by adding a custom connection reusability score to include circularity, resulting in a Corrected Shadow Cost method (CSC). A parametric model of a construction hall case study was made in Dynamo for Revit with a link to RFEM, a finite element software program for structural analysis. A genetic algorithm from Autodesk generative design is then implemented to perform both single and multi-objective optimisations of the model based on the ECI and CSC methods to minimise the shadow costs while maintaining structural integrity and also considering material costs. The optimisation model proved effective but was also based on many assumptions and only one parametric model, which calls for future research into the topic.

Finally Zorn (2023) presents a DSE software framework for Grasshopper by using model-based methods such as Machine-Learning (ML) to train the design space with the ultimate goal to minimise the environmental impact of building designs. Zorn acknowledges the limited selection of feasible design solutions and lack of aesthetic value given by traditional ADO methods, and introduces DSE as a more realistic method for architectural optimisation in practice. With a C# Windows Presentation Foundation (WPF) frontend and Python backend programming, a new DSE software architecture is created that trains and implements surrogate models to define a design solution space that can be explored by designers. Further research into this tool will be conducted in the future and will focus on enhancing the model's accuracy and the visualisation of multiple objectives.

2.4 Summary

The literature review underscores that there is a need for enhancing responsible material use in building designs through integrating aspects of LCA, LCC and circularity during the early design stages. Various studies in the field contribute in different ways to address this need, each using its own approach with digital assessment methods. Notably, among these approaches, the parametric design method stands out as particularly promising due to its flexibility, compatibility with complex designs and optimisation potential, making it an interesting design method to implement in early building design. The literature timeline in Figure 2.23 provides an overview of the key studies identified among the existing literature and highlights their new contributions on prior research in bold.

From this timeline, we can identify the research gap. The integration of both LCA, LCC and circularity is rare. While Karabinar (2021) managed to successfully integrate all three aspects in a BIM-based tool, and Reisinger et al. (2022) developed a parametric framework for this purpose, no actual tool or research exists that uses parametric design to integrate LCA, LCC and circularity to enhance responsible material use in the early design stages. This gap is further supported by the comparative studies from Säwén et al. (2022) and Dervishaj and Gudmundsson (2024) who mention the lack of LCC and circularity assessment among existing digital tools. Additionally, both Karabinar and Reisinger underscore the importance of adding an optimisation functionality for enhanced decision-making and support in Design Space Exploration (DSE). So from the timeline, we can conclude that there is a lack of tools and research exploring how parametric design can integrate LCA, LCC and circularity to enhance responsible material use in the early building design stages.

This research will therefore bridge this gap by developing *ReLifeCycle*, a tool for supporting research into this topic, thereby advancing parametric design for integrating LCA, LCC and circularity to enhance responsible material use in early building design.

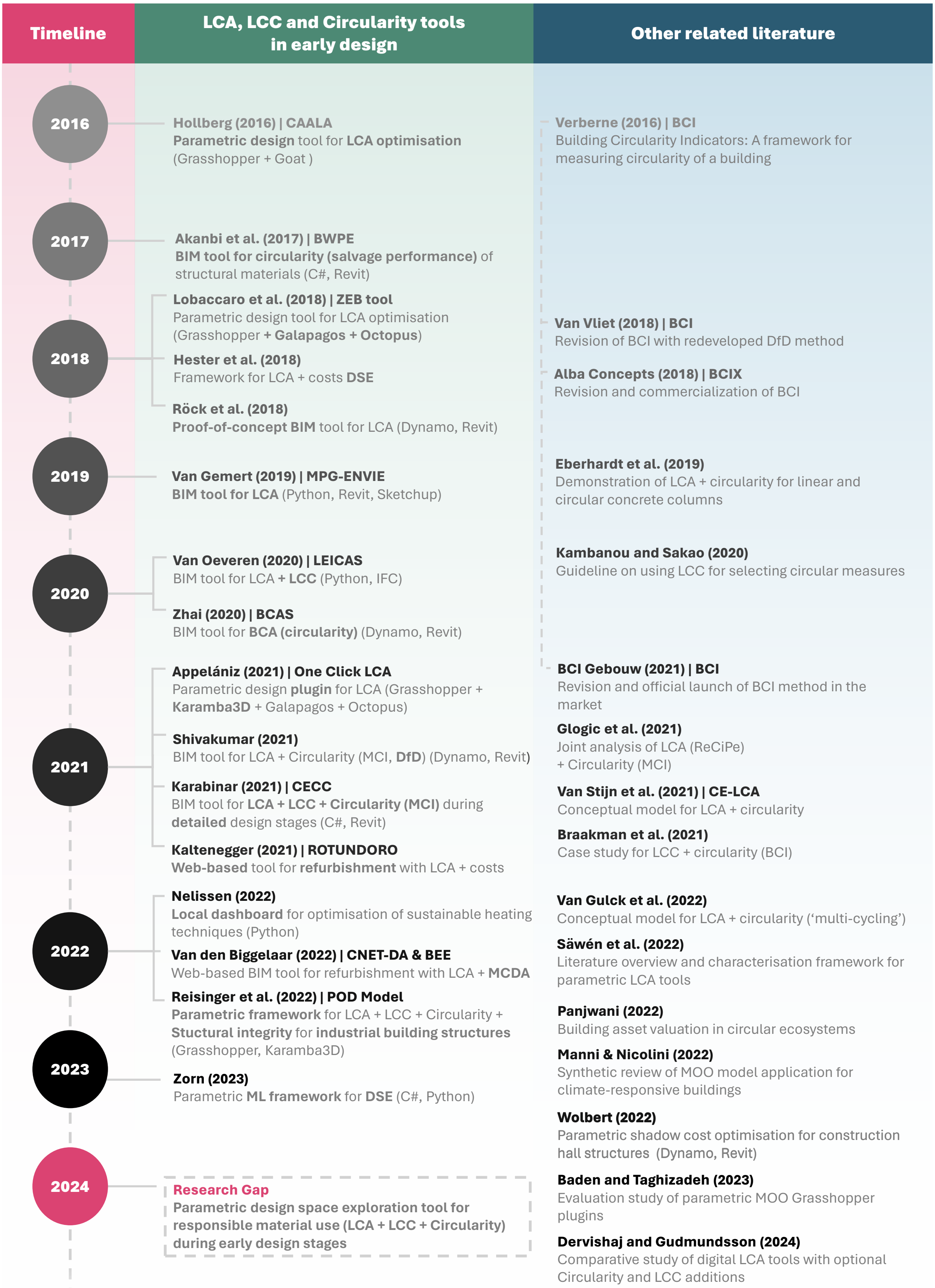


Figure 2.23: Literature timeline

3. METHODOLOGY

In the literature review, the theoretical background for this research was explored, concluding with the research gap and the proposal to develop *ReLifeCycle*, a parametric Design Space Exploration (DSE) tool for enhancing responsible material use in the early design stages. This section outlines the general methodology for the design, development, validation and reporting of *ReLifeCycle*. While this section provides an introduction to these methods, the subsequent sections offer a more detailed explanation of their application.

3.1 Research Approach

To develop *ReLifeCycle*, this study adopts the design science methodology from Wieringa (2014), since it deals with a design problem that calls for a change in the real world. This methodology follows the design cycle that goes through the steps of problem investigation, prototype design and prototype validation Figure 3.1. The design cycle is part of the broader engineering cycle which includes implementation and evaluation as extra steps; however, these are out of scope for this research.

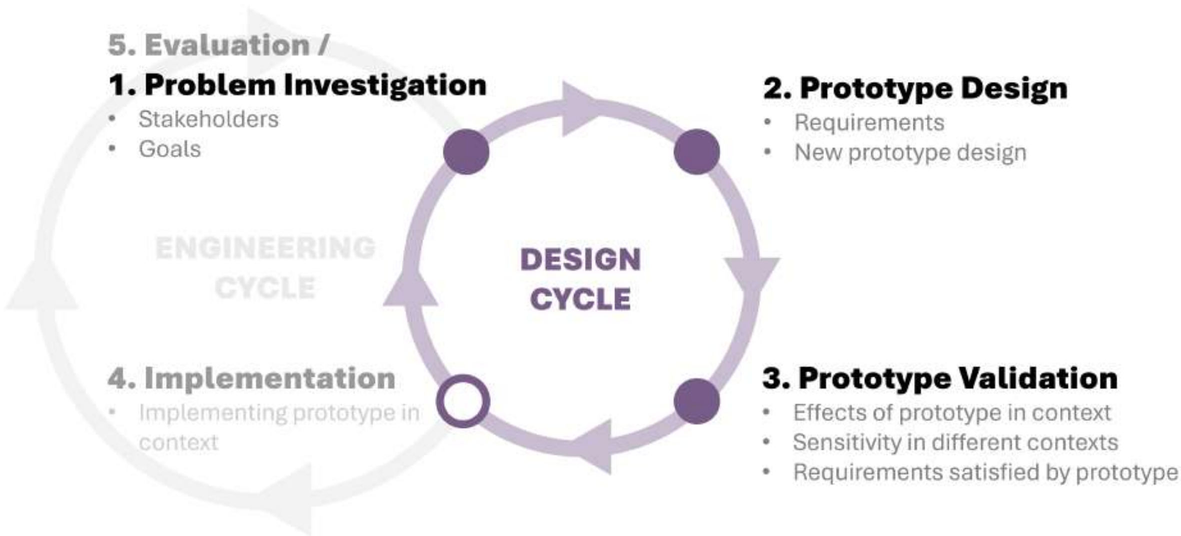


Figure 3.1: Design Cycle (adapted from Wieringa (2014)

3.2 Research Design & Methods

The design cycle in Figure 3.1 underpins the general methodological approach for this research. Based on this and insights from the literature review, the research design consists of the following five stages: (1) System design; (2) Framework Development; (3) Prototype Development; (4) Validation and (5) Reporting. A framework for the research design with its corresponding steps can be seen in Figure 3.2. For each stage in the research design, the corresponding steps are outlined and further elaborated in the following paragraphs.

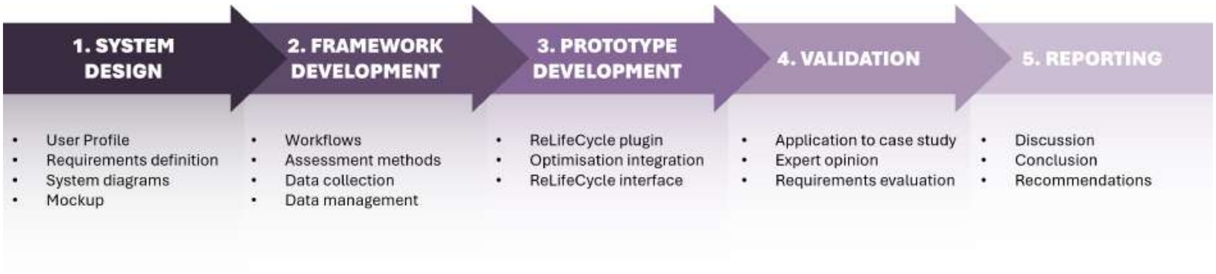


Figure 3.2: Research Design

3.2.1 System Design

To design the *ReLifeCycle* system, this research bases its method on the systems engineering principles from Kossiakoff et al. (2011), which provide guidelines for the engineering of complex systems. Systems engineering treats a system as a relational network of components working towards a shared objective. The objective of this research is to enhance responsible material use in early building design, and the proposed system "*ReLifeCycle*" will use parametric design to achieve this goal. The system design is driven by user requirements, ensuring that each component contributes to the overall objective and functionality.

The first step in the system design process is to define a user profile. A set of open-ended questions is then prepared to guide unstructured interviews with experts in the field of parametric design, circularity and sustainability. The insights gathered from these interviews, along with findings from the literature review, are evaluated on their importance and used to define a set of functional requirements, which specify the system's functions from the user's perspective. From these, non-functional requirements are derived that define how the system should fulfil the functional requirements. Next, the requirements are translated into use cases, representing the specific system functionalities to be developed.

From these use cases, a variety of behavioural system diagrams are created using the Unified Modeling Language (UML) to visualise and refine the system. A use case diagram is made first to define the interactions between the system's functionalities and actors (users and external systems). Next, an activity diagram is made to elaborate on the system's workflow and activities. The system architecture is then created to provide a high-level view of the system and its components. The Model-View Controller (MVC) software design pattern is applied for this, since it enables a more flexible use of system components. In this pattern, the Model handles the system's data logic, the View defines how data is presented to the end-user, and the Controller manages request flows between the Model and the View. Finally, UML sequence diagrams are made to visualise the detailed interactions and order of system components for a specific use case.

In the end, *ReLifeCycle's* system design is visualised in a mockup, which serves both to aid the prototype development process and as a useful tool to explain the system to participants during the expert interviews. The system design method is further elaborated in Section 4.

3.2.2 Framework Development

The framework development stage begins by outlining the three workflows of *ReLifeCycle*: (1) parametric building script; (2) responsible material use assessment and (3) responsible material use enhancement. The second workflow is the core of the *ReLifeCycle* development, with a framework developed to integrate LCA, LCC and circularity through both assessment methods and data. The scope of the assessment assumes a schematic design stage for the level of building detail. For this stage, the most suitable calculation approaches for LCA, LCC and circularity are defined and used to create an integrated assessment framework for enhancing responsible material use. For environmental impact (LCA), the MilieuPrestatieGebouw (MPG), Paris Proof (PP) indicator, and Construction Stored Carbon (CSC) are considered. For financial impact (LCC), direct costs and the True Price method are used. For circularity, the Building Circularity Index (BCI), Disassembly Potential (DP) and material input and output flows are included.

In terms of data collection, geometry data is extracted from a 3D Rhino building model generated with Grasshopper. To support LCA, LCC and circularity, multiple material databases are evaluated on their ability to provide brand-independent data on the material level, to match the schematic design level of detail within the scope of this research. Ultimately, LCA data is retrieved from the Nationale MilieuDatabase (NMD), LCC data from the ArchiCalc database and circularity data from the Nederlands Instituut voor Bouwbiologie en Ecologie (NIBE) database. The NL/SfB classification system is used to define building element classes (BNA, 1991). Data properties are based on the ISO14040 and 14044 LCA standards and properties from the source databases.

For data management, the NMD, ArchiCalc and NIBE databases are linked in a relational material database. Karabinar (2021) recommended the use of a dynamic database server for efficient data retrieval. Therefore, MySQL is used, a relational database management system that uses Structured Query Language (SQL) (MySQL, nd). This approach is particularly useful considering the multiple material databases that have to be linked. For this research, a prototype database is made with MySQL Workbench that includes linked LCA, LCC and circularity data for a limited set of materials. Further details on the framework development of *ReLifeCycle* are discussed in Section 5.

3.2.3 Prototype Development

ReLifeCycle is developed as a parametric DSE tool for Grasshopper. Research on parametric design refers to Grasshopper as one of the most popular parametric design software for the early design stages due to its flexibility in generating numerous design variants and ability to integrate optimisation algorithms (Gu et al., 2021), capabilities that are less prominent in other parametric design software like Dynamo, which primarily focuses on automating Revit tasks. Furthermore, Grasshopper has a wide user base and open ecosystem that allows everyone to develop and integrate plugins, making it a suitable platform for developing *ReLifeCycle*.

The prototype consists of three core components. The first is a responsible material use assessment tool, developed as a Grasshopper plugin. Unlike developing such a tool through visual programming in Grasshopper, a plugin greatly improves the workflow, usability and performance speed, making it a more suitable approach. The plugin is developed in C#, the standard language for Grasshopper plugin development (Rigdon-Bel, 2023). What the plugin primarily focuses on is the link between building geometry information and material-related properties, such as Global Warming Potential (GWP) and direct costs, that serve as input for LCA, LCC and circularity assessment. To ensure accuracy, iterative testing is conducted throughout the development.

The second component is the creation of a material-driven optimisation functionality that is able to generate an optimised set of material variants, making the DSE process more efficient by automating the exploration of multiple variants. This is achieved by investigating the integration of *ReLifeCycle* with the Single-Objective Optimisation (SOO) Grasshopper plugin Galapagos and the Multi-Objective Optimisation (MOO) plugin Wallacei.

The third component involves the development of a user interface to present the LCA, LCC and circularity assessment results in a user-friendly and intuitive overview, allowing users to explore results and identify high-impact building elements. This interface is developed with the Human UI Grasshopper plugin. Moreover, a connection between the user interface and the MOO Wallacei plugin is made, allowing users to efficiently explore material variants. The *ReLifeCycle* prototype is described in more detail in Section 6.

3.2.4 Validation

The *ReLifeCycle* prototype is validated and tested against a case study to assess the functionality of the tool in context and evaluate its accuracy, reliability, assessment methods and potential to enhance responsible material use. Further, the user-friendliness of the prototype is assessed as part of alpha testing with experts in the field of parametric design to gather feedback. The previously defined functional and non-functional requirements serve as validation metrics, and the feedback collected from alpha testing is evaluated against these requirements. Section 7 discusses the validation in detail.

3.2.5 Reporting

The reporting stage is the final stage of the research and begins with critically discussing the results from the validation and comparing *ReLifeCycle* to state-of-the-art tools in Section 8. The conclusion in Section 9 outlines the main contributions and addresses the research question by highlighting the key findings that reveal the meaning, added value and implications of the research. Finally, recommendations for future research are provided.

4. RELIFECYCLE DESIGN

This section defines the system design of *ReLifeCycle*, which follows the systems engineering principles outlined by Kossiakoff et al. (2011). These principles view systems as a whole, focusing on user needs and guiding the conceptual system design process. The section begins by identifying a user profile to narrow the target group, followed by a definition of functional and non-functional requirements derived from interviews and the literature review. These requirements are then translated into use cases, representing the functionalities of the system. A variety of system diagrams are introduced, including a UML (Unified Modeling Language) use case diagram, system architecture, sequence diagrams and an activity diagram. Finally a mockup of *ReLifeCycle* is designed, showing a preliminary visualisation of the system's user interface.

4.1 User Profile

A user profile is created and presented in Table 4.1, to identify the main target group of *ReLifeCycle*. The user is defined as a design-related decision-maker in the early building design stages, such as an architect, engineer, consultant or contractor. They play a significant role in shaping building design, influencing aspects such as building form and space, and enabling material variations. To contribute to solving the problem of climate change and complying with stricter governmental laws on this topic, they need a tool that can explore different design variants on responsible material use. The user region is limited to the Netherlands to suit the scope of this research. Since the system is designed for Grasshopper, parametric design skills in this software are required and at least a limited understanding of LCA, LCC and circularity is expected. Since parametric design is still a niche in the built environment, the user category focus is laid on the innovators and early adopters that account for about 10-17,5% of users (Indeed Editorial Team, 2024).

Table 4.1: User profile for ReLifeCycle

Region	The Netherlands
Occupation	Design-related decision-maker (architect, engineer, consultant, contractor)
Knowledge and skills	- Building design skills - Parametric design skills with Grasshopper and Rhino - Limited to high expertise in LCA, LCC and circularity assessment
User category	Innovators, early adopters
Needs	- A tool for exploration of design variants on responsible material use - A user-friendly interface to show results, variants and possibilities in a conversation with members of the design team or clients.

4.2 Requirements Definition

The requirements for *ReLifeCycle* are defined in preparation of the framework and prototype development stages. A distinction is made between functional and non-functional requirements. Functional requirements specify the desired functions and outcomes from the user's perspective whereas non-functional requirements specify what the system must do to fulfil the functional requirements and how it should do it (IBM, 2011). The requirements are derived from a combination of insights from the literature review, state-of-the-art tools from Table 2.5 and a series of unstructured interviews of experts on various fields related to the topic of this research. The interviews were conducted as natural, free-flowing conversations and did not have predetermined standard questions. During the interviews, a mockup of *ReLifeCycle* was shown to visually support the conversation. This mockup is elaborated in Section 4.4. A list of interviewees can be found in Appendix A.

All requirements have been carefully set up with the primary objective of this research in mind: enhancing responsible material use in the early building design stages with parametric design. Therefore each requirement is made to contribute toward the development of a tool that supports this goal. This involves integrating different assessment methods, implementing the system in the Grasshopper environment and ensuring good usability.

Based on the timeframe of this research, MoSCoW prioritisation is used to give each requirement a priority. This method was developed by Dai Clegg and suggests four prioritisation categories (Yalçıner, 2023):

1. **M – Must have:** Essential requirements that are necessary to achieve a functional system.
2. **S – Should have:** Important requirements that should be implemented if possible, but are not critical to achieving a functional system.
3. **C – Could have:** Desirable but non-essential requirements that would enhance the system, but are not as important as other requirements.
4. **W – Won't have:** Requirements that are considered, but will not be included in the system.

To implement structure, the requirements are divided into four main packages that define the system:

1. **Model Linking & Material Mapping:** This package involves linking Grasshopper geometry to the system and enhancing it with material data by mapping a material to each building element.
2. **Responsible Material Use Assessment:** Building on the linked material data, this stage evaluates the responsible material use of a building by performing an environmental impact, circularity and financial impact assessment.
3. **Responsible Material Use Enhancement:** This package applies optimisation algorithms to the assessment results to support the Design Space Exploration (DSE) process and explore different material variants to enhance the responsible use of materials.
4. **Results Interface:** This final aspect of the system presents the outcomes in a user-friendly Graphical User Interface (GUI).

The functional and non-functional requirements are presented in Table 4.2 and Table 4.3 with their corresponding MoSCoW priority. Each requirement is given a unique ID: "FR_X.X" for the functional requirements and "NFR_X.X" for the non-functional requirements.

4.2.1 Functional Requirements

Table 4.2: Functional Requirements

ID	Requirement	Priority
	1. Model Linking & Material Mapping	
FR_1.01	The user must be able to link a parametric Grasshopper 3D model to the system	MUST
FR_1.02	The user must be able to classify building model components	MUST
FR_1.03	The user must be able to map materials to building model components	MUST
FR_1.04	The user must see the geometry input requirements for a specific classification/material (line, surface, volume)	MUST
FR_1.05	The user should have insight into the environmental, financial and circularity data of each specific material to make comparisons during the material selection process	SHOULD
FR_1.06	The user should be able to assign a name to a building element or group of building elements	SHOULD
FR_1.07	The user won't be able to link a BIM model to the system	WON'T
FR_1.08	The user could be able to add a custom material	COULD
FR_1.09	The user could link a generic building mass to the system instead of building elements	COULD
FR_1.10	The user must be able to see an explanation of the workings of the tool with a demo script	MUST
	2. Responsible Material Use Assessment	
FR_2.01	The user must be able to assess the responsible material use of their building design	MUST
FR_2.02	The user must be able to set required calculation variables	MUST
FR_2.03	The user should have access to clear documentation of the used assessment methods in the calculation	SHOULD
FR_2.04	The user should have the option to choose if a material is new or reused	SHOULD
FR_2.05	The user could be able to include or exclude specific life cycle stages	COULD
FR_2.06	The user could be able to set a reference date	COULD
FR_2.07	The user won't be able to change the calculation methods internally	WON'T
FR_2.08	The user won't be able to combine multiple products into elements (prefab/modular units) to calculate the Element Circularity Index (ECI)	WON'T
	3. Responsible Material Use Enhancement	
FR_3.01	The user must be able to explore a generated set of design variants optimised for responsible material use	MUST
FR_3.02	The user must be able to set decision variables for the optimisation process	MUST
FR_3.03	The user must be able to set objective functions for the optimisation process	MUST
FR_3.04	The user must be able to set constraints for the optimisation process	MUST
FR_3.05	The user must be able to set a count for the amount of design variations	MUST
FR_3.06	The user should be able to name, store, and load variants	SHOULD
FR_3.07	The user could assign weights of importance to the objectives to select one optimal variant	COULD
	4. Results Interface	
FR_4.01	The user must be able to see an overview of the responsible material use assessment results in a user interface with clear, visual representations	MUST
FR_4.02	The user must be able to see real-time updates in the results as they adjust design parameters and materials	MUST
FR_4.03	The user should be able to evaluate the quality of the results by comparing them to reference standards	SHOULD
FR_4.04	The user should have insight into the investment costs of the design	SHOULD

Continued on next page

ID	Requirement	Priority
FR_4.05	The user should have insight into the results per building element	SHOULD
FR_4.06	The user should have insight into the results per classification	SHOULD
FR_4.07	The user could categorise the results based on the layers of Brand	COULD
FR_4.08	The user should be able to compare the results of variants from the optimisation process	SHOULD
FR_4.09	The user should be able to export the results into a PDF report	SHOULD
FR_4.10	The user should be able to export the results into an Excel report	SHOULD

4.2.2 Non-functional Requirements

Table 4.3: Non-Functional Requirements

ID	Requirement	Priority
	1. Model Linking & Material Mapping	
NFR_1.01	The system must be able to store general, environmental, circularity, and cost-related data of materials in a relational MySQL database	MUST
NFR_1.02	The system must be able to process data stored in an external MySQL database	MUST
NFR_1.03	The system won't have more than one database for each aspect of responsible material use (environmental impact, financial impact, circularity)	WON'T
NFR_1.04	The system won't have a direct connection with the original environmental, circularity and cost databases	WON'T
NFR_1.05	The system must allow the user to link building element Grasshopper geometry to the system with a custom Grasshopper component	MUST
NFR_1.06	The system must present the user with an overview of geometry input requirements	MUST
NFR_1.07	The system must be able to classify a building element from the model with an NL/SfB code	MUST
NFR_1.08	The system must be able to create a material set with suitable materials for each NL/SfB classification	MUST
NFR_1.09	The system must be able to link material data to building element Grasshopper geometry	MUST
NFR_1.10	The system must display an error when the building element geometry does not match the functional unit of the material	MUST
NFR_1.11	The material list should contain general environmental, circularity and cost information	SHOULD
NFR_1.12	The system could present the material list as a separate pop-up window	COULD
NFR_1.13	The material list could have a search function	COULD
NFR_1.14	The material list could have a filter function	COULD
NFR_1.15	The system should be able to assign a name to a building element	SHOULD
NFR_1.16	The system could include automatic structural dimensioning	COULD
NFR_1.17	The system could include automatic insulation dimensioning based on R-value	COULD
NFR_1.18	The system won't be able to process IFC data from a BIM model	WON'T
NFR_1.19	The system won't be able to link an imported BIM model by mapping the IFC categories to NL/SfB codes	WON'T
NFR_1.20	The system could be able to create a custom material based on data delivered by the user	COULD
NFR_1.21	The system could link a simple building mass with a custom Grasshopper component	COULD
NFR_1.22	The system could classify a simple building mass with general building information	COULD
NFR_1.23	The system must include a demo Grasshopper script that explains the workings of the tool with a case study	MUST

Continued on next page

ID	Requirement	Priority
	2. Responsible Material Use Assessment	
NFR_2.01	The system must be able to perform a responsible material use assessment for the linked building elements with a custom Grasshopper component for each responsible material use aspect (environmental impact, circularity, financial impact)	MUST
NFR_2.02	The system must be able to perform an environmental impact calculation by considering the MPG, Paris Proof and Construction Stored Carbon	MUST
NFR_2.03	The system must be able to perform a circularity calculation by considering the Building Circularity Index (BCI), Disassembly Potential (DP), material input flows and material output flows	MUST
NFR_2.04	The system must be able to perform a financial impact calculation by considering the material costs, labour costs and true pricing	MUST
NFR_2.05	The system must allow the user to set the following calculation variables: - Building lifespan [years] - Building function - GFA [m^2]	MUST
NFR_2.06	The system must measure the quantity of a building component used in the calculation according to the functional unit of the selected material (m, m^2, m^3, piece)	MUST
NFR_2.07	The system must be capable of processing design changes and parameter adjustments in real-time, updating results and visualisations immediately	MUST
NFR_2.08	The system should provide a text with documentation on the used assessment methods and databases	SHOULD
NFR_2.09	The system should give a user the option to choose if a material is new or reused with a toggle	SHOULD
NFR_2.10	The system should apply extra benefits for the circularity and environmental impact assessments when a reused material is selected	SHOULD
NFR_2.11	The system could give the user freedom to include or exclude specific life cycle stages with a multiple value list	COULD
NFR_2.12	The system could set a reference date and consistently retrieve the data used for the assessment on that date	COULD
NFR_2.13	The system will not give the user freedom to change the calculation methods	WON'T
NFR_2.14	The system will not consider the Element Circularity Index (ECI) in the BCI calculation	WON'T
	3. Responsible Material Use Enhancement	
NFR_3.01	The system must include an optimisation functionality by facilitating an integration with an external multi-objective optimisation Grasshopper plugin	MUST
NFR_3.02	The integration between the system and the multi-objective optimisation plugin must be explained in an example script with a simple building case	MUST
NFR_3.03	The system must be able to process decision variables (genome)	MUST
NFR_3.04	The system must be able to process objective functions	MUST
NFR_3.05	The system must be able to process constraints	MUST
NFR_3.06	The system must be able to set a count for the amount of design variations	MUST
NFR_3.07	The system must be able to perform an optimisation on material choices	MUST
NFR_3.08	The system could be able to perform an optimisation on geometry	COULD
NFR_3.09	The system must assign a unique name to each design variant	MUST
NFR_3.10	The system should be able to name, store and load variants generated during the optimisation process by storing their parameters and material choices	SHOULD
NFR_3.11	The system could set the standards from "Het Nieuwe Normaal" as objectives for the optimisation process	COULD
NFR_3.12	The system could integrate a Multi-Criteria Analysis into the optimisation process to assist a user in choosing one optimal variant based on their own weights of priority for each objective	COULD

Continued on next page

ID	Requirement	Priority
	4. Results Interface	
NFR_4.01	The results interface must include an "Overview Results" menu that visualises the most important results of the responsible material use assessment with graphs and charts	MUST
NFR_4.02	The results must be updated in real-time when parameters or material choices are adjusted by linking the results interface directly to the Grasshopper script	MUST
NFR_4.03	The results interface should compare the outcomes to performance levels set by "Het Nieuwe Normaal" and relevant benchmark studies	SHOULD
NFR_4.04	The results interface should be able to calculate indirect and additional costs based on percentages of direct costs, in order to calculate investment costs	SHOULD
NFR_4.05	The results interface should give the user control over the percentages for indirect and additional costs variables	SHOULD
NFR_4.06	The results interface should include a "Detailed Results" menu with results on the building element level and classification level	SHOULD
NFR_4.07	The system should be able to categorise the results on the building element level	SHOULD
NFR_4.08	The system should be able to categorise the results on the classification level	SHOULD
NFR_4.09	The system could categorise the results on the layers of Brand	COULD
NFR_4.10	The results interface should include an "Explore" menu that visualises the materialisation variants and results from the optimisation process by linking directly to the output from the external multi-objective optimisation Grasshopper plugin	SHOULD
NFR_4.11	The "Explore" menu should allow users to compare different design variants based on their performance results and material selections	SHOULD
NFR_4.12	When a user has chosen a final variant, the system should select this variant and update the results in the "Overview Results" accordingly	SHOULD
NFR_4.13	The results interface should include a "Report" menu for reporting the results to PDF and Excel	SHOULD
NFR_4.14	The system should transform internal Grasshopper data to PDF format	SHOULD
NFR_4.15	The system should transform internal Grasshopper data to Excel format	SHOULD

4.2.3 Use Cases

The most important functional and non-functional requirements from Tables 4.2 and 4.3 are translated to a total of twenty use cases that define the system's functionality. A use case organises a system's requirements into a specific interaction between the system and an actor, someone or something outside of the system. Appendix B provides a description of each use case, including its goal, involved actors and related requirements. These use cases are the core of the system design and are translated in the next paragraphs to a set of UML (Unified Modeling Language) system diagrams.

4.3 System Diagrams

4.3.1 Use Case Diagram

The UML (Unified Modeling Language) use case diagram in Figure 4.1 shows the interactions between the actors and the system. The primary actor in this case is the user, which is positioned left of the diagram. Secondary actors are external entities that the system interacts with, but that do not initiate interactions on their own. They are defined as a Grasshopper 3D building model, material database and optimisation plugin. Similar to the requirements, the use cases are divided into four packages. A distinction is made between a system package: a core package that only exists within the system; and an integrated external package, which is an external system that is integrated in such a way that it becomes part of the *ReLifeCycle* system. The first package "Model Linking & Material Mapping" is initiated by the user extracting a building element geometry from the Grasshopper model and linking this to the system. Consequently, the system and user must execute three use cases: assigning a name, classification and material to this linked building element. A classification categorises the element into a specific type, such as walls or floors, which is important for providing structure and overview when a large number of elements are linked. Assigning a name is mainly important to make a distinction between building elements of the same classification, but with different properties, think of two external walls with different cladding materials. The material database interacts with the classification and material use cases (UC_1.03 and UC_1.06) and contains linked environmental, circularity and financial data on materials, categorised per classification. When a classification is assigned, a user must be provided with a set of available materials for that chosen classification. The reason why a material set is created is to ensure only those materials that are suitable for a given classification are considered in the later stages of the responsible material use enhancement process, which involves material optimisation. This is essential to prevent inappropriate material assignments, such as using insulation material for a load-bearing structure. Additionally, at the same time as creating a material set, the system must verify if the geometry type of the linked Grasshopper geometry matches the unit of the material data, as these generally differ per classification (m^2, m^3, m, pieces). A user must finally select a material from the material set and assign it to the building element, finishing the model linking & material mapping process.

The second package "Responsible Material Use Assessment" requires the user to set calculation variables after which the responsible material use for all linked building elements is assessed by the system using data from the material database. This consists of a separate environmental impact, circularity and financial impact assessment.

The third package "Responsible Material Use Enhancement" considers an integrated external package. This functionality is namely achieved by allowing the *ReLifeCycle* system to be integrated with existing Grasshopper optimisation plugins, instead of incorporating optimisation algorithms in the system itself, which would greatly increase complexity. The advantage of Grasshopper is its open ecosystem, allowing everyone to create plugins that can interact with each other. Though the optimisation plugin is not a direct component of the *ReLifeCycle* system, it is still included in the use case diagram as the system will be designed in such a way that it facilitates this integration. After setting the decision variables, objective(s) and constraints, the user initiates the generation of a set of material-optimised variants, which can be explored to find the best variant for the design. For this research, only material optimisation is considered. Algorithmic optimisation on geometry for enhancing responsible material use is expected to create the smallest possible building that is allowed by the parameters and is therefore left out of scope.

In the fourth package, the system visualises the assessment results in a user-friendly interface that should provide an overview of results as well as detailed results per building element and classification. The optimisation plugin should also interact with this interface to allow a user to compare the results of variants from the optimisation process. Finally, the user should be able to export the assessment results to an Excel or PDF report for further analysis.

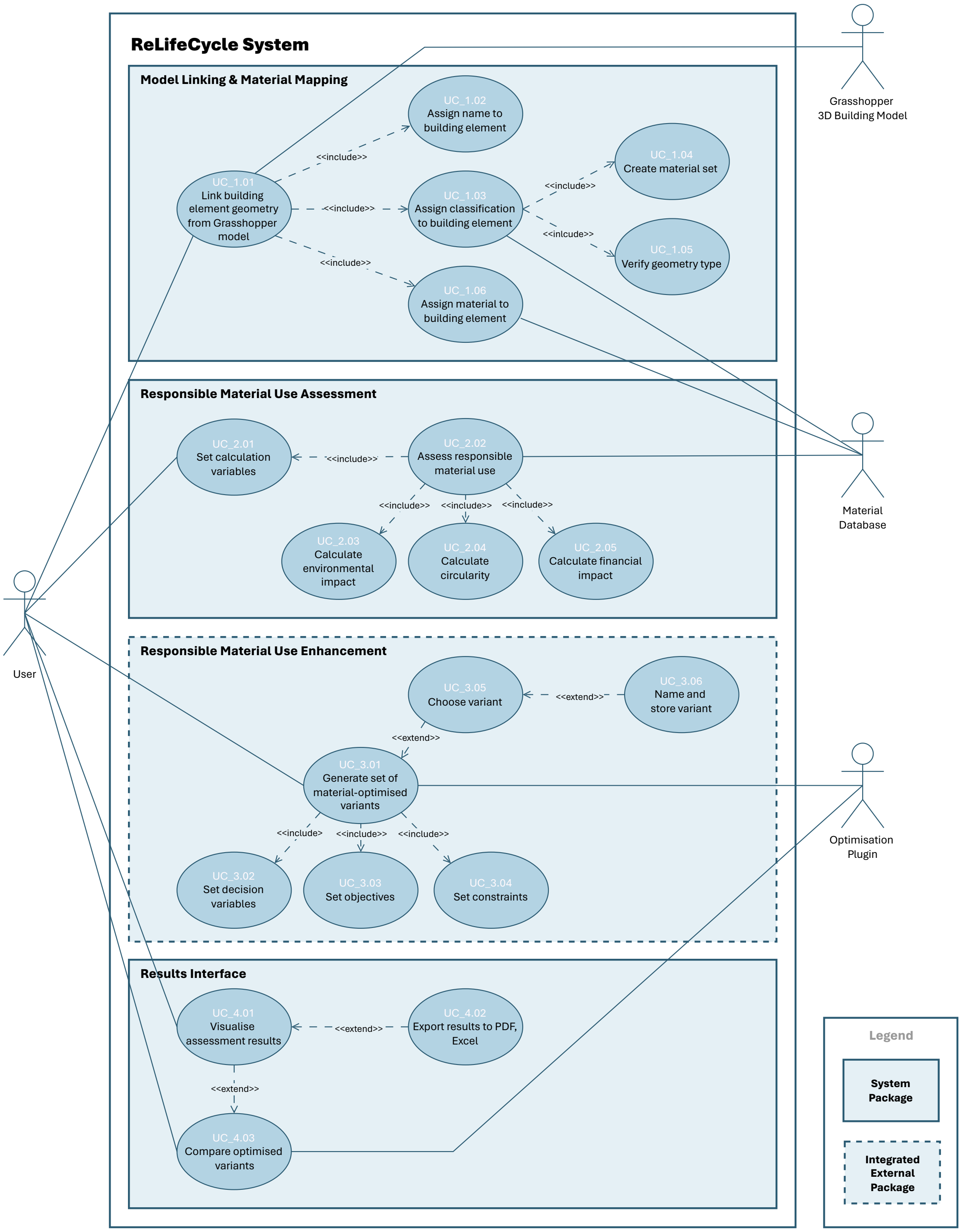


Figure 4.1: Use case diagram

4.3.2 Activity Diagram

The UML activity diagram in Figure 4.2 visualises the step-by-step workflow of the *ReLifeCycle* system, including decision points and parallel processes across three swimlanes: the user, the *ReLifeCycle* plugin, and an optimisation plugin. The process begins with the user creating a Grasshopper (GH) 3D building and linking building element geometries. If the geometry type is invalid, the user must adjust this in the GH model; otherwise, the system links the material data to the geometry. Next, the user sets the calculation variables and the system assesses responsible material use. If optimisation is needed, the optimisation plugin processes the decision variables and objectives and generates a set of material-optimised variants. The system then presents both the results interface and an additional explore interface in which the results from variants can be compared. Consequently, the user can use both interfaces to explore the design space and choose the best variant. If the user is still not satisfied with it, materials or geometry can be manually changed and the cycle starts again. Once satisfied, the system can export an Excel or PDF report of the final variant.

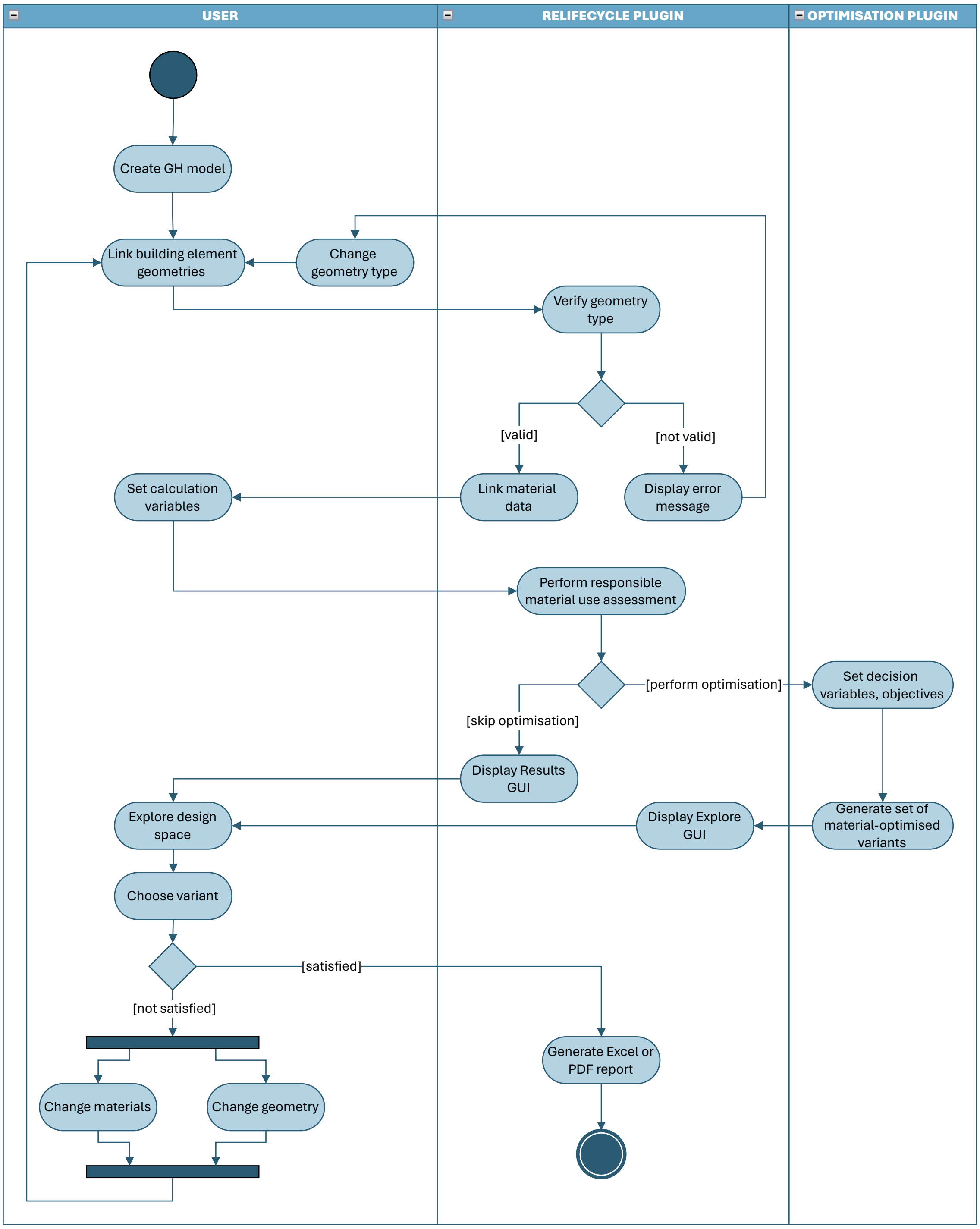


Figure 4.2: Activity diagram

4.3.3 System Architecture

The system architecture defines the overarching structure of the *ReLifeCycle* system and its components. It serves as the blueprint for the system design and development. As shown in Figure 4.3, it is based on the Model-View-Controller (MVC) software design pattern, which structures a system into three specific sections:

1. **Model:** Handles data logic and interacts with databases.
2. **View:** Handles data presentation in a user-friendly interface.
3. **Controller:** Mediates between the model and view, managing request flows.

For example, when a user interacts with the interface, the controller processes the action, retrieves the necessary data from the model, and updates the view accordingly. Since *ReLifeCycle* will be developed as a plugin for Grasshopper (GH), the view is integrated into the GH interface. For the "Model Linking & Material Mapping" and "Responsible Material Use Assessment" packages, custom GH components will be made. The data retrieval and definition of component logic are handled by the model with a C# script for each component, combined into a single plugin project file. This model retrieves data from the external material database, while geometry and component data are stored in GH's internal storage. Interaction between the model and view is handled directly by the GH API (Application Programming Interface), eliminating the need for separate controller components in the system. Standard GH components will have to be used to create a parametric script for a building design and extract building element geometries.

The responsible material use enhancement package consists of an integration with a separate GH script that includes a third-party optimisation plugin for both Single-Objective Optimisation (SOO) and Multi-Objective Optimisation (MOO). For SOO, Galapagos is considered, since this is an already built-in plugin that has proven to be useful in the literature (e.g. Lobaccaro et al. (2018); Apellániz et al. (2021); Hollberg and Ruth (2014)). For MOO, Wallacei is selected among the many MOO GH plugins evaluated in Table 2.6 in the literature review. Unlike plugins such as Octopus and Opossum, Wallacei allows users to export phenotypes and genomes directly within Grasshopper. This flexibility enables post-processing of results, as highlighted by (Baden and Taghizadeh, 2023). Such a feature enhances *ReLifeCycle's* integration by allowing optimisation solutions to be seamlessly processed within the *ReLifeCycle* results interface, further supporting design space exploration to identify balanced solutions. The system will provide an example script demonstrating how *ReLifeCycle* integrates with Galapagos and Wallacei. While other optimisation plugins could be used as well, this research focuses on these two.

Finally, the results interface is implemented as a pop-up GUI within GH. Due to limited programming knowledge, rather than being modelled in C#, this interface is built using the Human UI plugin, which allows an interface to be created with GH components instead of C#.

Appendix C.1 provides a more detailed version of the system architecture that defines all specific GH components, their corresponding C# scripts and the components of the results GUI.

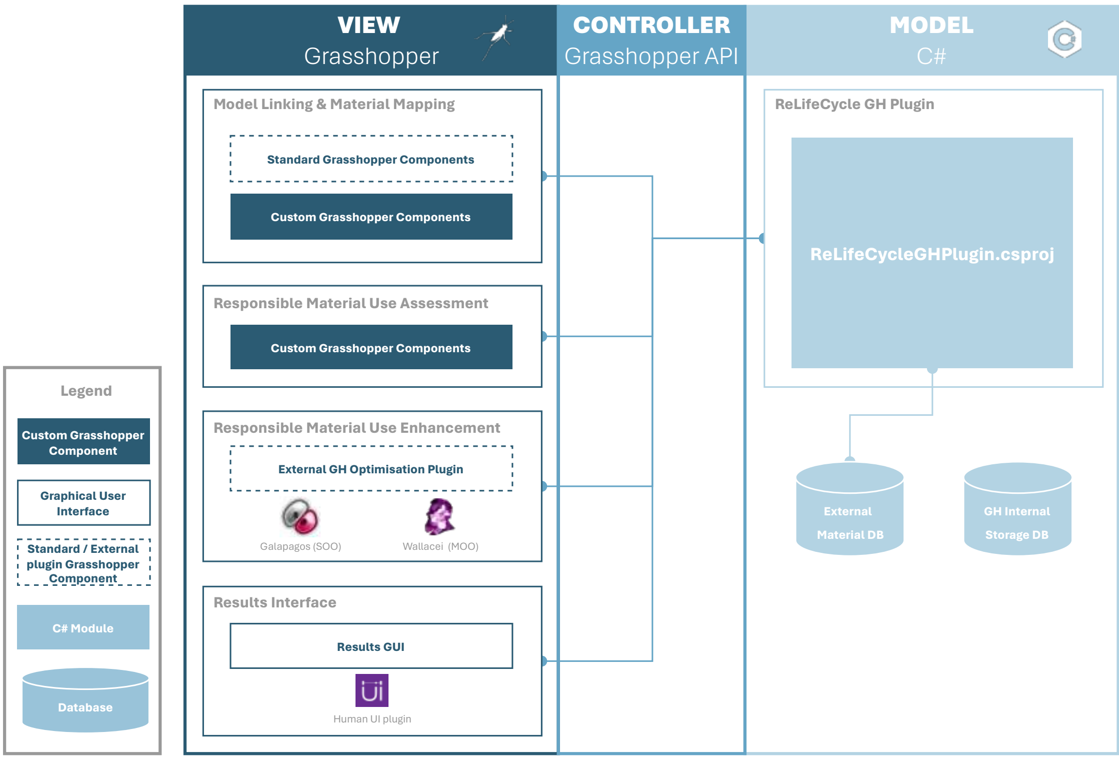


Figure 4.3: *ReLifeCycle* system architecture

4.3.4 Sequence Diagrams

A UML sequence diagram explains the chronological order of interactions between system components for a specific use case. Three sequence diagrams are made for the *ReLifeCycle* system, each representing one main package. No diagram is made for the "Responsible Material Use Enhancement" package since its functionality relies on an existing optimisation plugin with a predefined system. The sequence diagrams for the "Responsible Material Use Assessment" and "Results Interface" packages are provided in Appendix C.2. Figure 4.4 shows the sequence diagram for the "Model Linking & Material Mapping" package with the MVC structure from the system architecture. It combines the first six use cases and is therefore an abstracted version of a sequence diagram that does not detail all specific interactions.

The user must first drag the "Create Building Element" component to the GH canvas, which will be displayed by the GH interface along with a drop-down list of building element classifications, based on the NL/SfB (see Section F.2). Next, the user must assign four properties: (1) a name; (2) classification; (3) material; and (4) geometry. Important to note is that the View of a GH component always consists of input and output parameters. The processing of input into output is handled by the Model.

By entering a name in the standard GH "Panel" component and connecting it to the input, the name (1) is sent through the controller to the model, stored in GH's internal storage and displayed in the component's output. The user must then select a classification (2) from the drop-down list, which is immediately displayed in the output. Consequently, the material set for the chosen classification is requested by the Model from the material database. This database returns the material data, which is then displayed in the view. The user must select one material (3) from this list, and based on its material ID, the Model retrieves its data, which is displayed in the View. Simultaneously, the required geometry type for that material is displayed. Next, when the user links a geometry (4) to the component, its geometry type is compared to the required type. If valid, the geometry data is shown in the output. Alternatively, if the geometry type does not match the requirement, an error message is displayed to warn the user.

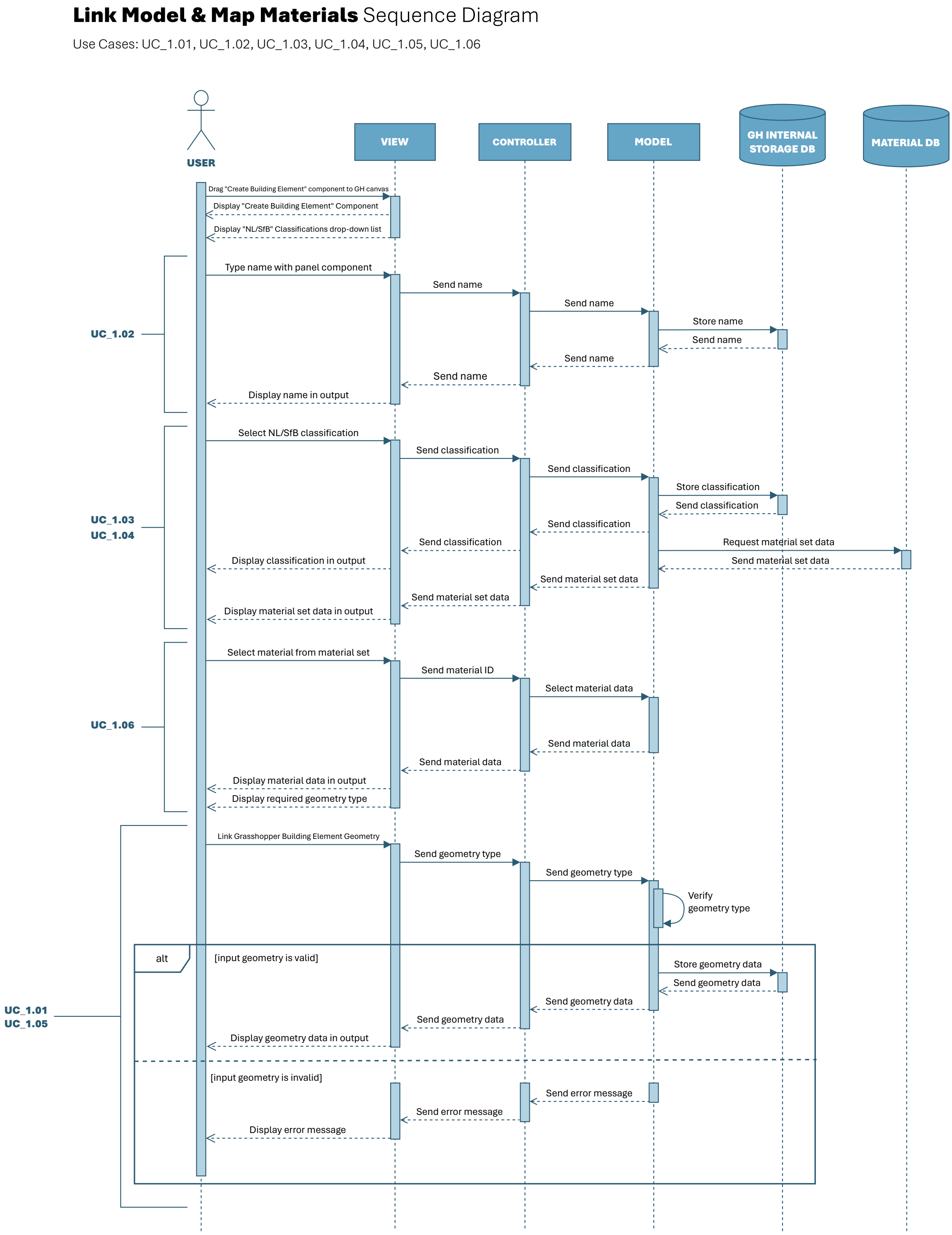


Figure 4.4: Sequence diagram for the "Model Linking & Material Mapping" package

4.4 Mockup

To visualise a preliminary version of the *ReLifeCycle* results interface and to facilitate discussions with interviewees, the mockup in Figure 4.5 was created. The design of the interface and its further development, discussed in Section 6, are based on the interfaces of the reference tools outlined in Section 2.2, as well as a review of LCA visualisations by Hollberg et al. (2021), who provide recommendations for various visualisation types suited to different goals. The mockup interface consists of the different tabs mentioned in the requirements in Table 4.3 and divides the results into the three key aspects of responsible material use: environmental impact, circularity and financial impact. Results are displayed with various graphs and are coloured red when a performance level is exceeded to show where the design can be improved. The origin of the specific assessment indicators and performance levels is elaborated in Section 5.

Figure 4.5: *ReLifeCycle* results user interface mockup

5. RELIFECYCLE FRAMEWORK

This section lays the foundation for the *ReLifeCycle* prototype by defining its workflows, assessment methods and data requirements. It begins with a clear overview of the three sequential workflows, illustrating how the *ReLifeCycle* system is designed to be used. Next, the responsible material use assessment framework is introduced, explaining the applied assessment methods. Finally, the section covers the collection of data for the assessments and how this data is managed.

5.1 Workflows

Building on the system design, Figure 5.1 introduces the three workflows of *ReLifeCycle*.

1. **Parametric Building Script:** A user creates a parametric Grasshopper script for a building design.
2. **Responsible Material Use Assessment:** The *ReLifeCycle* Grasshopper plugin, the core of the system development. Behind this plugin is a responsible material use assessment framework for evaluating environmental impact (LCA), financial impact (LCC) and circularity. To provide data for those assessments *ReLifeCycle* relies on a relational database model for each aspect.
3. **Responsible Material Use Enhancement:** Although it is up to the user to integrate *ReLifeCycle* with various other Grasshopper plugins, this research specifically focuses on optimisation plugins to enhance the responsible material use and support design space exploration. This integration will be facilitated with example scripts.

The following sections elaborate the assessment methods and data model for the second workflow.

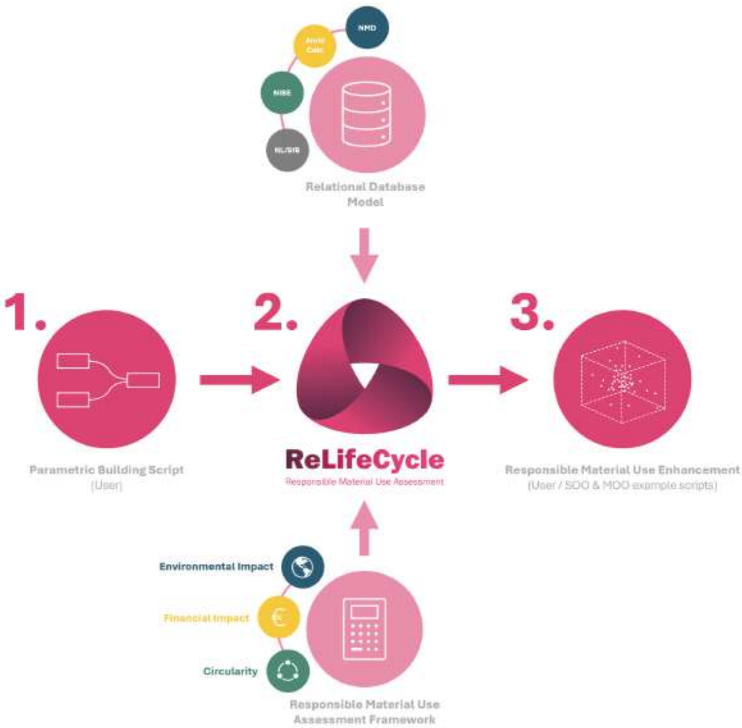


Figure 5.1: *ReLifeCycle* workflows

5.2 Assessment Methods

5.2.1 Assessment Framework

In Section 2, an elaborate study is conducted into responsible material use and its main objectives: (1) environmental impact; (2) financial impact and (3) circularity. Their integration is explored by investigating LCA, LCC and circularity indicators. To integrate these methods and perform a comprehensive responsible material use assessment, the *ReLifeCycle* assessment framework is introduced in Figure 5.2. This framework explains the assessment methods and their integration. The assessments are categorised around the three main objectives of responsible material use. Each objective is evaluated using a range of midpoints and endpoints. Midpoints represent factors at the raw data level and are used to calculate the endpoints: key performance indicators that provide meaningful insights. Displaying these endpoints side-by-side for each objective provides a comprehensive responsible material use assessment. Trade-offs between the endpoints can then be analysed to achieve a desired and balanced outcome.

To measure the environmental impact (LCA) objective, three assessment methods are used: (1) MilieuPrestatie Gebouw (MPG) (Equation D.3); (2) Paris Proof (Equation D.4) and (3) Construction Stored Carbon (CSC) (Equation D.6). The MPG is the standard environmental impact assessment method in the Netherlands. It is based on the ISO14040 and 14044 LCA standards and uses all environmental impact categories to calculate the shadow costs for each life cycle stage (Modules A1-D), expressed through the MilieuKostenIndicator (MKI) (Equation D.1). An additional advantage of the MPG is that it combines the results from these categories into a single score, making it easier to compare design variants. Given these factors and the Netherlands-focused scope, the MPG method is a relevant method to include. The Paris Proof method focuses on the short-term consequences of climate change, specifically assessing the Global Warming Potential (GWP) during the production and construction stages (Modules A1-A5). It allows the GWP to be compared to the carbon budget set by the Paris Agreement in 2015. So combining the Paris Proof method with the MPG provides a more holistic approach. Finally, Construction Stored Carbon (CSC) considers the carbon dioxide that is physically stored in construction materials, contributing to the decarbonisation of the construction industry. Since this is a positive environmental impact that serves as a motivator for the use of biobased materials, it is included as an additional method.

For the financial impact (LCC) objective, three types of LCC were identified in the literature review: conventional LCC (cLCC), environmental LCC (eLCC) and societal LCC (sLCC). eLCC appears to be most appropriate for the *ReLifeCycle* framework, as it will be used alongside an LCA. eLCC measures both financial and environmental impact costs. Since the MPG method already considers environmental impact costs through the MKI, only financial costs will be considered to avoid complexity and double-counted results. Two notable methods were identified for LCC: Net Present Value (NPV) and Total Cost of Ownership (TCO). The TCO method is chosen over the NPV because the NPV includes revenues, which are difficult to predict during the early design stages, whereas the TCO only considers costs. However, available cost data for the use and end-of-life stages of materials is limited (see also Section 5.3.1). As a result, only direct costs (Equation D.7) are considered; namely material and labour costs that are made in the product stage (A1-A3) and construction stage (A4-A5). Additionally, True Pricing (Equation D.8) is included, which combines direct costs with the shadow costs caused by environmental impact (MKI). This method provides a good insight into the actual financial impact of a material and is therefore included.

The circularity objective is measured using the Building Circularity Index (BCI) (Equation D.21). The BCI was found to be the most complete method for measuring circularity, as it considers the circular potential of materials on different building levels with the addition of a Disassembly Potential (DP) to include Design for Disassembly (DfD) aspects. This covers almost all circularity KPIs identified in the literature review in Table 2.4 except for the adaptability potential and use of renewable or non-renewable energy. Intermediate results of the BCI such as the material input and output flows (Equation D.23) and the Disassembly Potential (Equation D.22) are also included as endpoints in this framework.

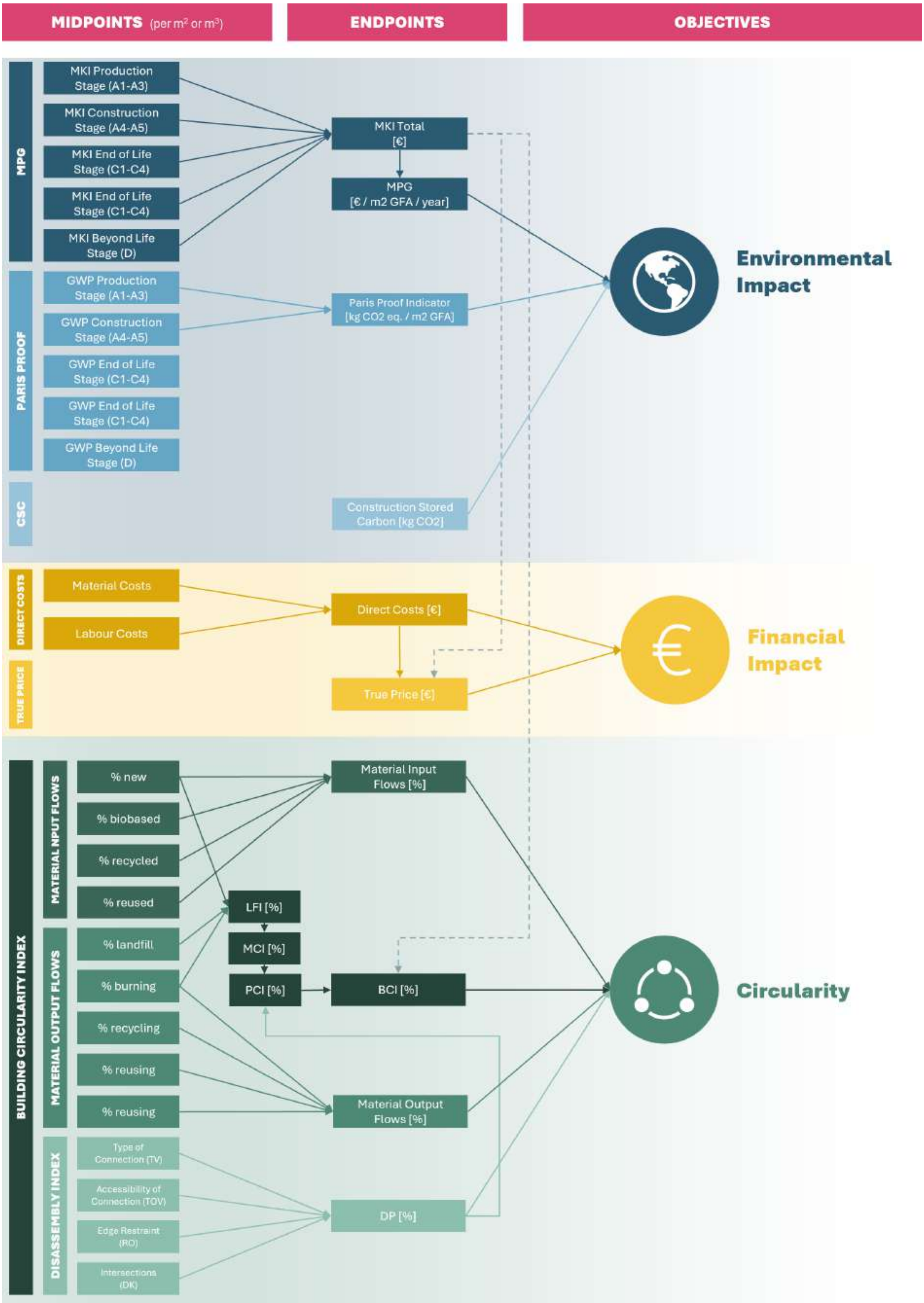


Figure 5.2: *ReLifeCycle* assessment framework (layout based on Kaltenegger (2021))

5.2.2 Explanation of Assessment Methods

An explanation of each assessment method from Figure 5.2 is given in Appendix D. This includes the sources that they are based on, the formulas and example calculations for a simple example case. The case is illustrated in Appendix D.1 and is also used to validate the *ReLifeCycle* prototype's calculations during the development process.

5.2.3 Performance Levels

To give meaning to the endpoint results from the *ReLifeCycle* assessment framework, performance levels are used for specific indicators. Performance levels are official benchmarks, criteria or standards that assign a certain limit to an indicator. One of these standards is "Het Nieuwe Normaal" (The New Normal), which is a framework for a sustainable and circular built environment with a focus on materials. Het Nieuwe Normaal has created a set of performance levels for the MilieuPrestatie Gebouw (MPG), Construction Stored carbon (CSC), material input flows and Disassembly Potential (DP), which can be found in Appendix E. The performance level for the MPG is based on the A1 set, whereas *ReLifeCycle's* database uses A2 data. While its A2 performance level has not yet been published, it is expected to be doubled. However, based on a small test calculation, this is too high and will not be a relevant performance level. It is therefore taken stricter for this research. The final performance levels for *ReLifeCycle* are presented in Table 5.1.

Table 5.1: *ReLifeCycle* performance levels

Indicator	**Performance level per building type**		
	Residential ground-based	Residential stacked	Utility
MPG [€ / m^2 GFA / year]	$\leq$ 0.45	$\leq$ 0.7	$\leq$ 0.7
PP [kg CO_2 eq. / m^2 GFA]	$\leq$ 200	$\leq$ 240	$\leq$ 240
DP [%]	$\geq$ 55	$\geq$ 50	$\geq$ 55
New [%]	$\leq$ 75	$\leq$ 80	$\leq$ 75

5.3 Data Collection

Data collection consists of finding relevant material databases for LCA, LCC and circularity respectively. To categorise these databases, a classification system is defined. How the data is retrieved and the criteria for selecting the data are explained in this section as well.

5.3.1 Evaluation of Databases

To find the databases most suitable for assessing responsible material use with the aforementioned methods in Section 5.2, an evaluation of several existing LCA, LCC and circularity databases is conducted. Table F.1 in Appendix F gives an overview of these databases with their corresponding data category, region, short description, accessibility and data type.

To assess the environmental impact of materials, the required LCA data for this research involves emissions data for the environmental impact categories during all life cycle stages, MKI values per life cycle stage and the construction stored carbon. Since the scope of this research is the early design stages, generic data on these topics is required. These are industry-average values for different materials and products. The region in this research is narrowed down to the Dutch construction industry. For data accuracy, it is therefore necessary to choose a Dutch database from Table F.1. For LCA assessment in the Netherlands, the Nationale MilieuDatabase (NMD) is used the most as it contains both emissions and

MKI data. The NMD is the national standard and its adoption is obligated when used for professional MPG calculations. Only limited data is publicly accessible through an online viewer. To gain access to the complete database, a professional license is required. While the NMD does not include data on construction stored carbon, this information is available in the Nederlands Instituut voor Bouwbiologie en Ecologie (NIBE) database, which is another Dutch LCA and circularity database.

To perform a financial impact assessment, data on estimated direct costs of building products and materials is necessary. The reviewed LCC databases from Table F.1 mostly contain both material costs and labour costs, which is sufficient for the early design stages. Again, it is important to choose a database that is accurate for the Netherlands. Bouwkostenkompas is interesting as it provides average data for the total costs of a building based on the GFA, type and location, which is suitable for estimating costs in the early design stages. However, since this research focuses on material use, a change in building material should be reflected in the cost results. For example, when a concrete structure is replaced with a timber structure, the costs should increase. Bouwkostenkompas unfortunately does not contain such a level of detail. In contrast, the ArchiCalc and Casadata databases do offer cost data on the material level.

In terms of circularity assessment, it is necessary to gather data on the input and output flows of materials, expressed as percentages of mass, along with product disassembly factors. This data is essential for determining the MCI and Disassembly Potential, which are needed to compute the PCI and eventually the BCI. Input and output flows for the Dutch construction industry can be found in the NIBE and Madaster databases, though their accessibility is limited. Neither of these databases includes product disassembly factors. However, BCI Gebouw, the developer and official software platform for the BCI, links NIBE data with its own database of product disassembly factors, ensuring that the data is complete for BCI calculations. This database requires a BCI Gebouw license.

While NMD and NIBE data are only limited in their accessibility and format on the web, the complete data sets can be provided by Alba Concepts, the collaborating company for this research, who have access to those databases for their work on the BCI Gebouw Platform. This also includes the additional BCI database with disassembly factors. Therefore, these databases are used for this research. Concerning financial impact data, the ArchiCalc database is chosen as it provides accessibility through a student license.

To conclude, the following databases will be used for the *ReLifeCycle* database:

1. **NMD**: For environmental impact (LCA) data.
2. **ArchiCalc**: For financial impact (LCC) data.
3. **NIBE and BCI**: For circularity data.

Figure 5.3 visualises the connections between these databases and their content.

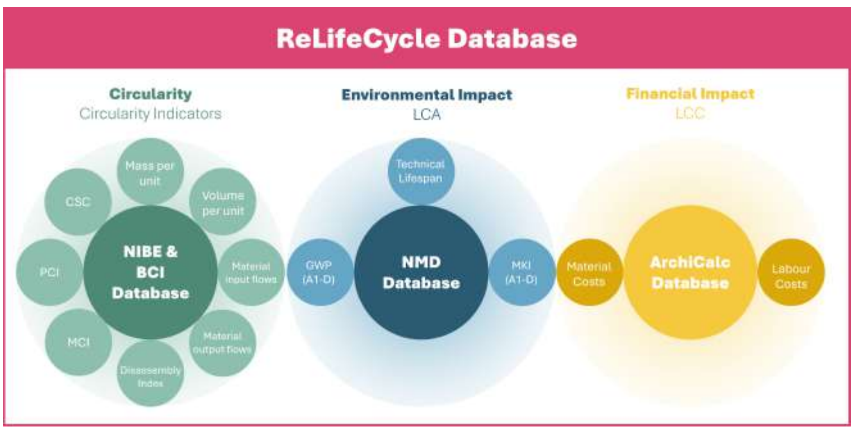


Figure 5.3: *ReLifeCycle* database content

The next paragraphs will go into more detail about the origin and quality of each database.

5.3.1.1 NMD Database

The NMD consists of two main databases: (1) an environmental impact database and (2) a process database (Stichting Nationale MilieuDatabase, nd). The NMD environmental impact database consists of Environmental Product Declarations (EPDs) for a range of building products. An EPD is a report that presents the results of an LCA for a specific product, such as the emissions data for all environmental impact categories and life cycle stages. The NMD process database contains data on product processes used for setting up EPDs. This data originates from the international Ecoinvent database.

The NMD follows a strict data quality control process. When a new product is added, a professional LCA practitioner first conducts an LCA for that product. This LCA can be set up with the NMD process database. The EPD generated from that LCA is then reviewed by a recognised LCA expert from the NMD before it is published in the NMD environmental database.

NMD data is divided into three categories (Stichting Nationale MilieuDatabase, 2022b):

1. Brand-specific data from manufacturers and suppliers, tested with an NMD protocol
2. Brand-independent average data from classes of manufacturers and suppliers, tested with an NMD protocol
3. Brand-independent generic data, for which 30% is added to account for inaccuracies

Category 1 and 2 data follow from official EPDs, while Category 3 data comes directly from the basic processes of the NMD process database.

5.3.1.2 ArchiCalc Database

ArchiCalc provides material and labour cost estimates for generic building products. It therefore provides data on life cycle modules A1-A3 (product stage) and A5 (construction and installation stage). All prices in the ArchiCalc database are inclusive of Value Added Taxes (VAT). The material costs are set up by Archidat, the developer of ArchiCalc, in collaboration with about 600 building product producers and suppliers (Archidat, 2018). Data from these companies is used to calculate the national average prices of building materials. Labour costs are calculated by estimating the average man-hours it takes to construct the building element and multiplying it with a standard hourly rate. The average man-hours and hourly rates are based on experience from Archidat and a wide range of construction companies.

For this research, the ArchiCalc student version is used, which is limited to residential construction with reference date 15-10-2024.

5.3.1.3 NIBE and BCI Database

The NIBE database consists of NIBE's "Environmental Classifications", product sheets that contain, amongst others, circularity data about the input and output flows of materials. This data is set up by professional LCA practitioners from NIBE itself by using mainly category 3 data from the NMD process database (BCI Gebouw, 2024). BCI Gebouw has made a separate database that includes disassembly factors and has mapped this data to the NIBE products. The disassembly factors are determined and mapped by circularity and sustainability experts from BCI Gebouw and Alba Concepts, who analyse detailed drawings of the connections to assign disassembly scores.

5.3.2 Classification System

The NMD, ArchiCalc and NIBE databases, all classify building products according to the NL/SfB classification system, a nationally adopted standard for categorising building elements (BNA, 1991). This system divides building elements into main classes, which can each be further subdivided into subclasses. The *ReLifeCycle* database also adopts the NL/SfB classification system but with a few modifications to apply to the early design stages. The standard NL/SfB subclasses are excluded, as they often provide excessive detail. Another limitation is that these subclasses focus mainly on building element type, rather than building element material, which is more relevant for this research on responsible material use. For instance, within "23.2 Floors, load bearing", both structural and insulation materials are included. As explained in the system design in Section 4, it is important to make a distinction between materials within the NL/SfB categories to create material sets for the optimisation process. The optimisation process should only consider materials of the same type, to prevent inappropriate substitutions, such as selecting concrete for insulation.

Therefore, instead of using the standard NL/SfB subclasses, *ReLifeCycle* introduces additional divisions within the main classes, indicated with a letter to avoid confusion with the original NL/SfB codes. For example, class "23 Floors" is divided into "23A Floors - Structure" and "23B Floors - Insulation". NL/SfB main classes about services, facilities and terrain are excluded completely from the classification system as they are beyond the scope of this research. Table 5.2 gives an example of *ReLifeCycle's* modified classification system. An overview of all classifications can be found in Table F.2 in the Appendix.

Table 5.2: Example of *ReLifeCycle's* modified NL/SfB classification system

NL/SfB Code	NL/SfB Class (EN)	NL/SfB Class (NL)
2	**Primary elements, Carcass**	**Ruwbouw**
21A	external walls - structure	buitenwanden - constructie
21B	external walls - insulation	buitenwanden - isolatie
23A	floors - structure	vloeren - constructie
23B	floors - insulation	vloeren - isolatie

5.3.3 Data Retrieval and Selection Criteria

Data from the NMD and NIBE databases are retrieved by exporting them as CSV files from the BCI Gebouw online platform, which can be accessed through the collaborating company Alba Concepts. The ArchiCalc database cannot be directly exported from the ArchiCalc desktop software. Therefore, a cost estimate is made within the ArchiCalc software for specific products that will be included in the prototype database, further explained in Section 5.4.3. A CSV file is generated of this cost estimate to obtain the required data.

Several criteria are established for the data. First, the NMD, ArchiCalc and NIBE databases all provide data on both complete building element assemblies (comprising multiple products) and individual building products. To allow greater flexibility in combining products, such as using different insulation materials within timber stud walls, only data on the individual building product level is included in the *ReLifeCycle* database.

Second, it should be noted that at the time of this research, a national transition is underway from the A1 set of environmental impact categories to the A2 set (Table 2.1, Table 2.2). This transition requires a revision of all environmental data. To align with this change, only data from the A2 set is selected for use.

Third, for the development of the *ReLifeCycle* database, it is important to have a consistent NMD data category to avoid unfair comparisons between materials. Since *ReLifeCycle* is focused on the early design stages, category 2 data is preferred, as it provides average product data tested with NMD protocols for validation. However, the switch from the environmental impact category set A1 to A2 limits the amount of available data in this category. So, for the prototype database, data from NMD category 2 will be selected wherever possible. In cases where specific product data is unavailable in this category, category 1 data will be used. Category 3 is excluded from the database for two reasons: (1) its data is untested and therefore less reliable; and (2) the additional 30% to account for this inaccuracy, makes it unfair to compare these materials to materials from categories 1 and 2 in the design exploration process. An exception is made for load-bearing structural materials. *ReLifeCycle* will provide the user with three material options in this class: concrete, steel and timber. To estimate the amount of structural material, data on these materials is required in terms of kg or m^3. Since this specific data is only available in NMD category 3, this category is selected for the structural materials.

Finally, the environmental, circularity and cost data are given for different units per building product. For instance, the Global Warming Potential (GWP) can be given in kg CO_2 eq. per m^3, m^2, linear meter, kilogram, or per piece. This data has to be linked to Grasshopper geometry which presents a challenge, as the geometry itself can be delivered in multiple ways as well (e.g. lines, surfaces, volumes). So clear data or model requirements must be made to facilitate this linking process. This can be approached in two ways:

1. **Standardise data to a universal unit:** Convert all material data in the database to a per-kilogram basis by using the mass per unit. In this way, the data is universally measured per kilogram instead of different units. This means that Grasshopper geometry should be delivered either as volumes or as surfaces with a specified thickness. However, given the tool's focus on the early design stages, letting users define the thicknesses of different materials can be challenging and often relies on estimation. Additionally, if the material of a building element is changed, its thickness would need to be manually adjusted. Thus, managing the data in this way may not be the most practical approach for handling varying units.

2. **Adapting geometry to the corresponding unit:** The alternative method is to keep the different units from the database and require the Grasshopper geometry to adapt accordingly, using surfaces for m^2, volumes for m^3, and lines for linear meters. However, this approach presents a challenge, as the user would need to manually adjust the geometry for each material. A possible solution is to set specific requirements for a user's parametric 3D model. Fortunately, the majority of the data in the databases is given per m^2 with a standard, most common thickness.

Since the scope of the research is the early design stages, option two is most appropriate, as it already gives an estimation of the thickness of a building element, preventing the need for a user to guess. Thus, the following requirements for the Grasshopper geometry are set up:

- All Grasshopper geometry should be modelled as surfaces
- An exception is made for columns and beams, which should be modelled as volumes

Simultaneously, the data in the material database should be carefully selected to align with these requirements, giving the following data criteria:

- Data for columns and beam materials should be given per m^3
- All other data should be given per m^2
- The standard thickness for insulation materials should be based on an R-value of 3.5 $m^2 \cdot K/W$
- The standard thickness for structural floor and roof materials should be based on a span length of 6 - 7.5 meters.

5.4 Data Management

5.4.1 Data Storage

To conduct an integrated assessment, the NMD, ArchiCalc and NIBE databases should be linked and stored in a relational material database. MySQL Workbench is used for this end, which is an open-source relational database management system, capable of relating multiple data tables with each other with Structured Query Language (SQL) (MySQL, nd). This allows for efficient data retrieval and is especially useful considering the multiple material databases that have to be combined. MySQL Workbench is a graphical tool for creating and handling MySQL databases in an integrated development environment. A MySQL server is created for the *ReLifeCycle* database: *local_mysql_relifecycle_db*. In this server, a database model is created that sets up the general database structure.

Figure 5.4 shows how the databases are stored and managed. The raw NMD, ArchiCalc and NIBE data are exported as CSV files, along with a table of NL/SfB classifications. This data is then imported into the MySQL database. The ADO.Net driver transfers the data from the server directly to the *ReLifeCycle* system, which links the data to the geometry from the user's Grasshopper 3D model.

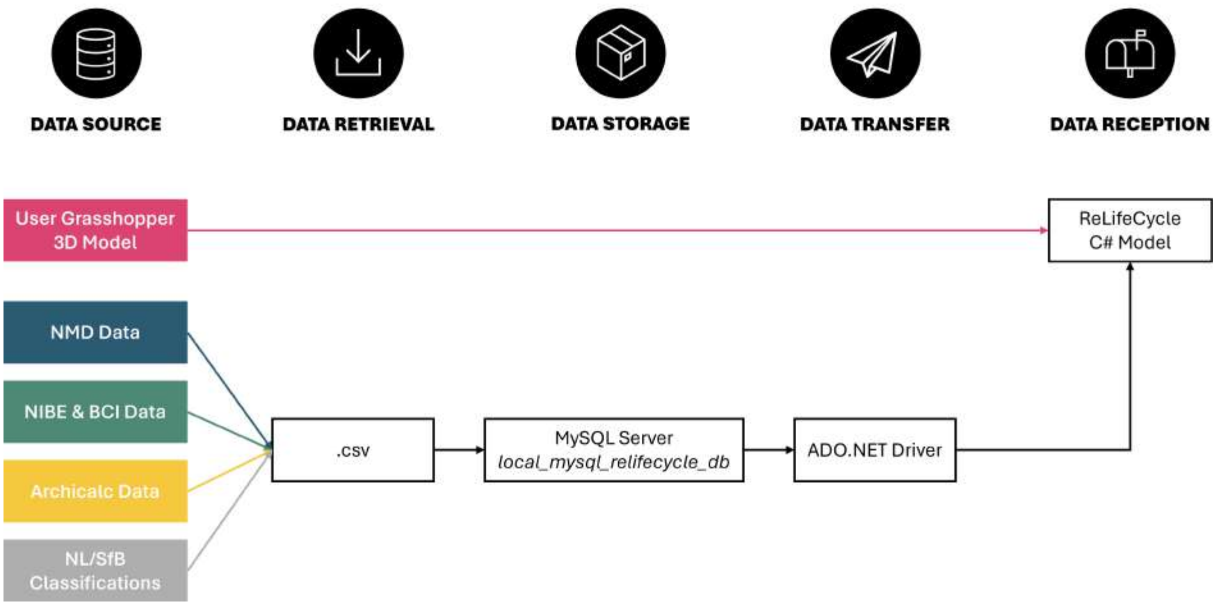


Figure 5.4: Database management schematic framework

5.4.2 Database Model

To create a logical, relational database structure, a database model is made by drawing an Entity Relationship (ER) diagram. An ER diagram defines entities, objects represented by data, with their corresponding attributes and relationships. The ER diagram for the *ReLifeCycle* database is made with MySQL workbench and can be seen in Figure 5.5.

In this ER diagram, the following entities are established. Each entity has a primary key that serves as a unique identifier for each data record.

1. **NMD database:** Contains data on environmental impact and, since it has the most complete building material library, simultaneously acts as the main material database. The NMD is a child table of the NIBE and ArchiCalc entities and has two foreign keys that link to their primary keys. This means that NIBE and ArchiCalc products are mapped to the NMD products.

2. **NIBE database:** Contains data on material input and output flows, construction stored carbon and material density. It has a one-to-many relationship with the NMD, as one NIBE product can be mapped to multiple NMD products.

3. **ArchiCalc database:** Contains data on financial impact. It has a one-to-many relationship with the NMD, as one ArchiCalc product can be mapped to multiple NMD products.

4. **Classification table:** Contains a list of the custom NL/SfB classifications including their name and code. It has a many-to-many relationship with the NMD since multiple NMD products can be within multiple NL/SfB classes.

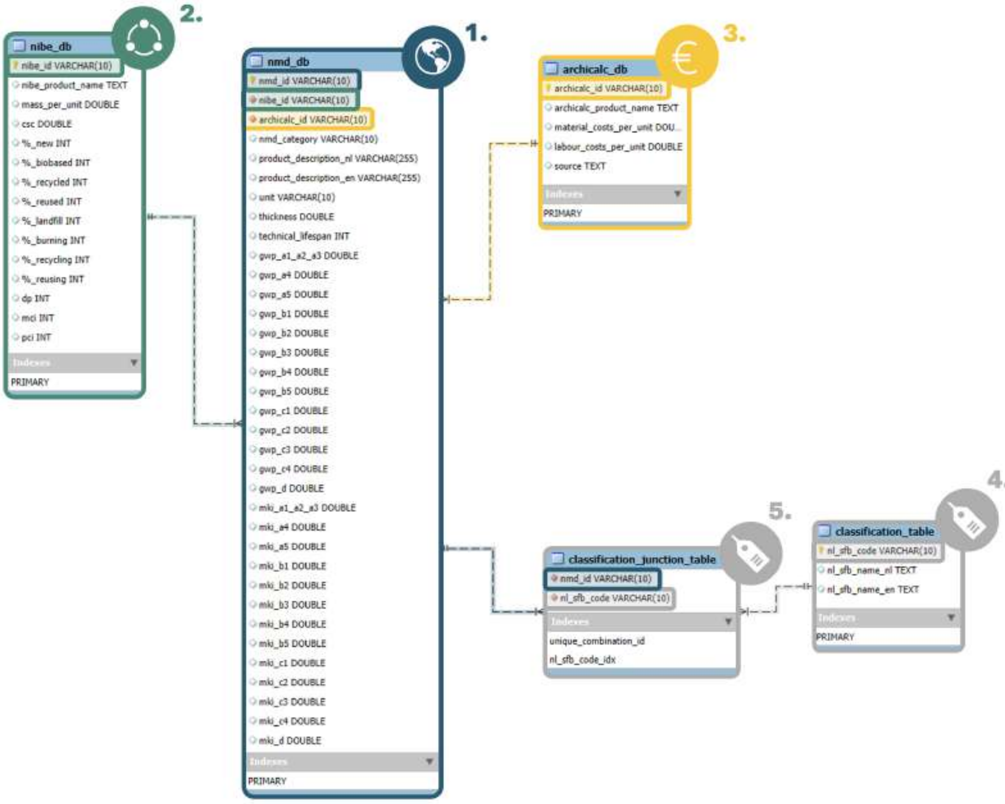


Figure 5.5: MySQL Entity Relationship Diagram

5. **Classification junction table:** Links NMD products to the NL/SfB classifications. This table consists of two foreign keys, the primary keys of the NMB and classification table, and links these keys by assigning a unique composite key to each combination. This ensures the many-to-many relationship between the NMD and the classification table.

The data types of each attribute are selected so they match the corresponding source data. The mapping between the NMD and NIBE databases is already done in the BCI Gebouw software. Experts from BCI Gebouw and Alba Concepts have mapped each NMD product with the closest related NIBE product. Therefore, this mapping is adopted as well in this research. The ArchiCalc database is new and its materials are manually mapped to the NMD for the prototype database. This is done by finding the ArchiCalc product that most closely resembles the corresponding NMD product.

The ER diagram from Figure 5.5 is eventually translated to database tables by using the forward engineer function in MySQL Workbench. To create a joined database table, a custom view is created with an SQL query.

5.4.3 Prototype Database

To test *ReLifeCycle* for this research, a prototype database is made, based on the previously defined database model. Important to note is that the database model is developed to be scalable. So it is still possible to link large datasets to this database structure. The prototype database itself contains three material options per NL/SfB class. However, there are some exceptions. The materials for class 16 "Foundation" and 13A "Floors on the ground - structure" are limited to concrete since a different material is rarely used and accurate data on other foundation and ground floor materials could not be found. Furthermore, the glazing materials are limited to one double-glazing material. The reason for this is that different glazing types mainly influence the insulation level of the building and therefore its energy efficiency. Thus, choosing a glazing type is more related to an energy assessment, which is out of scope for this research.

Additionally, some NL/SfB classes in the *ReLifeCycle* prototype database are left empty for simplification, which includes ground, doors, stairs, ramps and balustrades.

The material options in the prototype database are based on BCI Gebouw calculations of the case study. This case study is further described in Section 7.1.1. Mapping between NMD and BCI products is already done in the exports from BCI Gebouw. ArchiCalc products for this prototype are manually mapped by finding the ArchiCalc product that most closely resembles the corresponding NMD product. When ArchiCalc products are measured with a different unit, their data is converted to the NMD unit. Products that are not included in the standard ArchiCalc database are looked up on product sheets from manufacturers and manually added. The source of the product sheets is therefore added to the database as an attribute. In the case of load-bearing structural materials that are measured per m^3 or kg, either external resources are consulted or an average is taken of all similar materials in the ArchiCalc database.

The prototype database consists of 58 entries and its included materials per NL/SfB class can be seen in Appendix F.3.

6. RELIFECYCLE PROTOTYPE

This section builds on the system design and framework. It explains the development of the *ReLifeCycle* prototype, which consists of a Grasshopper plugin, third-party optimisation plugin integration and a user interface. The development followed iterative implementation cycles, where each cycle involved adding a new functionality and testing it with the simple test case introduced in Appendix D.1 until the functionality worked as expected. This iterative process continued until all essential requirements were successfully met. The section begins with a general description of the development environment, assumptions, dependencies and the general workflow in Grasshopper. It then proceeds to explain the code behind the prototype and highlights important decisions that have been made. The code and all necessary files to run the *ReLifeCycle* plugin are included in the GitHub repository[2] of this research.

6.1 General Description

6.1.1 Development Environment

The development environment is described in Figure 6.1. The *ReLifeCycle* prototype consists of roughly three parts: a Grasshopper (GH) plugin, GH scripts for integrating external optimisation plugins and a user interface made with a GH script. The *ReLifeCycle* plugin is developed for GH in Rhino 8. It includes custom components that can be used within the GH interface in the front-end. These components are made with a C# back-end code using Visual Studio 2022 and the Grasshopper Software Development Kit (SDK), which allows developers to create custom GH components and plugins. The MySQL server set up in Section 5 is used to store and retrieve material data. The C# back-end communicates with the GH interface through the GH API. In the front-end a distinction is made between the GH interface and the additional *ReLifeCycle* results interface. The latter is namely created with a GH script using the Human UI plugin for creating interfaces. The optimisation function is included with a GH script as well using either the Wallacei or Galapagos plugins. Although the user can see the script that generates the *ReLifeCycle* results interface, the user does not interact with it.

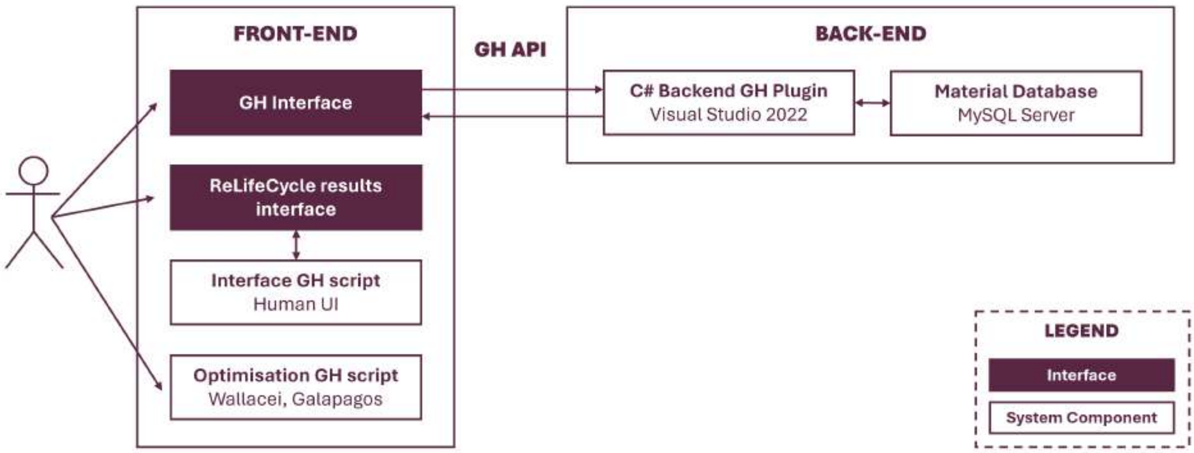


Figure 6.1: Development environment diagram for the *ReLifeCycle* prototype

[2]https://github.com/DePimmer/ReLifeCycleGraduationProject

6.1.2 Assumptions and Dependencies

6.1.2.1 Assumptions

The *ReLifeCycle* prototype assumes the following:

- The user has made a Grasshopper script for a building design.
- The user has extracted each building element as a surface, except columns and beams, which are modelled as solids.
- The user has defined the building parameters in meters.
- Data is available in the MySQL server.

6.1.2.2 Dependencies

The *ReLifeCycle* prototype depends on the following. While the prototype may be compatible with earlier or later versions of the software and plugins, this has not been explicitly tested.

ReLifeCycle Plugin

- .NET Framework 4.8 & 7.0
- Grasshopper SDK package
- Grasshopper, Rhino 7 & 8
- MySql.Data package
- MySQL Workbench 8.0

ReLifeCycle Results Interface

- Human UI Plugin Version 0.8.8
- Metahopper Plugin Version 1.2.4

Material Optimisation

- Wallacei Plugin Version 2.7
- Galapagos Plugin Version 0.2

6.1.3 General Grasshopper Component Structure

For developing a custom GH component, the GH SDK provides a C# template. This template is provided in Appendix G.1 and summarised in Algorithm 1. The process begins by creating a new class for the GH component, followed by initialising the component with essential details. Afterwards, the input and output parameters are registered and the SolveInstance method handles the core functionality that processes the inputs to the output parameters. Finally, three properties are assigned: the position of the component in the GH ribbon, an icon and a Global Unique Identifier (GUID).

Algorithm 1 Structure of a Grasshopper Component

```
procedure MyComponent1
    CLASS MyComponent1 INHERITS GH_Component
    METHOD Constructor (Initialise component with name, description, category, subcategory)
    METHOD RegisterInputParams (Register input parameters)
    METHOD RegisterOutputParams (Register output parameters)
    METHOD SolveInstance (Retrieve data from inputs, perform calculations, store results)
    PROPERTY Exposure (Define visibility in Grasshopper ribbon)
    PROPERTY Icon (Set component icon)
    PROPERTY ComponentGuid (Assign unique GUID to component)
end procedure
```

6.1.4 Grasshopper Workflow

Figure 6.2 shows a break-down of the *ReLifeCycle* workflow in Grasshopper. This workflow is structured into the four system packages defined in Section 4. The first two packages "Model Linking & Material Mapping" and "Responsible Material Use Assessment", are implemented through the *ReLifeCycle* plugin, which consists of custom Grasshopper components. This process begins with the "Create Material Set" and "Select Material" components, which generate a set of materials for a specific NL/SfB class and select one material from that set. Afterwards, the "Create Building Element" component links a building element's geometry to the material data, followed by the "Create Building" component, which combines the data of all building elements into a single component including general building information and calculation variables. Subsequently, separate components for environmental impact, financial impact and circularity assessment perform calculations and output the final results of the responsible material use assessment. These results can be linked to a separate GH script, developed using the Human UI plugin, to generate a user-friendly results interface. Additionally, the assessment component outputs can be linked to optimisation plugins such as Galapagos (Single-Objective Optimisation) and Wallacei (Multi-Objective Optimisation). For the Wallacei plugin specifically, the optimisation results can be connected to the interface as well, allowing material-optimised variants to be compared efficiently.

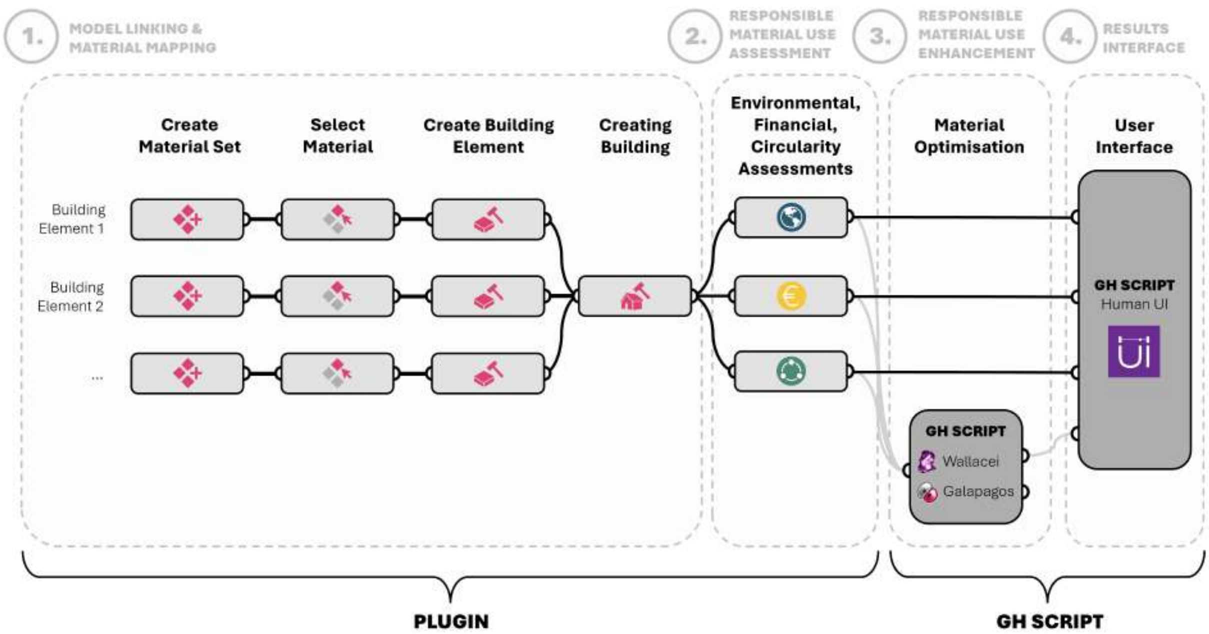


Figure 6.2: *ReLifeCycle* plugin workflow in Grasshopper

6.2 Code Description

The following sections elaborate on the code and thinking behind each component and script. You can find the code on the *ReLifeCycle* GitHub repository.

6.2.1 Model Linking & Material Mapping

6.2.1.1 Create Material Set

The "Create Material Set" component generates a set of materials for a chosen NL/SfB class. This is an important initial step in the Grasshopper workflow, as it filters the material database to include only suitable materials for that specific class, narrowing down the list of options. Additionally, during the material optimisation process later on, this function ensures that no invalid materials are mapped to the

NL/SfB class. Algorithm 2 explains the code behind this component. It starts by creating a connection string to link with the MySQL database server. An example of this string is provided in Listing 1.

```
private string connectionString = "server=127.0.0.1;user=root;database=
    local_mysql_relifecycle_db;port=3306;password=........";
```

Listing 1: Database connection string (the password is removed because of data sensitivity)

The component has one input parameter: "NL/SfB Class". A button[3] is created that, when clicked, automatically connects a value list[4] with all NL/SfB classes from Table F.2 to this input. These classifications are retrieved directly from the database by executing an SQL query using the connection string. Consequently, when a user selects a class, the code queries the database to retrieve all material data for that specific class. This means all general, environmental, financial and circularity data for each material that is included in the set of that NL/SfB class. This data is directed to two output parameters: "Material Set Data" and "Material Names". The latter is a simple list displaying the materials included in the set. "Material Set Data" contains all relevant material data structured as a data tree to ensure the data is well-organised. Grasshopper organises data in three structures: item, list and tree, as illustrated in Figure 6.3. An item is a single piece of data, a list is a collection of items within a single branch, and a tree is a hierarchical structure of multiple lists organised into branches.

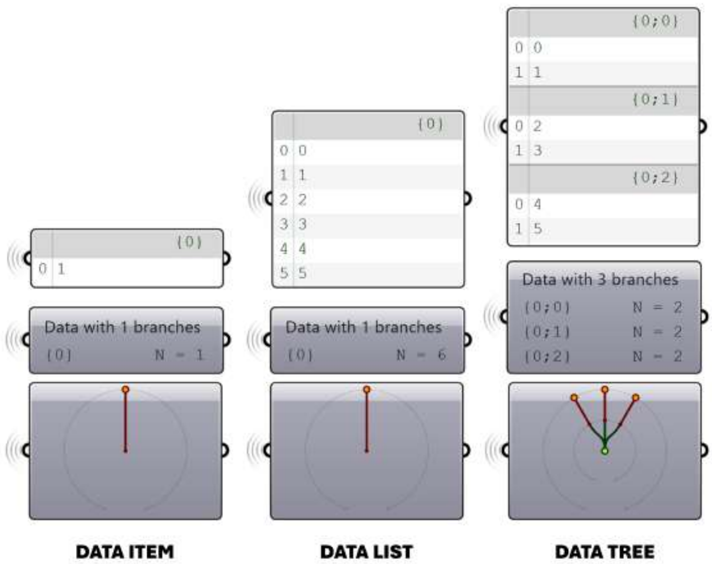


Figure 6.3: Explanation of Grasshopper data structures

For the "Material Set Data" tree, each material has its own branch. This branch is further divided into sub-branches for each database entry. Each sub-branch contains two items: item 0 being a string description of the data and item 1 its corresponding value. This gives the user a readable overview of the data. Additionally, the descriptions in item 0 serve as identifiers, allowing specific data values to be retrieved for calculations in subsequent components. Figure 6.4 shows the "Create Material Set" component in Grasshopper.

[3] Custom object display documentation: https://mcneel.github.io/grasshopper-api-docs/api/grasshopper/html

[4] The NL/SfB value list is also added as a separate GH component, allowing users to classify a building element without assigning a material. This enhances the flexibility and usability of the tool and extends its use to other functionalities as well.

Algorithm 2 Create Material Set Component

procedure CREATEMATERIALSETCOMPONENT(NL/SfB Class)
  Initialise:
  Create connection string to MySQL database
  Create GUI Button: "Load NL/SfB Classes" button
  When clicked, trigger the process to retrieve NL/SfB classes from MySQL database
  Database Query:
  Open connection to MySQL using $connectionString$
  Execute query: `SELECT nl_sfb_code, nl_sfb_name_en FROM relifecycle_db.classification_table`
  Display NL/SfB Classes in Popup List:
  Create popup with list of NL/SfB classes from query result
  When user selects a class, proceed to the next step
  Retrieve Materials for Selected NL/SfB Class:
  Execute query: `SELECT ...FROM relifecycle_db.relifecycle_joined_db WHERE nl_sfb_code = @selectedClass`
  Populate Material Set:
  for each material in query result **do**
    Add material data to $MaterialSet$
  end for
  Create Material Names List:
  for each material in $MaterialSet$ **do**
    Extract material name
    Add material name to $MaterialNames$
  end for
  Set Outputs:
  Set $MaterialSet$ (as tree), $MaterialNames$ (as list)
end procedure

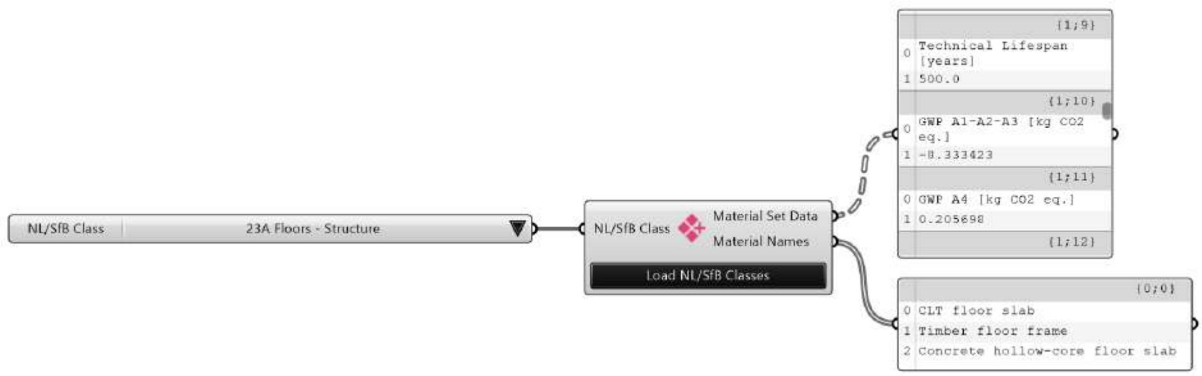


Figure 6.4: "Create Material Set" component in Grasshopper

6.2.1.2 Select Material

The "Select Material" component allows users to choose a single material from a generated material set, which can be assigned to a building element later. Algorithm 3 explains the code for this component. The component has two input parameters: "Material Set Data" and "Index". The data tree output from the "Create Material Set" component can be connected to the "Material Set Data" input. When this happens, a slider with integer values pops up and connects automatically to the "Index" input, allowing users to select a material by changing its index. The slider's maximum value updates dynamically based on the material set size. The reason for using a slider instead of a more convenient drop-down list, is to facilitate integration with third-party optimisation plugins, which require numerical sliders as genes (decision variables). Since materials are categorical, a slider is used with integer values representing different material options, ensuring compatibility with optimisation workflows (see 6.2.3). For usability, the selected material name is displayed on the UI of the GH component, along with the material set's unit of measurement and required building element geometry type. If the unit is m^2, a surface is required, whereas if the unit is m^3 a solid is needed. The component contains one output parameter "Material Data", which contains all relevant data for the selected material. Figure 6.5 shows the "Select Material" component workflow.

Algorithm 3 Select Material Component

procedure SELECTMATERIAL(MaterialSet, SliderIndex)
    Check Input:
    if A slider is connected to the "Index" input **then**
        Update slider properties based on material set size
    else
        Create Slider: Add a new slider connected to the "Index" input
    end if
    Filter Material Data:
    for each path in $MaterialSet$ **do**
        if path[0] matches $SliderIndex$ **then**
            Append corresponding branch to $MaterialData$
        end if
    end for
    $MaterialName \leftarrow$ GetMaterialName($MaterialData$)
    $Unit \leftarrow$ GetMaterialUnit($MaterialData$)
    Process Unit:
    if Unit is "m2" **then**
        $unitGeometryDisplay \leftarrow$ "unit (use surfaces)"
    else if Unit is "m3" **then**
        $unitGeometryDisplay \leftarrow$ "unit (use solids)"
    else
        $unitGeometryDisplay \leftarrow$ "unit (unknown geometry type)"
    end if
    Update Display:
    Update $materialNameDisplay$ and $unitGeometryDisplay$ for component UI
    Set Output: Set $MaterialData$ (as tree)
end procedure

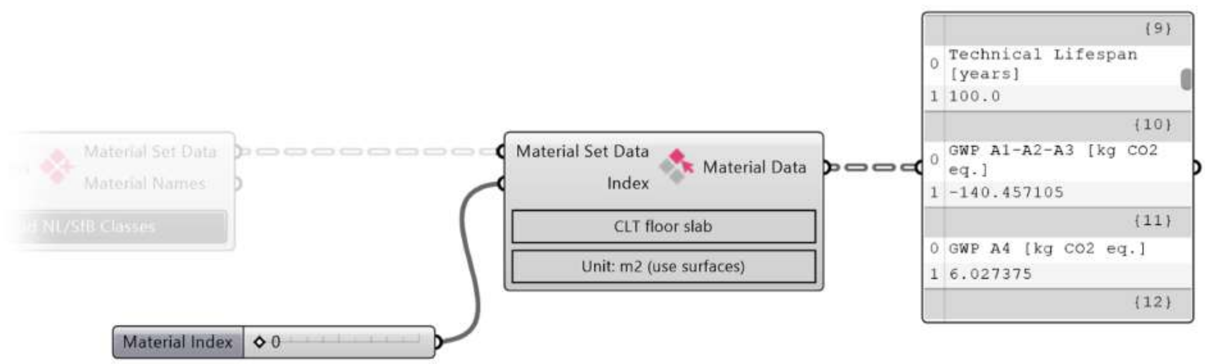


Figure 6.5: "Select Material" component in Grasshopper

6.2.1.3 Create Building Element

The "Create Building Element" component adds classification and material data to a GH geometry, defining it as a building element. Algorithm 4 outlines the code behind this component. It requires four input parameters: a name, NL/SfB class, material data and geometry. The output from the "Select Material" component should be connected to the "Material Data" input. The geometry input requires a mesh, as Grasshopper generally defines two types of 3D geometry, Breps (Boundary Representations) and meshes (polygonals). Meshes are simplified geometries with faster computational speed than Breps, which improves the performance of *ReLifeCycle*. If the user still inserts a Brep, the component automatically converts this to a mesh. Next, the code validates the geometry type by checking if it matches the material's unit of measurement (e.g. an error message is shown if a solid is used for a material measured in m^2). Once validated, the component calculates the total volume or area, depending on the geometry type, and multiplies the environmental, financial and circularity data by this value to calculate the intermediate results for the building element. This data is sent to the "Building Element Data" output. Additionally, three specific values are extracted from this data and placed in separate output parameters: area (for surfaces), volume (for solids) and mass. These values provide the user with flexibility for further functions, such as using the mass of specific building elements for structural analysis. Figure 6.6 shows the resulting "Create Building Element" component in Grasshopper.

Algorithm 4 Create Building Element Component

procedure CREATEBUILDINGELEMENTCOMPONENT(Name, NLSfBClass, MaterialData, Geometry)
    Retrieve NL/SfB class code and name from ValueList
    Validate Geometry Type:
    if $Unit$ is "m3" and Geometry contains non-solids **then**
        Output error: "Geometry can only contain solids for 'm3'"
        Exit
    else if $Unit$ is "m2" and Geometry contains solids **then**
        Output error: "Geometry can only contain surfaces for 'm2'"
        Exit
    end if
    Prepare Building Element Data Tree:
    Add Name, NL/SfB Code, NL/SfB Name to data tree
    Set volumeOrArea to "Total volume [m3]" or "Total area [m2]"
    Add Geometry to tree under "Geometry"
    Add Total Mass to tree under "Mass"
    Process Material Data:
    for each branch in MaterialData **do**
        if Branch matches target **then**
            Multiply and append updated data to tree
        else
            Append original branch
        end if
    end for
    Set Outputs: Set $BuildingElementData$ (as tree), $VolumeOrArea$ (as item), $TotalMass$ (as item), $MaterialData$ (as item)
end procedure

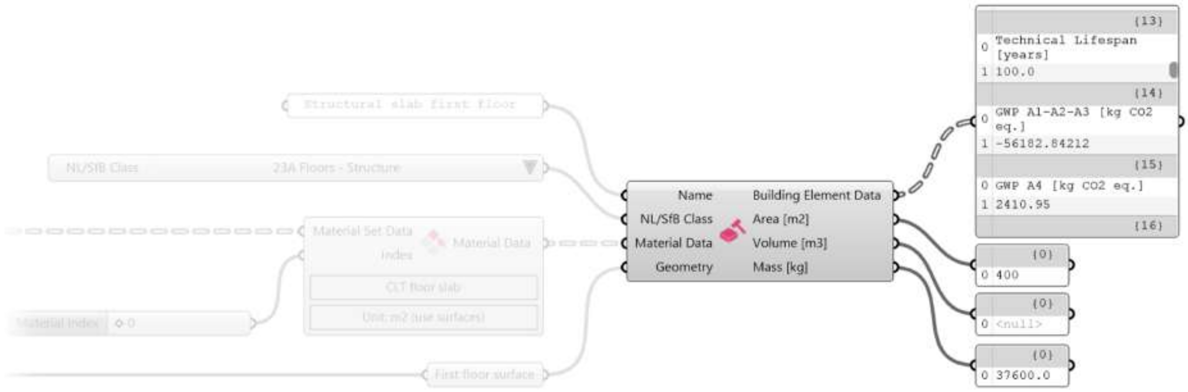


Figure 6.6: "Create Building Element" component in Grasshopper

6.2.1.4 Create Building

The "Create Building" component combines the data from all building elements into a single component and sets calculation variables for the assessment: the building's lifespan, function and Gross Floor Area (GFA). For the building function, a user is presented with a set of five fixed options, based on the same functions from Het Nieuwe Normaal (Het Nieuwe Normaal, 2023). In the "Building Element Data" input, the data outputs from all "Create Building Element" components should be inserted to streamline this data into a single output "Building Data". Algorithm 5 illustrates how this data is structured into a tree with branches for each element. The component also compares the building's functional lifespan to the technical lifespans of the materials, adding impact for replacements if the former exceeds the latter (see Equation D.2 in Appendix D). Finally, building information, materials and geometries are extracted from the "Building Data" tree and organised into separate outputs, making it easier for users to access this data in their own workflows. Figure 6.7 presents the "Create Building" component in its GH workflow.

Algorithm 5 Create Building Component

procedure CREATEBUILDINGCOMPONENT(Name, BuildingLifespan, BuildingFunction, GFA, BuildingElementData)
  Retrieve Data: Read values from input parameters
  Process Building Element Data: Initialise $buildingData$
  for each branch in $buildingElementData$ **do**
    Extract and append to new branch in $buildingData$
  end for
  Retrieve Materials: Initialise $buildingMaterials$
  for each branch in $buildingData$ **do**
    Extract and store material data in $buildingMaterials$
  end for
  Retrieve Geometry: Initialise $buildingGeometry$
  for each branch in $buildingData$ **do**
    Extract and store geometry data in $buildingGeometry$
  end for
  Calculate Replacements: Group $buildingData$
  for each group **do**
    Accumulate impact values, calculate replacements
  end for
  Set Outputs: Set $BuildingData$ (as tree), $BuildingInformation$ (as tree), $BuildingMaterials$ (as tree), $BuildingGeometry$ (as tree)
end procedure

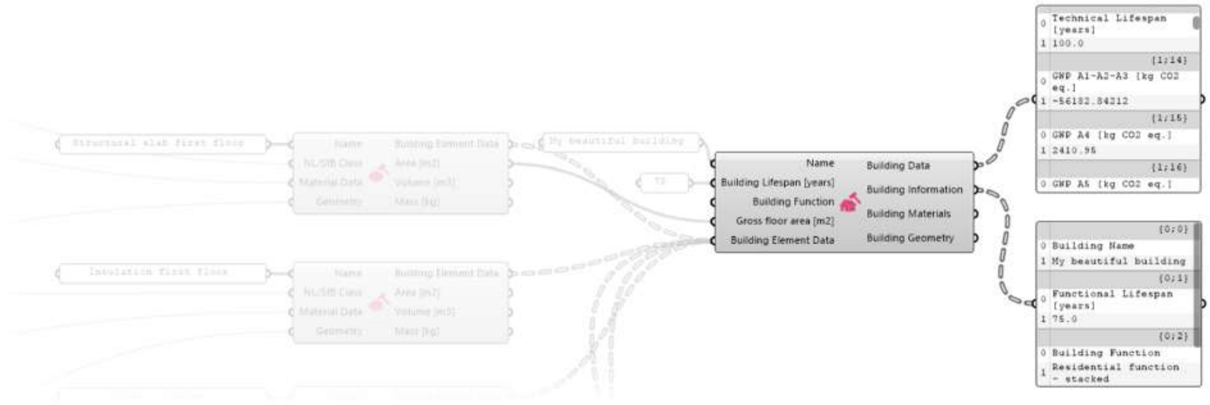


Figure 6.7: "Create Building" component in Grasshopper

6.2.2 Responsible Material Use Assessment

The "Responsible Material Use Assessment" system package is achieved in Grasshopper with three different components, one for each aspect: environmental impact assessment, financial impact assessment and circularity assessment. The code behind their components performs the calculations as defined in Appendix D and all follow a similar structure. They start by calculating the results on the building element level and place these in a "Detailed Results" output parameter. Afterwards, the building element results are combined to calculate the results for the complete building, which are placed in a "Total Results" output. Algorithm 6 provides the pseudocode for the "Environmental Impact Assessment" component. Code explanations for the financial impact and circularity assessment components are provided in Appendix G.2.

Algorithm 6 Environmental Impact Assessment Component

procedure ENVIRONMENTALIMPACTASSESSMENTCOMPONENT(BuildingData)
    Calculate Detailed Results: Group $buildingData$ by main path index
    for each building element group in $buildingData$ **do**
        Initialise $totalMKIElement$, $totalGWPElement$, $mpgElement$, $parisProofElement$
        for each subbranch in group **do**
            Retrieve description and value
            if description starts with "MKI", "GWP" **then**
                Add value to $totalMKIElement$, $totalGWPElement$
            end if
            if description is "GWP A1-A2-A3" or "GWP A4" or "GWP A5" **then**
                Add value to $GWPA1A5$
                Calculate $parisProofElement$
            end if
            Calculate $mpgElement$
        end for
        Update Results: Append results to $detailedResults$
    end for
    Calculate Total Results:
    Calculate $totalMKI$, $totalMPG$, $totalParisProof$, $totalCSC$
    Update Results: Append results to $totalResults$
    Set Outputs: Set $totalResults$ (as tree), $detailedResults$ (as tree)
end procedure

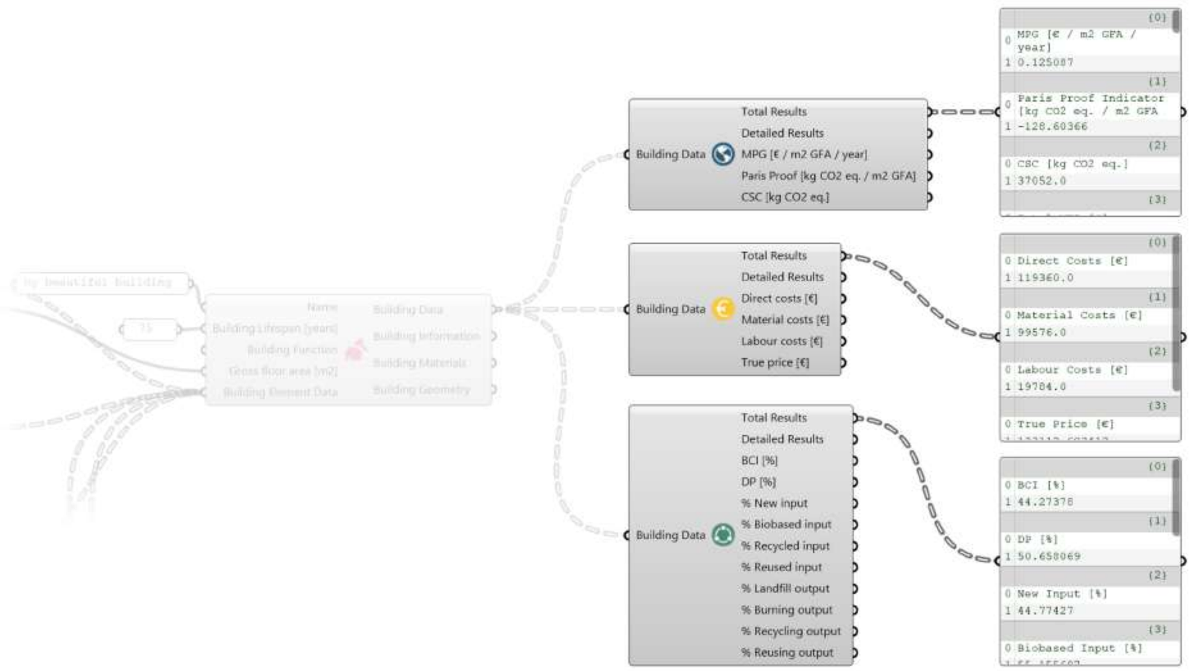


Figure 6.8: "Environmental Impact Assessment", "Financial Impact Assessment" and "Circularity Assessment" components in Grasshopper

6.2.3 Responsible Material Use Enhancement

The third system package of *ReLifeCycle* focuses on responsible material use enhancement, optimising the assessment results to achieve a better materialisation for the environment. This research considers two methods: Single-Objective Optimisation (SOO) and Multi-Objective Optimisation (MOO). Both are achieved by integrating *ReLifeCycle* with third-party optimisation plugins and demonstrating this integration through example scripts. For SOO, Galapagos is used, which uses metaheuristic methods and provides both a genetic and simulated annealing algorithm to find a global optimum by adjusting the genome (decision variables). An integration with *ReLifeCycle* can be made by using the material sliders from the "Select Material" components as genes for the optimisation, as illustrated in Figure 6.9. This allows an optimisation on material choice. An example script with a demo explaining this integration is provided in the GitHub repository.

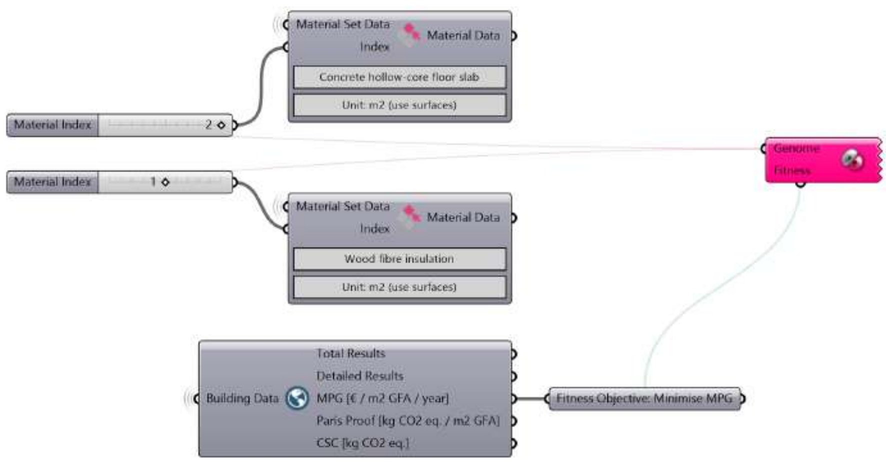


Figure 6.9: Integration between Galapagos and *ReLifeCycle* explained with a simple example

A more compelling approach, given the multi-objective nature of responsible material use, is to integrate the Wallacei MOO plugin. Wallacei uses the NSGA-II genetic algorithm as its primary MOO method and the K-means clustering method for aiding solution selection (Makki et al., 2019). Its ability to export phenotypes and genomes within Grasshopper allows Wallacei to be connected directly with the *ReLifeCycle* results interface. To establish this connection, each gene slider should be named as "wlc_xx" where xx is the slider's number. This is highlighted in Figure 6.10, which shows how Wallacei can be integrated with *ReLifeCycle* with an example for three objective functions. An example script for this integration can also be found in the GitHub repository.

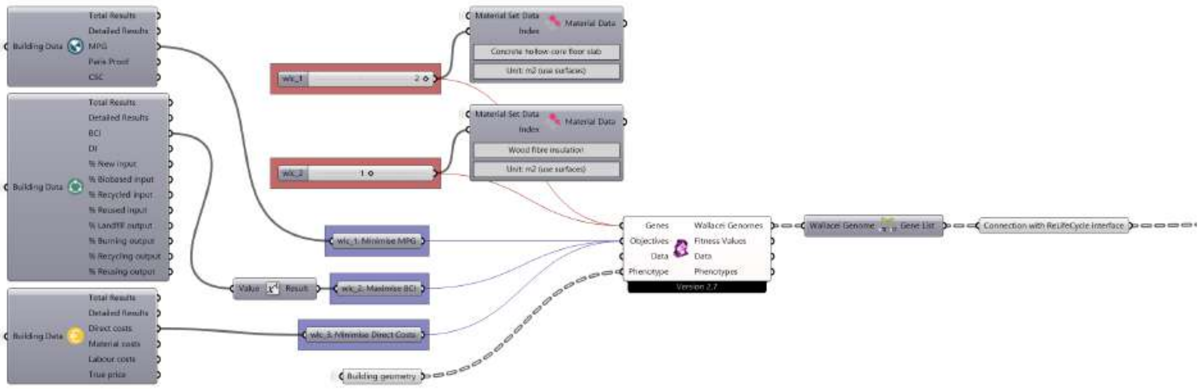


Figure 6.10: Integration between Wallacei and *ReLifeCycle* explained with a simple example

6.2.4 Results Interface

The *ReLifeCycle* results interface is designed to provide users with an intuitive, user-friendly presentation of the responsible material use assessment results. To develop the interface, Human UI is used; a Grasshopper plugin specifically designed for making interfaces. Human UI offers custom GH components that can be connected in the same visual programming manner as a standard GH script. Therefore, a special GH script is made for the interface. To link the assessment results from the *ReLifeCycle* plugin, users simply have to connect the total and detailed results outputs to this script and the interface can be launched. For a complete overview and understanding of the interface script, it is recommended to explore it through the interface example file provided in the GitHub repository.

The interface windows and tabs are structured based on the functional and non-functional requirements from Tables 4.2 and 4.3. It consists of two windows: a "Results" window for visualising the assessment results, and an "Explore" window for comparing different variants from a Wallacei optimisation. Both windows are explained in the next paragraphs. The design of the interface is based on reference tools and a review of LCA visualisations by Hollberg et al. (2021).

6.2.4.1 Results Window

When the user launches the interface from Grasshopper, the "Results" window will pop up. This window is divided into four tabs outlined in Figures 6.11 to 6.14: (1) Overview Results; (2) Detailed Results; (3) View and (4) Explore.

The "Overview results" tab (1) displays general building information along with a list of material choices. It further includes sections for environmental impact, circularity and financial impact results. Two toggles are available as well. One compares the indicators to the performance levels outlined in Table 5.1. If an indicator exceeds its level, it will turn red, highlighting indicators that require attention. The performance levels will also change based on the selected building function. The second toggle can be used to disable live updates, which helps increase computation speed when the building script is running slowly. Financial impact (Figure 6.12) includes total costs and costs per m^2 GFA, with a breakdown by element class to identify high-impact elements. Additionally, investment costs are estimated for a more realistic assessment and users can adjust variables for indirect and additional costs based on their project. The cost variable categories are based on general categories set up by (Arcadis, 2024).

In the "Detailed Results" tab (2), all results are presented, with specific sections for results on the total building, building element and NL/SfB level. Not only are the final indicator results shown, but also midpoint results such as the MKI and GWP, as well as results per life cycle stage. Bar charts categorise the results based on impact, with the highest-impact elements or classes displayed at the top. Users can navigate through the tabs to explore the results for each aspect.

The "View" tab (3) lets users adjust settings for the 3D model of the building design in the Rhino viewport. Building elements are categorised into generic classes, with visibility toggles and the option to assign custom colours for better visualisation. Additionally, users can display results for six indicators in the 3D model using a gradient colour override, based on the relative impact of the elements compared to each other. This quickly highlights which elements have the most impact.

Finally, the "Explore" tab (4) contains a toggle that launches an additional "Explore" window.

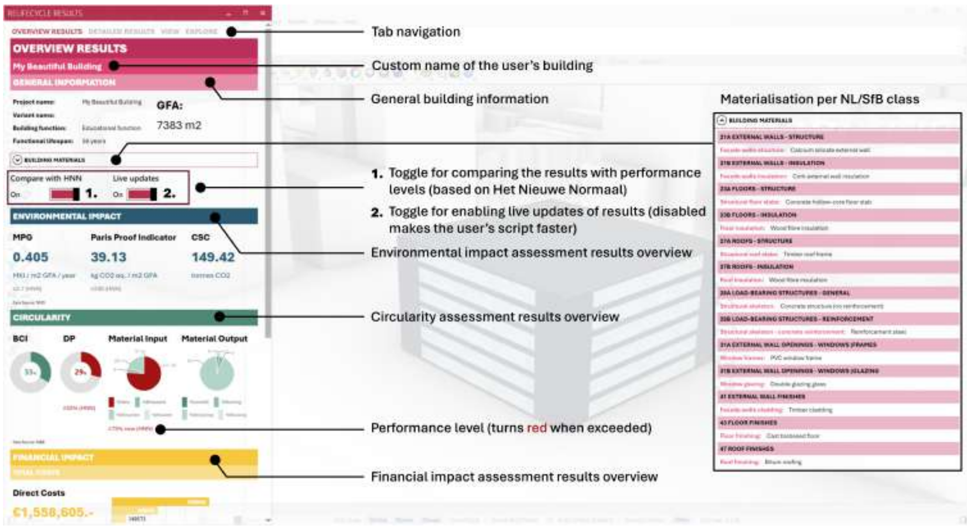


Figure 6.11: "Overview Results" tab

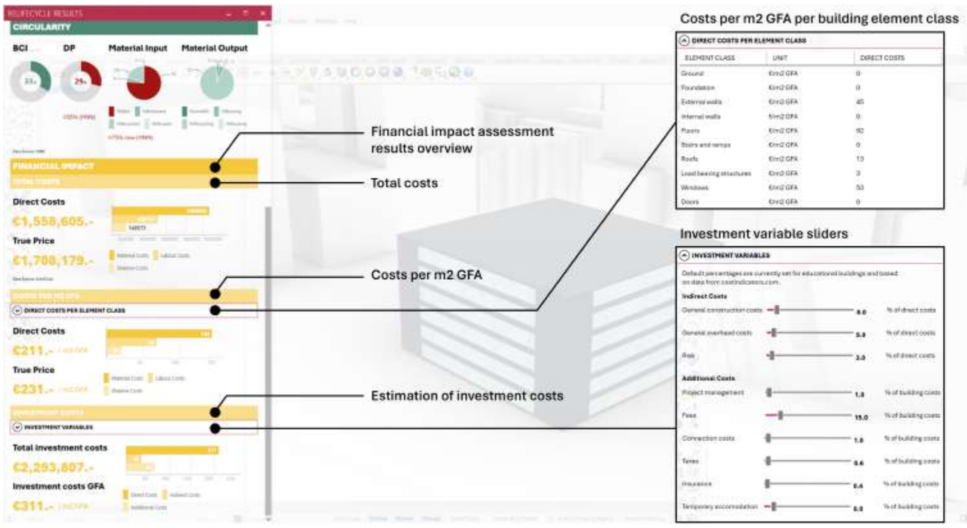


Figure 6.12: "Overview Results" tab (continued)

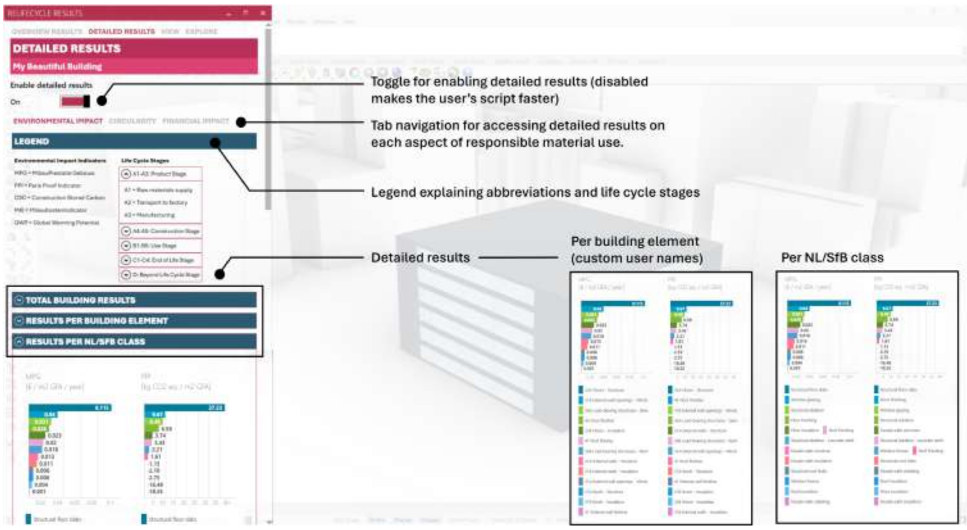


Figure 6.13: "Detailed Results" tab

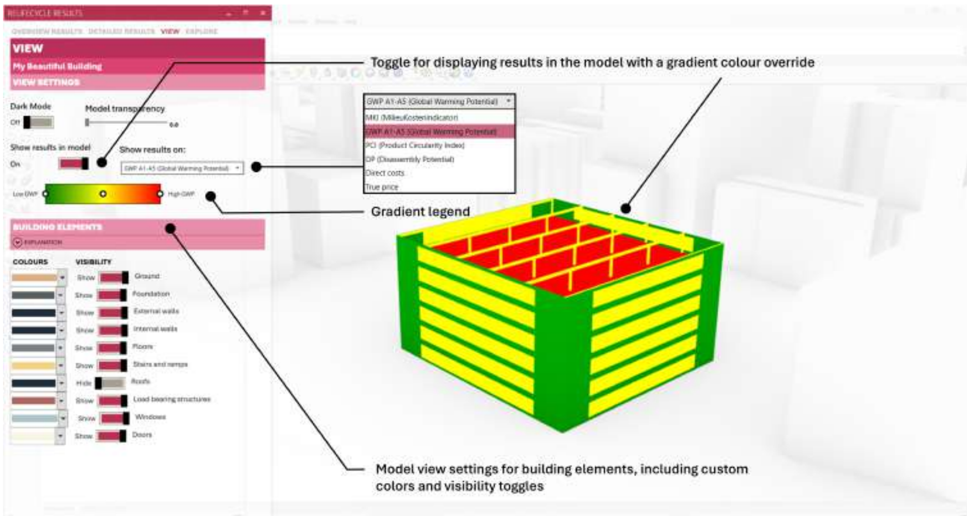


Figure 6.14: "View" tab

6.2.4.2 Explore Window

After enabling the "Start exploring!" toggle in the "Results" window, the "Explore" window appears on the opposite side of the screen (Figures 6.15 and 6.16). This window is specifically designed to make a direct connection with the Wallacei MOO plugin and visualise the results for optimised solutions. While Wallacei has its own interface for analysing and selecting solutions, it only considers results for the included objectives, without offering in-depth insights into all assessment results and materialisations. To address this, the "Explore" window integrates Wallacei with the *ReLifeCycle* interface, providing a user-friendly visualisation and deeper comparison of results.

After running an optimisation simulation, high-potential solutions can be selected through Wallacei's interface and exported to Grasshopper. The genotypes for the exported solutions can then be linked to the *ReLifeCycle* interface as in Figure 6.10, which processes this data. By naming gene sliders as "wlc_1", "wlc_2", etc. as previously explained, we can retrieve all slider values using the Metahopper plugin, which is designed for controlling Grasshopper components. Combining the slider values with the genotype data makes it possible to switch quickly between optimised solutions. This functionality is added in the "Explore" window, which contains two tabs: (1) Settings and (2) Compare.

In the "Settings" tab (1), a toggle activates the solution selector, a slider for switching between optimised solutions (Figure 6.15). Changing the selected solution directly updates the results in the "Results" window so users can explore them in detail. A save and load function allows to name and store interesting variants, which can later be reloaded, updating all gene sliders in the Grasshopper script to match the saved genotype. An additional toggle allows a variant to be set as comparison variant.

The "Compare" tab (2) enables side-by-side comparison between a baseline and comparison variant (Figure 6.16). This tab duplicates the "Overview Results" tab, providing a clear overview of the differences in performance and materialisation between two variants. Deviation percentages indicate differences in results and are colour-coded to highlight whether the comparison variant performs better or worse for specific objectives. The combination between the "Results" and "Explore" windows offers an efficient workflow for comparing optimised variants to select the most suitable solution, supporting the design space exploration process.

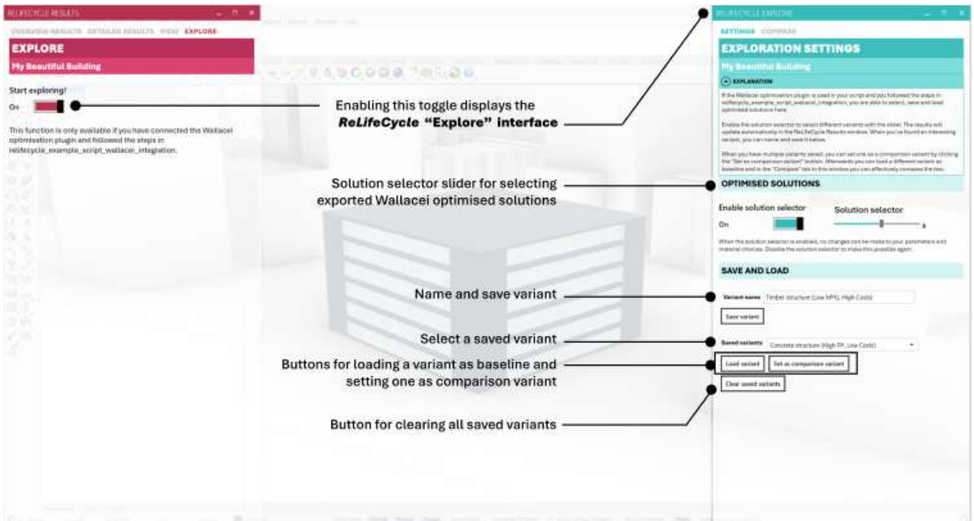


Figure 6.15: "Settings" tab

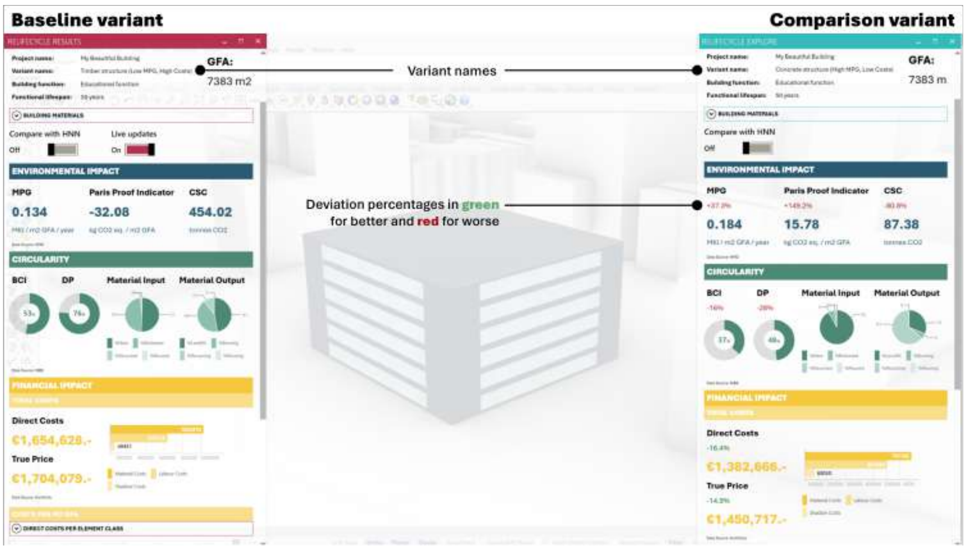


Figure 6.16: "Compare" tab

6.3 Prototype Result

6.3.1 Installation and Setup

The prototype result consists of a set of files required to set up *ReLifeCycle*, which are available in the GitHub repository. Its contents are given in Table 6.1. The repository includes the source code files of the plugin, a README file with setup instructions and example scripts for demonstrating the plugin's workflow, connection with the interface, and integrations with the Galapagos and Wallacei optimisation plugins. Due to confidentiality concerns regarding company-sensitive data, the data used in this research cannot be publicly shared. As a solution, the MySQL database model from Section 5.4.2 is provided as a schema in the repository to serve as an empty template, allowing users to add their own data. By modifying the data connection string from Listing 1, users can link the *ReLifeCycle* plugin to their personal data server.

Table 6.1: *ReLifeCycle* installation package contents

File	Description
README.md	Provides instructions for setting up the plugin and database, including links to used packages, plugins, and demo videos.
Code folder	Contains all source code files necessary for setting up ReLifeCycle.
relifecycle_db_schema.sql	SQL query for creating the ReLifeCycle database schema, tables, and views.
relifecycle_example_script_getting_started.gh	Example GH file demonstrating the general workflow and function of each GH component.
relifecycle_example_script_interface.gh	Example GH file demonstrating how to connect the ReLifeCycle Human UI interface.
relifecycle_example_script_galapagos_integration.gh	Example GH file demonstrating how to integrate ReLifeCycle with Galapagos for single-objective optimisation.
relifecycle_example_script_wallacei_integration.gh	Example GH file demonstrating how to integrate ReLifeCycle with Wallacei for multi-objective optimisation, including a connection with the ReLifeCycle interface.

6.3.2 Demo Videos

To provide a detailed explanation of the workings of *ReLifeCycle* and its integration with Wallacei, the links below include two demo videos.

- ReLifeCycle Demo 1: Workflow and Interface
- ReLifeCycle Demo 2: Integration with Wallacei Multi-Objective Optimisation Plugin

7. VALIDATION

This section documents the validation process of the *ReLifeCycle* prototype with two approaches: (1) a case study application and (2) expert opinion. The first approach introduces a case study that is used to evaluate the prototype on its accuracy and potential to enhance responsible material use in early building design. The application process follows the *ReLifeCycle* workflows as introduced in Section 5.1 and begins by explaining the parametric model of the case study. It then moves on to the responsible material use assessment workflow, where the results are compared to benchmark calculations. It finally proceeds to go through the responsible material use enhancement process that consists of multiple optimisation simulations to find the best solution for the case study. The section concludes with feedback from three experts in the field of parametric design, assessing the prototype's functionality and user-friendliness.

7.1 Application to Case Study

7.1.1 Case Study Description: "Het Schoolvoorbeeld"

The case study for this research is "Het Schoolvoorbeeld" (The Example School), a project initiated by the Innovation Partnership for School buildings (IPS) of the Municipality of Amsterdam, and executed by the contractor Hegeman (Het Schoolvoorbeeld Team, 2024). Due to the increasing demand for residential houses in Amsterdam, there is a simultaneous need for more school buildings. Het Schoolvoorbeeld therefore proposes a standardised construction concept that focuses on quality, sustainability and adaptability. It proposes a circular grid of 7.2 x 8.4 meters with no load-bearing internal walls, creating an open floor plan. This makes the building adaptable to other functions such as offices when future demands will change. In terms of environmental impact and circularity, the concept is designed according to Paris Proof standards, and aims to increase the use of biobased materials. Figure 7.1 shows the general construction concept of Het Schoolvoorbeeld.

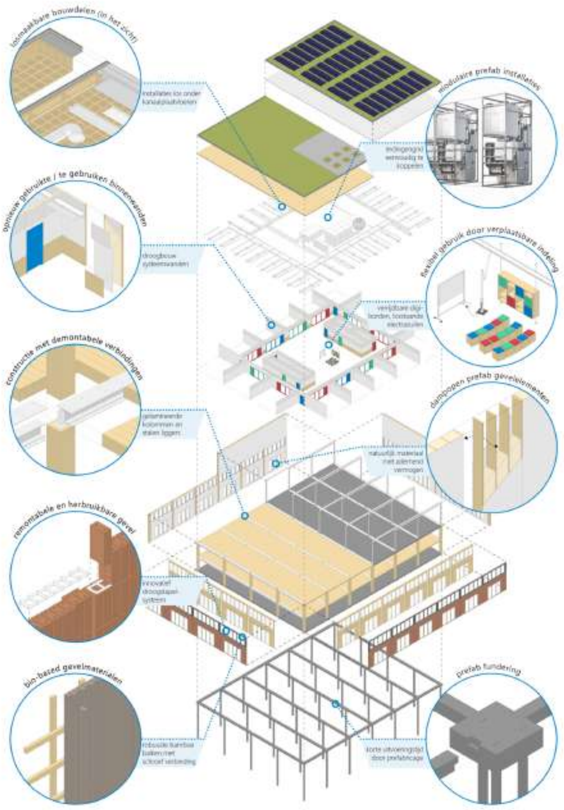


Figure 7.1: Construction concept of case study "Het Schoolvoorbeeld"

Multiple variants can be made from this concept (Figure 7.2), which makes it an excellent case for a parametric application that uses one script to generate many design variants. To simplify the validation process, however, the O&O variant is chosen as the main case study for this research. Its building design consists of single-storey classrooms on the ground and first floor, and a double-storey gym hall on the second floor. Several design and performance criteria have been set up for this variant, which are based on documents about the case study and the *ReLifeCycle* performance levels. These criteria are given in Table 7.1. Since there is no fixed budget, the estimated maximum costs should align with the direct costs of the original O&O variant plus 20% which amount to approximately €1,304,824.-. The minimum required Gross Floor Area (GFA) is 3337 m^2.

Table 7.1: Case study requirements

Indicator	Requirement	Goal
MPG [€ / m^2 GFA / year]	$\leq$ 0.7	0.4
PP [kg CO2 eq. / m^2 GFA]	$\leq$ 240	155
DP [%]	$\geq$ 55	80
New [%]	$\leq$ 75	50
Direct Costs [€]	$\leq$ 1,304,824	-
GFA [m^2]	$\geq$ 3337	-

Figure 7.2: Three variants created from "Het Schoolvoorbeeld" concept. From left to right: O&O, Azalea, Strandeiland

7.1.2 Workflow 1: Parametric Building Script

The first workflow of *ReLifeCycle* is to create a parametric building script. While this is usually created by the user itself, no parametric script exists for this specific case study. Therefore, a Grasshopper script is made especially for this research. The script generates a schematic, early design of the school building that consists of floors, roofs, external walls, windows and a load-bearing structural skeleton made of columns and beams. All building elements have been modelled as mesh surfaces as required by the *ReLifeCycle* plugin input data types, except for the columns and beams which are modelled as mesh solids. Parameters include general aspects such as building width, length, storey height, number of floors and window-to-wall ratio, as well as the ability to add up to four wings to the main building, each with its own dimensions, location and number of extra floors. This allows for a greater variety of design variants and makes it possible to achieve all three variants created from "Het Schoolvoorbeeld" concept as seen in Figure 7.3.

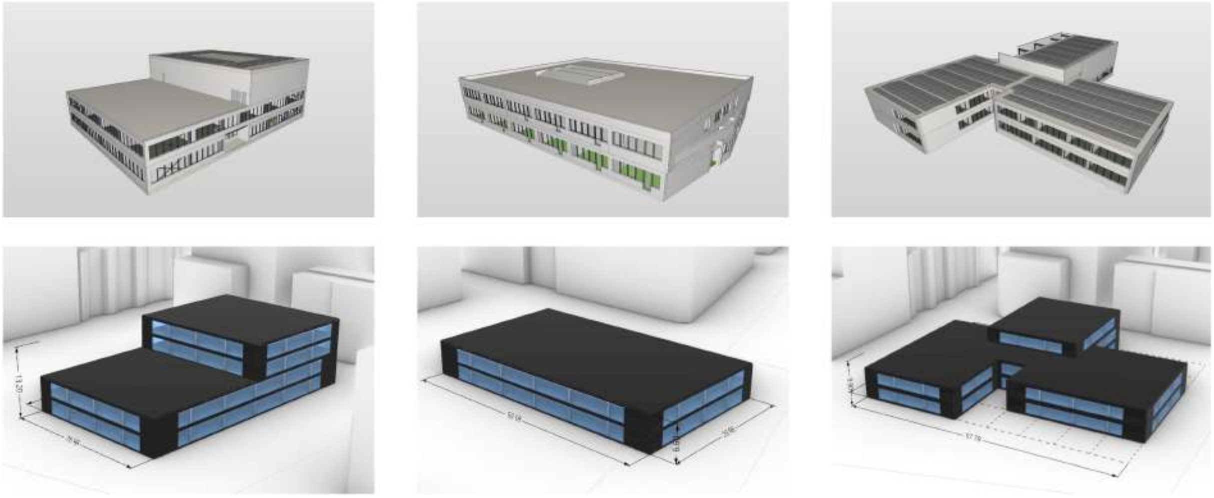


Figure 7.3: Three variants created from "Het Schoolvoorbeeld" concept with their corresponding parametric Grasshopper model outputs. From left to right: O&O, Azalea, Strandeiland

Structural integrity is not considered in the *ReLifeCycle* plugin itself. However, it is deemed important to include it when analysing different structural materials. A timber structure is dimensioned differently than a concrete structure, and exact steel profiles need to be modelled to get an accurate volume output for the responsible material use assessment. To show how parametric design can be used to its advantage, structural integrity is therefore included in the Grasshopper script by adding three structural material options for the column-beam structure: timber, concrete and steel. Based on the chosen material, the structure will dimension automatically based on rules of thumb for global dimensioning (Blok et al., 2015). In this way, the structural materials can be compared quickly without having to manually change their dimensioning.

Finally, the script is linked to the *ReLifeCycle* plugin by assigning a classification, material set and material to each building element. The chosen materials are the same as those of the O&O benchmark case. This leads to the final parametric model with materialisation in Figure 7.4. Appendix I.2 shows the materialisation for this base case per NL/SfB class.

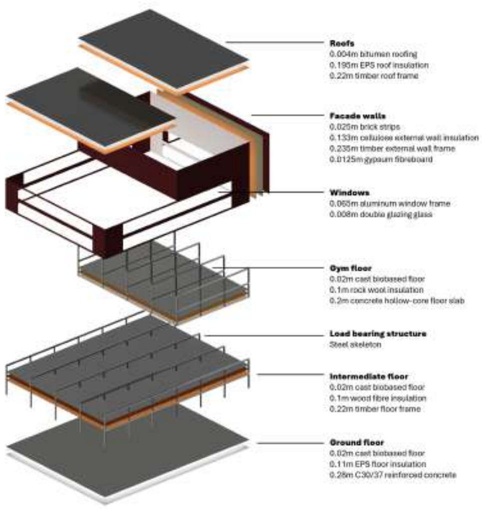


Figure 7.4: Exploded parametric model of the O&O case study variant with its initial materials

7.1.3 Workflow 2: Responsible Material Use Assessment

The second workflow consists of the responsible material use assessment performed by the *ReLifeCycle* plugin. After linking the case study script to the plugin, an environmental impact, circularity and financial impact assessment is performed. To validate the output of those assessments, the results are compared to schematic design benchmark calculations of the O&O case study. These consist of an environmental impact and circularity calculation, executed with the BCI Gebouw software, and direct cost estimations performed by an external cost consultant. The BCI Gebouw benchmark uses the same databases as *ReLifeCycle*: the NMD and NIBE, whereas the data source for the cost benchmark is unknown.

Before a comparison can be done, a few adjustments are made to the benchmark calculations. First of all, the BCI Gebouw benchmark was made with the A1 set of environmental impact categories, whereas the *ReLifeCycle* database uses the A2 set, which is more strict. The original calculation is therefore manually converted to set A2. Secondly, the benchmark calculations consider more building elements than the parametric model, such as internal walls, stairs and installations. This makes sense since the model is a simplified version of the building due to its parametric nature. To make a fair comparison, building elements that are not included in the parametric model are excluded from both the BCI Gebouw and the cost calculations. Additionally, the benchmark considers a hybrid structural system of steel beams and timber columns. Since the parametric model is limited to one material for the complete structure, the column material from the benchmark is changed to steel.

For each aspect of the *ReLifeCycle* responsible material use assessment, the results are compared to the benchmark and discussed in the next paragraphs. Both calculations are performed for an educational building with a lifespan of 50 years.

Table 7.2: Benchmark comparison results for environmental impact assessment

Indicator	ReLifeCycle result	Benchmark result	Deviation
MPG [€ / m^2 GFA / year]	0.565	0.526	7.41%
PP [kg CO2 eq. / m^2 GFA]	90.26	86.56	4.27%
CSC [tonnes CO2]	37.32	39.14	-4.66%
Total MKI [€]	104199	101245	2.92%
Total GWP [kg CO2 eq.]	574452	560505	2.49%

The environmental impact assessment results seem accurate when compared to the benchmark in Table 7.2, with a maximum deviation of 7.41% for the MPG score. Overall, the *ReLifeCycle* results have a slightly higher environmental impact compared to the benchmark results. This difference can be explained by small deviations in the geometry of the parametric model compared to the quantities of the benchmark and differences in material thicknesses between both calculations. The *ReLifeCycle* prototype database assigns one standard thickness to each material as explained in Section 5.3.3. So it might be that this thickness is larger or smaller than in the benchmark, resulting in small deviations.

Table 7.3: Benchmark comparison results for circularity assessment

Indicator	ReLifeCycle result	Benchmark result	Deviation
BCI [%]	38	39	-1.00%
DP [%]	40	40	0%
Material input			
New [%]	86	85	1.00%
Biobased [%]	4	4	0%
Recycled [%]	11	11	0%
Reused [%]	0	0	0%
Material output			
Landfill [%]	13	13	0%
Burning [%]	7	7	0%
Recycling [%]	80	80	0%
Reusing [%]	0	0	0%

From the circularity comparison results in Table 7.3 it can also be concluded that *ReLifeCycle* provides accurate results in this aspect, with a maximum deviation of only 1%. This minor variation can also be attributed to slight differences in material thicknesses and quantities between the calculations. The overall consistency between results can be explained by the fact that both calculations use the same materials, and since the circularity indicators are calculated as a weighted percentage of the total building, they are less sensitive to variations in material quantity and thickness.

Table 7.4: Benchmark comparison results for financial impact assessment

Direct costs per NL/SfB Class	ReLifeCycle result	Benchmark result	Deviation
13 Floors on the ground	€ 167,130	€ 146,704	14%
21 External walls	€ 69,423	€ 306,357	-77%
23 Floors	€ 114,225	€ 700,909	-84%
27 Roofs	€ 69,338	€ 500,486	-86%
28 Load-bearing structures	€ 163,547	€ 288,014	-43%
31 External wall openings	€ 215,783	€ 437,702	-51%
41 External wall finishes	€ 94,998	€ 195,440	-51%
42 Internal wall finishes	€ 20,740	€ 51,365	-60%
43 Floor finishes	€ 122,834	€ 78,089	57%
47 Roof finishes	€ 49,338	€ 34,528	43%
Total direct costs	**€ 1,087,356**	**€ 2,739,594**	**-60%**

Looking at the deviations of the financial impact assessment benchmark in Table 7.4, we can conclude that the *ReLifeCycle* cost estimation is not realistically accurate, with the deviation between total direct costs being 60%. This is most likely related to the accuracy of the used data and the lack of sustainable materials in the ArchiCalc database. For instance, if we take a look at the NL/SfB classifications with the highest deviation, 23 Floors and 27 Roofs, the benchmark study considers timber Kerto-Ripa floors as material, estimated at 613,294 euros, whereas the closest material that was found in the ArchiCalc database was a standard timber frame floor, estimated at 73,403 euros. Sustainable materials tend to be more expensive than traditional materials, and since the ArchiCalc database mainly consists of traditional materials, this leads to significant cost deviations.

Moreover, generic costs are difficult to accurately estimate as they depend on many factors such as building function, location and current market conditions. A large contribution to the inaccuracy in data is that the ArchiCalc database only provides data for residential buildings, while the benchmark study is likely estimated for an educational (utility) building, which has higher costs in general.

So, for the previous benchmark comparisons, building elements were excluded from the benchmark calculation to test the accuracy of the *ReLifeCycle* calculations. Table 7.5 shows a comparison with the raw benchmark calculation results, which also include building elements that are not in the parametric model, such as installations, stairs and internal walls. By looking at the deviation percentages, we can see that they are especially larger for environmental and financial impact than in the previous comparisons. This shows that the ability of the results to represent real-life scenarios depends on the completeness of the parametric model. The parametric model gives lower scores because it includes fewer building elements. The exclusion of installations in the parametric model and also in the *ReLifeCycle* database has the most influence on the magnitude of these deviations, as installations have a significant impact on all aspects of responsible material use.

Table 7.5: Raw benchmark comparison results for responsible material use assessment

Indicator	ReLifeCycle Result	Raw Benchmark Result	Deviation
Environmental impact			
MPG [€ / m2 GFA / year]	0.565	0.775	-27.10%
PP [kg CO2 eq. / m2 GFA]	90.26	107.88	-16.33%
CSC [tonnes CO2]	37.32	48.98	-23.81%
Total MKI [€]	104199	149024	-30.08%
Total GWP [kg CO2 eq.]	574452	742529	-22.64%
Circularity			
BCI [%]	38	40	-2%
DP [%]	40	47	-7%
Material input			
New [%]	86	84	2%
Biobased [%]	4	6	-2%
Recycled [%]	11	10	1%
Reused [%]	0	0	0%
Material output			
Landfill [%]	13	22	-9%
Burning [%]	7	9	-2%
Recycling [%]	80	68	12%
Reusing [%]	0	0	0%
Financial impact			
Direct costs per NL/SfB Class			
Total direct costs	€ 1,087,356	€ 9,102,402	-88.05%

7.1.4 Workflow 3: Responsible Material Use Enhancement

The final workflow of *ReLifeCycle* aims to enhance the responsible use of materials in the building design. This is achieved by exploring the design and objective space through an optimisation of building materials, using the material sets assigned to each building element. These optimisations are performed with the help of external Grasshopper optimisation plugins: Galapagos and Wallacei. To evaluate how different optimisations affect the results, two types of optimisation are conducted: Single-Objective Optimisation (SOO) for each responsible material use aspect, and Multi-Objective Optimisation (MOO) for a combination of these aspects. The three main aspects of responsible material use are: environmental impact, circularity and financial impact. Expected is that the SOO simulations on environmental impact and circularity will result in a selection of sustainable, circular materials that are more expensive, while the SOO simulation on financial impact will probably result in more traditional, less expensive materials. The MOO optimisation is expected to produce a set of solutions that balance the outcomes across all objectives.

In the next paragraphs, the base scenario for the O&O case study (initial materialisation and results found in Appendix I, Tables I.1 and I.8) will serve as the starting point for the responsible material use enhancement process. Figure 7.5 outlines the process of the different optimisation simulations applied to the O&O case. The resulting solutions from the SOO and MOO simulations are used to explore and find one balanced solution that enhances the use of responsible materials while considering the requirements outlined in the case study (Table 7.1). The exploration process finishes with a manual geometry optimisation to demonstrate how adjusting geometry parameters can further improve the design.

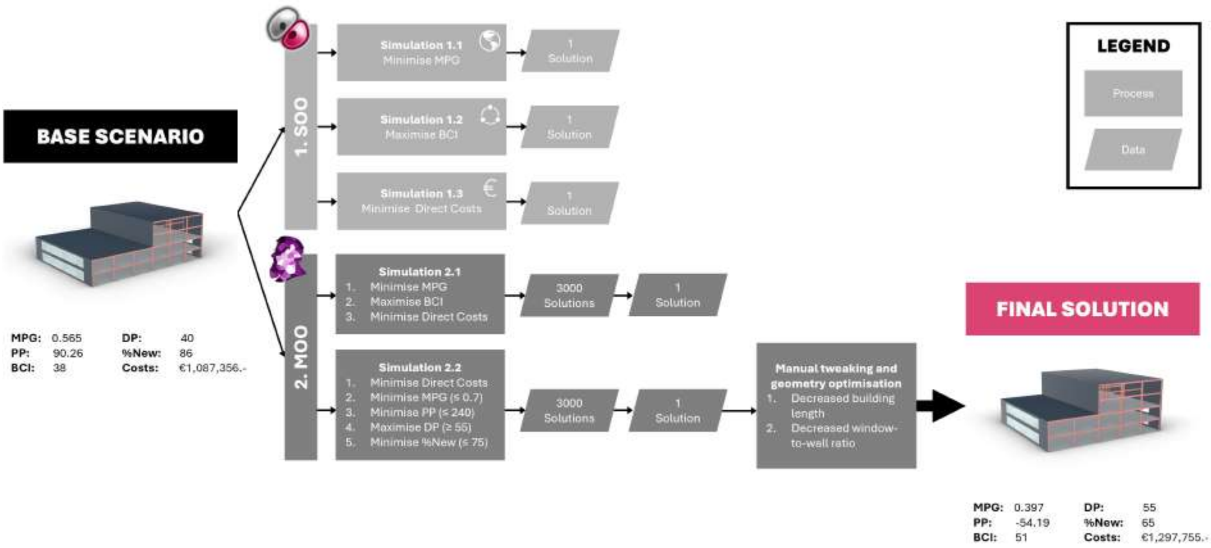


Figure 7.5: Optimisation process for the case study

7.1.4.1 Single-Objective Optimisation

For the SOO optimisations, the Galapagos Grasshopper plugin is used with its simulated annealing solver. This solver is chosen over the evolutionary solver because of its lower computational cost and simplicity, making it more suitable for SOO simulations. The Galapagos setup script for Grasshopper can be found in Appendix H. First, all material sliders from the "Select Material" *ReLifeCycle* components are connected to the genome input. Next, the fitness objective is attached, which is the objective to be minimised or maximised. Afterwards, the Galapagos simulation is run for about 15 minutes, and the resulting solution is explored in the *ReLifeCycle* results interface. In this case, the simulation is run for two to three indicators per responsible material use aspect, resulting in eight simulations. This approach helps to understand how each indicator influences the materials and results. The results of all simulations and their corresponding materialisations can be found in Appendix I. Table 7.6 summarises this analysis by showing the results for one indicator per aspect: the MPG for environmental impact, the BCI for circularity and the direct costs for financial impact. These indicators are chosen as they represent a combination of the other indicators.

Table 7.6: Overview of single-objective optimisation assessment results (one indicator per responsible material use aspect)

Indicator	Minimise MPG	Maximise BCI	Minimise Direct Costs
Environmental impact			
MPG [€ / m^2 GFA / year]	0.311	0.377	0.464
PP [kg CO2 eq. / m^2 GFA]	-62.53	-104.14	39.27
CSC [tonnes CO2]	267.58	459.7	100.46
Circularity			
BCI [%]	40	55	32
DP [%]	45	60	32
Material input			
New [%]	81	57	93
Biobased [%]	18	37	5
Recycled [%]	1	6	2
Reused [%]	0	0	0
Material output			
Landfill [%]	17	6	14
Burning [%]	1	36	7
Recycling [%]	66	58	79
Reusing [%]	0	0	0
Financial impact			
Total direct costs [€]	1,278,320	1,709,015	900,537
Total true price [€]	1,335,439	1,778,417	992,291
Direct costs per m^2 GFA [€]	348	464	245
True price per m^2 GFA [€]	363	482	270

A materialisation list for each simulation in the overview of Table 7.6 is provided in Appendix I.2 Table I.9. In the next paragraphs, the assessment results and materialisations for the SOO simulations will be discussed.

Starting with the SOO optimisations for environmental impact, the optimisation on MPG results in a selection of mostly biobased products, as expected, with one exception: PVC is chosen for the window frame instead of the more sustainable timber option. This unexpected result suggests that PVC may appear less impactful than timber, though this does not align with logical thinking, highlighting the tool's dependence on data quality. Interesting as well is that the Paris Proof (PP) indicator becomes negative, which may seem counter-intuitive. However, this occurs due to the use of biobased materials, which can have a negative impact on the production stages since the adoption of the A2 data set. In the future, the method of the PP might be adjusted to exclude biogenic GWP (Nossek et al., 2023) for this reason. The circularity scores are average with a BCI of 40%, indicating that a design with a low MPG does not necessarily mean that it has a high circularity level. In terms of cost, the MPG-minimised variant seems to perform average as well with a total direct costs of €1,278,320.-, which is in between the costs of the BCI-maximised and cost-minimised variants. Alternatively, optimising on the other environmental impact indicators: the PP and CSC (Tables I.2 and I.10 in Appendix I) also give interesting outputs. An optimisation on the PP will select materials with the lowest carbon dioxide production values, which results in a preference for biobased materials with a high mass such as CLT and a timber structure, since these store the most carbon. This is reflected in the higher costs, €2,360,588.- for the PP-minimised variant. The CSC-minimised variant gives almost the same results but with more biobased materials than the PP variant. So, though the MPG might include the aspects of PP and CSC, an optimisation on each individual indicator gives different results. This highlights the importance of including multiple factors instead of one, to provide a bigger picture. The MPG score might not always be the best indicator to use, this depends on the scenario. If the ambition of a user is to align with the Paris Agreement, the PP is more interesting, if the ambition is to design with as much biobased materials as possible, the CSC is a good indicator to optimise on.

Looking at circularity, an optimisation on BCI gives a score of 55% and a DP of 60%, which is relatively low. This is mainly due to the structural ground floor slab, which is nearly always made of concrete and therefore has only one option in its material set: a reinforced concrete slab. Detailed calculations show that this material has one of the lowest PCIs (24%) and the highest MKI of all elements, making it the most influential factor in the BCI score due to MKI-based weighting. Aside from the lower-than-expected score, the BCI-maximised variant generates a mixed set of biobased and steel materials since these have a high reusability potential. Optimisation for the DP-maximised variant gives the same results as the BCI-maximised variant because the BCI is highly influenced by the DP. The %New-minimised variant selects more biobased variants to increase the %Biobased material input.

Finally, the optimisation on financial impact shows a large difference in results and materials compared to the environmental impact and circularity variants. It results in a total of €900,537.- for direct costs, making it the cheapest variant. However, this also negatively affects the environmental impact and circularity scores. In terms of materials, it results in mostly traditional choices such as a concrete structure. What's interesting, however, is that it still selects timber floor and roof frames instead of expected concrete slabs. This also suggests that the cost estimate data for timber floors is too low, again highlighting the importance of data quality for a good assessment. Optimisation for a True Price-minimised variant gives nearly the same output, mainly because the direct costs will always have the highest share in the calculation of the True Price.

7.1.4.2 Multi-Objective Optimisation

Multi-Objective Optimisation is performed by integrating the Wallacei Grasshopper plugin with *ReLifeCycle* as explained in Section 6. The Wallacei setup script is provided in Appendix H. Two different MOO simulations are run to find an optimal solution for this case study. The first simulation optimises one indicator per aspect: minimising the MPG, maximising the BCI and minimising the direct costs. The second simulation optimises on the direct costs along with all performance indicators from the case study requirements (MPG, PP, DP and %New) while including their performance levels as constraints. Both simulations are analysed and evaluated on the requirements from the case study, and one final solution is chosen as the best. Figure 7.6 outlines the simulation steps. First, Wallacei's optimisation parameters are configured (Appendix I Figures I.1 and I.8). Each simulation runs with a generation size of 30 and a generation count of 100, resulting in an objective space of 3,000 solutions. A larger generation size increases solution diversity, while a higher generation count enhances refinement. This balance ensures meaningful results while limiting the runtime to 30 minutes per simulation. After running the simulations, the Pareto fronts from the final generations are extracted and analysed further in the Wallacei interface. The three to four most promising solutions are then exported and explored using diamond fitness charts and the *ReLifeCycle* results interface, leading to a final solution. The results and selection processes of each simulation are elaborated in the next paragraphs and documented in Appendix I.

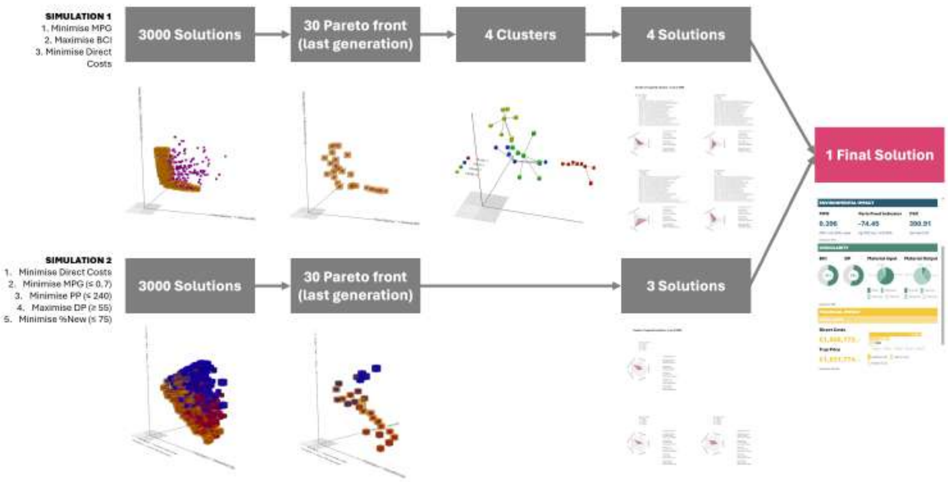


Figure 7.6: MOO process for two simulations

MOO Simulation 1: Optimise MPG, BCI, Direct Costs

The goal of the first simulation is to find a set of balanced solutions that make trade-offs between low-impact, circular materials and traditional, cost-effective materials. No weights are applied to the objectives to avoid biasing the optimisation to a specific preference. Instead, trade-offs are considered during the analysis and selection process after running the simulation. Figure I.2 shows the analytic charts for all solutions from the first simulation. The red lines represent the first generation and the blue lines the last. If we take a look at the Standard Deviation (Std Dev) graphs and trendlines we can see that the early generations show a high variation between solutions (wide Std Dev curves). As the generations evolve, they gradually converge toward more balanced solutions with reduced variation (narrow Std Dev curves). This trend is also reflected in the parallel coordinate plot, where the final generations generally show lower objective scores and fewer peaks compared to the first. For the MPG objective, the Std Dev graph converges to a semi-wide curve, meaning some variation remains. The BCI objective stabilises with a narrower curve, showing more consistent results, while the costs objective ends with the widest Std Dev curve, suggesting a high variation, likely due to material choices impacting costs more than MPG or BCI scores.

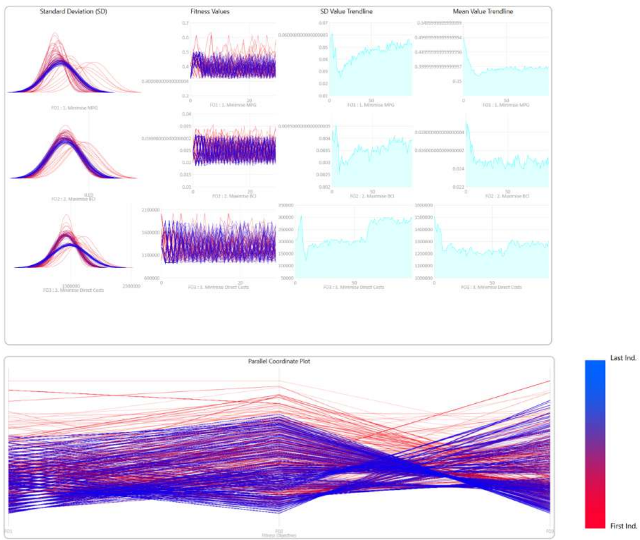


Figure 7.7: MOO simulation 1 analytic charts

To narrow down the number of solutions, the Pareto front of the final generation is extracted and clustered with the built-in K-means algorithm (Figure 7.8). K-means clustering helps group solutions with similar performance and selects a representative solution for each cluster. A common rule of thumb for setting the k-value (number of clusters) is $k = \sqrt{n/2}$, where n is the number of solutions to cluster (Kodinariya and Makwana, 2013). This gives $k = \sqrt{30/2} = 3,87 \approx 4$ clusters. For each cluster, its representative solution is exported so they can be explored in more detail. This can be done in two ways: with the graphs and charts of Wallacei in the Rhino viewport (Figure 7.9a), or with the *ReLifeCycle* Results and Explore interface (Figure 7.9b). In this case, the diamond fitness charts are generated in the Rhino viewport and are used to investigate the general performance of the objectives, as these only show limited results. Afterwards, the solutions are connected to the *ReLifeCycle* Explore interface for deeper analysis and efficient comparison between solutions by looking at their deviation percentages. Based on the results, each solution is given a descriptive name: (1) lowest direct costs; (2) highest direct costs; (3) high BCI, low MPG and (4) balanced. The responsible material use assessment results and materialisation for each solution are provided in Appendix I Tables I.5 and I.13.

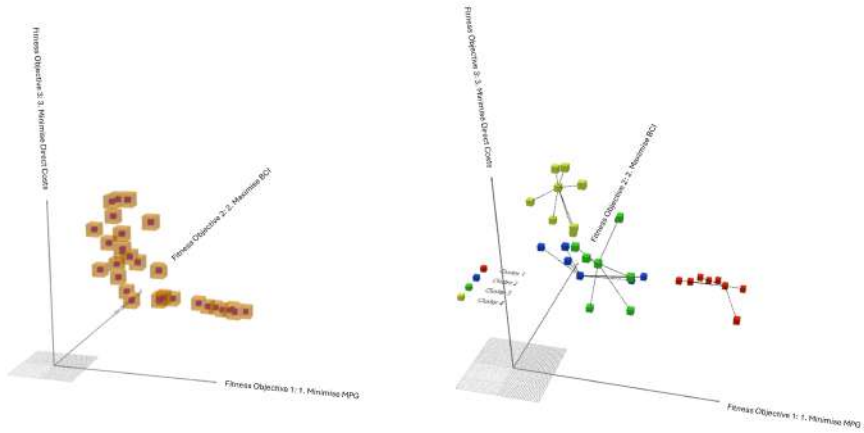
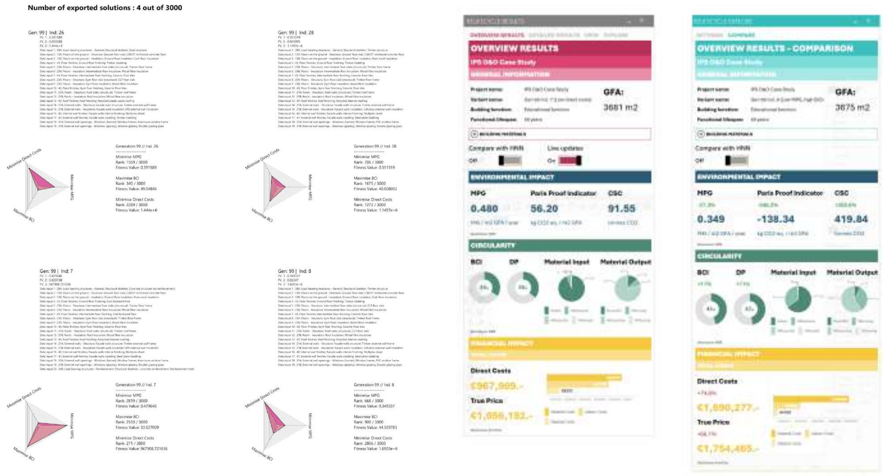


Figure 7.8: Pareto front (left) and clustered solutions (right) for MOO simulation 1



(a) Exploring results in the Rhino viewport

(b) Exploring results in the *ReLifeCycle* interface

Figure 7.9: Two methods for exploring the optimised solutions

In contrast to the SOO simulations, this MOO shows more variety in the material choices. Instead of mostly biobased or mostly traditional materials, it combines both to achieve more balanced results. The assessment results also show a high variety between the selected solutions as seen before in the Std Dev graphs. For instance, the MPG ranges from 0.351 to 0.48, the BCI from 34% to 49% and the costs from €967,909.- to €1,690,277.-. This wide range of results indicates trade-offs between environmental impact, circularity and financial impact, demonstrating that different solutions can weigh these aspects to varying degrees.

Based on the requirements from the case study, the best solution from this MOO simulation would be the "High BCI" solution, as it performs best in terms of both environmental impact and circularity. The MPG and PP meet the performance criteria, while DP and %New slightly exceed them. Although the direct costs (€1,444,039.-) exceed the budget (€1,304,824.-), the difference is relatively small, making this solution a strong candidate. Its materialisation includes a steel structural skeleton, timber floor slabs, biobased insulation materials and a combination of biobased and non-renewable finishings.

MOO Simulation 2: Optimise Direct Costs, Case study requirements

The second MOO simulation uses a different method compared to the first simulation. Instead of optimising one objective for each aspect of responsible material use, it tries to minimise the direct costs while staying within the performance levels of the case study requirements (Table 7.1). These constraints are achieved with Wallacei by simultaneously optimising each performance indicator from the requirements and adding a penalty of 50% of the maximum or minimum boundary of an objective. The Grasshopper script for this can be seen in Appendix H. This leads to the following objectives:

1. Minimise Direct Costs
2. Minimise MPG (≤ 0.7)
3. Minimise PP (≤ 240)
4. Maximise DP (≥ 55)
5. Minimise %New (≤ 75)

The analytical graphs and charts for this simulation can be found in Appendix I.3.2. In contrast to the first MOO, the Std Dev graphs show a low initial variety, suggesting that the constraints significantly limit the search space early on. Over time, this variety is slightly increased as the algorithm explores a wider range of feasible solutions. The most difficult constraints seem to be the DP and %New material, which show sawtooth curves in their fitness value diagrams, meaning that penalties are often given. The Pareto front also shows that, as direct costs are optimised, the DP and %New objectives become less favourable.

To select the best fitting solutions, the K-means clustering algorithm was applied but turned out to be ineffective, since the representative solutions did not satisfy all constraints, which is likely because the number of feasible solutions is limited. Instead, all 30 solutions from the final generation's Pareto front are exported. By investigating their diamond fitness charts (Appendix I.3.2 Figure I.12), and the assessment results in the *ReLifeCycle* interface, three solutions are found to satisfy the constraints and are described as follows: (1) lowest direct costs; (2) medium direct costs and (3) highest direct costs. The results and materialisations of these can be found in Appendix I Tables I.6 and I.14. The solutions show relatively higher costs compared to the first MOO simulation, ranging from €1,558,772.- to €1,818,988.-, because the constraints generate more circular, expensive material sets. The medium costs variant gives the best circularity scores (BCI of 54%, DP of 57%) and the high costs provides the best PP (-133.38 kg CO_2 / m^2 GFA). Overall, the variety between results is relatively small compared to the first MOO, indicating that the simulation has achieved a small set of near-optimal solutions with fewer trade-offs. The material sets are therefore quite similar: a balanced set of biobased and reusable materials with only a few material differences per set.

When we compare the final solutions to the case study requirements, all of them meet the environmental impact and circularity constraints, but none fall within the budget of €1,304,824.-. Therefore, the "Lowest Direct Costs" solution becomes the strongest candidate. This solution includes a steel structural skeleton, CLT and timber frame floor slabs, and a combination of biobased and non-renewable insulation materials.

7.1.4.3 Solution Choice and Manual Geometry Optimisation

From both MOO simulations, one solution was selected. To make a choice, they are compared to the case study requirements in Table 7.7. Because the solution from the second MOO simulation satisfies the most requirements, this one is preferred. However, when we look critically at its material set (Appendix I.15), we see that the intermediate floor slabs are CLT and the gym floor is a timber floor frame. Choosing different structural floor materials is not a practical choice and besides, the gym floor needs to be stronger due to high live loads. Its material is therefore changed to CLT. Consequently, the material of the roof slabs is changed from CLT to timber frame as they need to transfer significantly fewer loads. After manually tweaking the materials, the resulting solution still meets the requirements and minimises the direct costs even further (€1,459,143.-), showing that while MOO can provide a solution close to an optimum, it may not always give the best or most practical outcome.

Table 7.7: Final solutions from the MOO simulations compared against the case study requirements

Indicator	MOO 1 solution	MOO 2 solution	Requirement
MPG [€ / m^2 GFA / year]	0.392	0.396	$\leq$ 0.7
PP [kg CO2 eq. / m^2 GFA]	-29.24	-74.45	$\leq$ 240
DP [%]	53	55	$\geq$ 55
New [%]	78	62	$\leq$ 75
Direct Costs [€]	1,444,039	1,558,772	$\leq$ 1,304,824

Since the costs are still above the budget from the case study, we can try to manually optimise the geometry of the parametric building model. This can also be done by connecting geometry parameters to the genome of the optimisation plugins, however, this will likely result in the smallest building elements possible within the boundaries of the parameters. Algorithmic geometry optimisation is therefore excluded from this validation. Manually changing parameters is more intuitive and incorporates other design aspects as well, such as aesthetics and practicality. So to decrease the costs, we can first use the *ReLifeCycle* interface to see which building elements have the highest impact. By using the colour override function, we can see the results in the 3D model for direct costs in Figure 7.10.

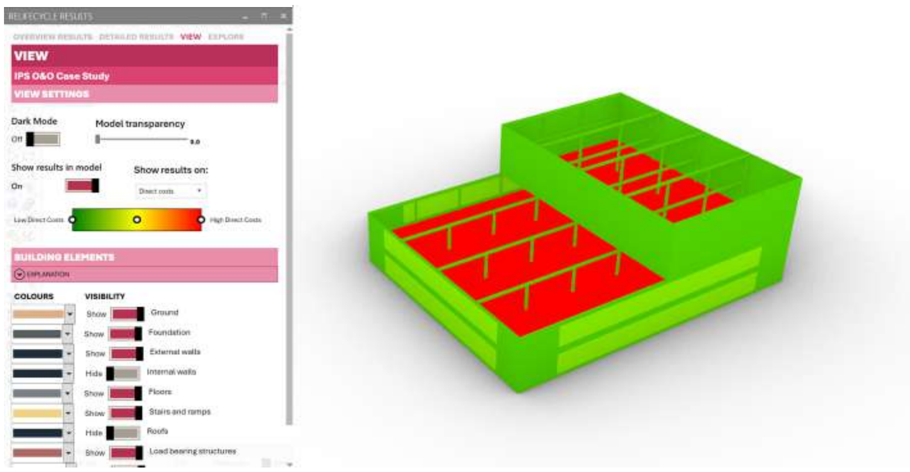


Figure 7.10: Impact on direct costs per building element, visualised in the 3D model with a gradient

We can see that the floor elements have the highest impact on costs. One option to decrease their impact is to decrease the Gross Floor Area (GFA) because the current GFA (3686 m^2) is higher than the asked GFA (3337 m^2). Decreasing the general building length reduces the direct costs to €1,292,273.-, bringing it within the budget. The GFA becomes 3199 m^2, which is 138 m^2 less than asked. In practice, this is something that should be discussed with the client, but for this research, this deviation is accepted as it results in a design with a more responsible use of materials.

To demonstrate how we can even further enhance the responsible material use of the design by adjusting geometry parameters, we can try to lower the environmental impact. For instance, if we show the results on the Global Warming Potential (GWP) for LCA stages A1-A5 (Figure 7.11) it can be seen that the windows have a high contribution. When changing the window-to-wall ratio slightly from 0.75 to 0.7, it reduces the MPG and PP (-51.99 to 54.19) and increases the CSC, leading to the final assessment results in Appendix I.7.

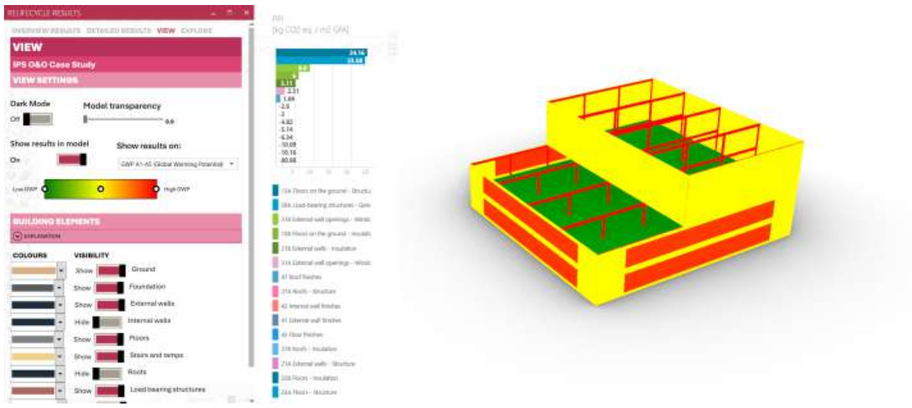


Figure 7.11: Impact on GWP per building element, visualised with a bar chart and in the 3D model

7.2 Expert Opinion

A prototype test was conducted, to gather expert feedback on the user-friendliness and usability of *ReLifeCycle*. This test provided key insights into the strengths and weaknesses of the tool, as well as recommendations for improvement. Three participants, selected based on the user profile, took part in the test. Their expertise varied across structural design, BIM, sustainability and circularity, with all participants having sufficient knowledge of Grasshopper. During the test, the participants were asked to follow the demo script of the prototype and link a roof to the *ReLifeCycle* plugin by creating building elements and assigning materials. Afterwards, they explored the results interface. Next, the integration with Wallacei was demonstrated and ten Pareto front solutions were exported, which the participants analysed and compared using the "Results" and "Explore" windows of the interface. Instead of a survey, the participants were asked to think aloud and provide feedback on the four system packages: Model Linking & Material Mapping, Responsible Material Use Assessment, Results Interface and Responsible Material Use Enhancement. The average runtime of each test session was 90 minutes.

Overall, the participants found the workflow in Grasshopper to be straightforward and intuitive. The demo script and the descriptions of the components provided sufficient guidance for all participants to complete the assignment without help. Participants expressed high appreciation for the intermediate output parameters of components, such as structured material data lists, total mass, area and volume, as these allowed for further processing of the results. One participant even came up with using them in their own workflow by extracting the total mass of the building elements to perform a structural analysis. The structured data tree outputs, which include data for a material set, material, building element, building and assessment, were also positively received. The data descriptions allowed the participants to immediately understand the data.

The *ReLifeCycle* interface was highly appreciated and praised for transforming the rather flat data outputs in Grasshopper into a more accessible overview with clear graphs and charts, enhancing user-friendliness. The ability to view results for environmental impact, circularity and financial impact in a clear and organised manner was noted as helpful for understanding the impact of the building on multiple aspects. The overall interface was found to be intuitive and participants valued its variety of functions. In particular, the ability to see an overview of results, detailed results and results integrated into a 3D model with colour overrides was seen as useful, as it allowed them to better understand the impact of various building elements on different objectives.

The integration between Wallacei and the interface was valued for offering a more user-friendly overview of the optimisation results. The ability to compare the exported Wallacei variants side-by-side within the interface, along with deviation percentages, was particularly appreciated. Participants found this feature more effective for choosing a materialisation than relying solely on Wallacei's interface and results analysis, enhancing the overall design space exploration process. They naturally tried to find solutions that balanced environmental impact, circularity and financial impact and emphasised the intuitiveness of this function, indicating that it helped the exploration of optimised solutions to make a decision.

However, one identified weakness of the prototype was its dependency on the user's input and handling of the GH components. For instance, during the test, a participant tried to flatten and graft data outputs before the assessment stage. The assessment components still ran without warning and therefore gave incorrect results. Another participant linked an incorrect GFA at first, which affected the results of indicators such as the MPG and Paris Proof. So the internal calculations remain a black box trequiresuire careful handling of the components' inputs and outputs. All participants therefore emphasised the need for better documentation of the prototype and its assessment methods, for instance with a manual.

There was also some confusion concerning the GH components that automatically pop up and connect to input parameters, which are the NL/SfB value list for the "Create Material Set" component and the material slider for the "Select Material" component. For some users, it was not clear at first that those inputs require no manual user input, which led to attempts to add values manually, disrupting the component workflow. Additionally, using the material slider to select materials was found to be less user-friendly and concerns were expressed when a larger database with more materials would be used.

Regarding the Wallacei integration with the *ReLifeCycle* interface, participants highlighted that the sole focus on Wallacei limits the use of the "Explore" interface function if they wanted to use a different MOO plugin. While comparing optimised variants in the interface was seen as efficient, one user indicated the lack of a final step for weighing the results and making a final decision. Some participants also noted irregular material combinations resulting from the optimisation process, such as heavy walls on timber frame floors, and expressed the lack of logical relations between materials in the optimisation process.

When asked whether they would adopt *ReLifeCycle* in their own workflow, one participant noted that the tool would be useful for discussions with clients and project teams, supporting design and material decisions and integrating sustainability and circularity already in the early design stages. The participant believed the simplicity of the Grasshopper workflow and quick linking of geometry would make it easy to integrate *ReLifeCycle* into parametric models. However, the participant with structural design expertise mentioned that the tool would be less valuable for their field, since structural analysis models primarily work with GH lines rather than surfaces and volumes.

Finally, several recommendations were given by the participants. One suggestion was to expand the "Create Material Set" function by allowing a user to choose which materials should be included or excluded from the optimisation process. In this way, critical thinking can already be applied upfront, minimising irregular material combinations from the optimisation and also narrowing the amount of material options when a larger database would be connected. Another recommendation was to increase the reusability aspect of circularity by calculating the remaining technical lifespan of building elements at the end of the building's functional life. This would give a user insight into the value of the materials at the end of their lifecycle, potentially opening the door for residual value calculations. Most participants also recommended adding a report function so the results can be communicated in design teams.

7.3 Requirements Evaluation

After validating and testing the prototype, we can evaluate the requirements set up in Section 4. Table 7.8 shows which of the functional requirements have been completed, partially completed or not completed. The statuses of the corresponding non-functional requirements are provided in Appendix J. Two additional requirements are added to Table 7.8 based on recommendations from the expert opinion tool tests; these are made italic and include the abilities to include or exclude materials in a material set, and to see the remaining lifespan of building elements at the end of the building's life. From the original 35 functional requirements, 21 have been completed, 10 have not been completed and 1 has been partially completed. All of the "MUST" and most of the "SHOULD" requirements have been met. One "SHOULD" requirement that remains incomplete is the availability of clear documentation on the used assessment methods of *ReLifeCycle*, which was also highlighted in the expert opinion test. This can be added in the future by creating a manual that is accompanied with the installation of the plugin. Another incomplete "SHOULD" requirement is the option to choose if a material is new or reused. This feature is important to include in future work as it enhances the circularity aspect of responsible material use. It can be implemented by applying benefits to the environmental and circularity calculations when the user indicates that a material can be reused. Finally, two" SHOULD" requirements that are also included in the envisioned system design have not been met: the PDF and Excel report functions. These unfortunately were not possible within the time frame of this research. However, they are important to include to be able to implement *ReLifeCycle* in practice for communicating results between members of the design team. Requirement FR_1.05 is partially met and concerns the insight into detailed environmental, circularity and financial data for each material. This is because, while a user can see this data for each material by connecting a GH "panel" component to the data output of the "Create Material Set" component, this data visualisation is not user-friendly as it is a long list, limited by the "panel" component's UI. Ideally, the user should be able to see the materials and their data in a pop-up interface with search and filter functions to enhance usability. The remaining unmet requirements are "COULD" requirements, features that are desirable but not essential. These could be considered in future developments.

Table 7.8: Functional Requirements Evaluation

ID	Requirement	Priority	Status
	1. Model Linking & Material Mapping		
FR_1.01	The user must be able to link a parametric Grasshopper 3D model to the system	MUST	Completed
FR_1.02	The user must be able to classify building model components	MUST	Completed
FR_1.03	The user must be able to map materials to building model components	MUST	Completed
FR_1.04	The user must see the geometry input requirements for a specific classification/material (line, surface, volume)	MUST	Completed
FR_1.05	The user should have insight into the environmental, financial and circularity data of each specific material to make comparisons during the material selection process	SHOULD	Partially completed
FR_1.06	The user should be able to assign a name to a building element or group of building elements	SHOULD	Completed
FR_1.07	The user won't be able to link a BIM model to the system	WON'T	-
FR_1.08	The user could be able to add a custom material	COULD	Not completed
FR_1.09	The user could link a generic building mass to the system instead of building elements	COULD	Not completed
FR_1.10	The user must be able to see an explanation of the workings of the tool with a demo script	MUST	Completed
	2. Responsible Material Use Assessment		

Continued on next page

ID	Requirement	Priority	Status
FR_2.01	The user must be able to assess the responsible material use of their building design	MUST	Completed
FR_2.02	The user must be able to set required calculation variables	MUST	Completed
FR_2.03	The user should have access to clear documentation of the used assessment methods in the calculation	SHOULD	Not completed
FR_2.04	The user should have the option to choose if a material is new or reused	SHOULD	Not completed
FR_2.05	The user could be able to include or exclude specific life cycle stages	COULD	Not completed
FR_2.06	The user could be able to set a reference date	COULD	Not completed
FR_2.07	The user won't be able to change the calculation methods internally	WON'T	-
FR_2.08	The user won't be able to combine multiple products into elements (prefab/modular units) to calculate the Element Circularity Index (ECI)	WON'T	-
FR_2.09	*The user should be able to see the remaining technical lifespan of a building element at the end of the building's functional life*	*SHOULD*	*Added*
3. Responsible Material Use Enhancement			
FR_3.01	The user must be able to explore a generated set of design variants optimised for responsible material use	MUST	Completed
FR_3.02	The user must be able to set decision variables for the optimisation process	MUST	Completed
FR_3.03	The user must be able to set objective functions for the optimisation process	MUST	Completed
FR_3.04	The user must be able to set constraints for the optimisation process	MUST	Completed
FR_3.05	The user must be able to set a count for the amount of design variations	MUST	Completed
FR_3.06	The user should be able to name, store, and load variants	SHOULD	Completed
FR_3.07	The user could assign weights of importance to the objectives to select one optimal variant	COULD	Not completed
FR_3.08	*The user should be able to select which materials are included or excluded in the materials set for the optimisation process*	*SHOULD*	*Added*
4. Results Interface			
FR_4.01	The user must be able to see an overview of the responsible material use assessment results in a user interface with clear, visual representations	MUST	Completed
FR_4.02	The user must be able to see real-time updates in the results as they adjust design parameters and materials	MUST	Completed
FR_4.03	The user should be able to evaluate the quality of the results by comparing them to reference standards	SHOULD	Completed
FR_4.04	The user should have insight into the investment costs of the design	SHOULD	Completed
FR_4.05	The user should have insight into the results per building element	SHOULD	Completed
FR_4.06	The user should have insight into the results per classification	SHOULD	Completed
FR_4.07	The user could categorise the results based on the layers of Brand	COULD	Not completed
FR_4.08	The user should be able to compare the results of variants from the optimisation process	SHOULD	Completed
FR_4.09	The user should be able to export the results into a PDF report	SHOULD	Not completed
FR_4.10	The user should be able to export the results into an Excel report	SHOULD	Not completed

8. DISCUSSION

This section discusses the *ReLifeCycle* prototype and its results and relates them to the literature review. It begins by discussing the results from the validation on five aspects: (1) accuracy and reliability; (2) impact of optimisation methods; (3) reflection on assessment methods; (4) reflection on data management; and (5) user-friendliness. The section then compares the *ReLifeCycle* prototype to existing digital tooling, highlighting its unique contributions and differences.

8.1 Results Discussion

8.1.1 Accuracy and Reliability

During the validation, *ReLifeCycle* was applied to the case study and compared with benchmark calculations to test the accuracy and reliability of the system. The environmental impact and circularity results showed a high accuracy with minimal deviation percentages. This is mainly due to *ReLifeCycle* using the same databases (NMD and NIBE) as the benchmark calculation. However, inaccuracies in the NMD or NIBE database may have affected both the benchmark and *ReLifeCycle* results, particularly given the recent adoption of the A2 dataset for environmental impact assessments. For instance, it was found that data on the construction stored carbon of cork was missing, a significant benefit of cork that is therefore not considered in both the *ReLifeCycle* and benchmark calculations. This also affected the optimisation simulations and highlights the dependency on data quality for accurate results.

Contrary to the relatively low environmental impact and circularity deviations, the financial impact results deviated significantly from the benchmark, with the total direct costs being 60% lower. One of the main reasons for this is that the financial impact database, ArchiCalc, only gave data for residential buildings, whereas the case study benchmark was done for an educational utility building, for which higher cost estimations are made due to a higher labour requirement. This further emphasises that data quality is of utmost importance for a reliable assessment. In order to provide accurate results, cost data should be updated based on the building function.

Inaccuracies in material mapping between the three databases also influence the results. It was found that rock wool insulation from the environmental database was mapped with wood fibre insulation from the circularity database, causing wood fibre and rock wool to have the same circularity data. This was later manually changed in the database. However, there could be other overlooked inaccuracies that are not accounted for. Additionally, mapping is done by finding the most closely related product, which means this is not always accurate. This was especially the case for mapping the financial database, which lacked many circular and sustainable materials. As a result, biobased materials such as Kerto-Ripa floors were mapped to timber frame floors, which are significantly cheaper. This made them highly favourable in the optimisation simulations due to low scores on all objectives, even though their realistic costs might be higher. Therefore, accurate mapping is crucial for obtaining reliable results.

Furthermore, slight deviations in results with the benchmark were likely caused by the *ReLifeCycle* database assigning a single standard thickness to each material, which can also affect the results. For instance, the chosen standard thickness for structural floor materials could be too high or low for the corresponding span in the design. Also, insulation thickness could be smaller when a lower R-value is desired by a user, which is currently not possible.

Additionally, during the validation, certain building elements were excluded from the benchmark calculation to match the *ReLifeCycle* calculation for the parametric model. However, an additional comparison was made with the raw benchmark calculation, which included all building elements such as installations, to assess the reliability of the results in representing a real-world scenario. This comparison showed us higher deviations, indicating that the exclusion of building elements led to lower scores, which can be misleading. Especially when comparing the results to the performance levels, a score may be below a performance level even though it would actually exceed it in practice. Therefore, the representation of the results for a real-world building depends on the completeness of the parametric model and the materials included in the *ReLifeCycle* database. When building elements are excluded, the scores show the results "so far" for the elements present in the model, meaning the additional impact of excluded elements is not accounted for.

In conclusion, the current *ReLifeCycle* prototype is not yet fully reliable for accurately representing real-world building calculations, primarily due to issues with data quality, material mapping, standard thickness assumptions, and the exclusion of high-impact building elements such as installations. However, as a Design Space Exploration (DSE) tool for responsible material use, it remains valuable, as the results are still useful for comparison, provided that the data is of considerate quality and the ratios between materials are realistic. To enhance its reliability for more accurate comparisons, it is essential to update the financial database to include a broader range of sustainable materials.

8.1.2 Impact of Optimisation Methods

After the assessment benchmark, methods to enhance responsible material use were applied to the case study. To investigate how prioritising environmental impact, circularity or financial impact affects the materialisation and results, multiple SOO simulations were conducted with the simulated annealing algorithm from Galapagos. One representative indicator was selected for each aspect and used as the objective function: MPG for environmental impact, BCI for circularity, and Direct Costs for financial impact. The results were as expected. The environmental impact SOO led to a materialisation of mostly biobased products, while the circularity SOO combined these with high-reusability materials like steel. The financial impact SOO favoured more traditional, cost-effective materials.

Additionally, to find the best solution for the case study requirements, MOO simulations were performed with the Wallacei plugin that uses the NSGA-II genetic algorithm. Two MOO simulations were run to make trade-offs between multiple objectives: the first optimising one indicator per aspect and the second optimising the direct costs and the performance indicators of the case study requirements with their performance levels as constraints. The MOO outperformed the SOO through its ability to achieve more balanced solutions, as well as the generation of multiple solutions that can be explored, aiding the DSE process. The second MOO simulation provided the best solution for the requirements of the case study. However, since materials are only evaluated on the assessment indicators, practical implementation is not considered. This gave some unsuitable materials such as a timber frame for a gym floor. An important step in the optimisation process is therefore to critically look at the results and adjust where necessary. You will always have to think about structural integrity and if combinations of materials make sense. Overall, the MOO process with a genetic algorithm proves useful for DSE and generating initial materialisation variants, especially if the database is expanded beyond the prototype database. The simulation runtime only took 30 minutes, which is more efficient than manually testing different materialisations.

To further demonstrate the advantage of parametric design, the best solution from the MOO simulation was manually optimised on the geometry. The ability to instantly see updated results when adjusting parameters significantly improved the DSE process and resulted in a final case study variant that met all requirements, proving the effectiveness of the MOO optimisation on enhancing responsible material use. However, the number of parameters that can be adjusted to optimise geometry for responsible material use is limited, as most of them relate to design decisions, and geometry optimisation typically leads to minimising the building's size, which is not always preferred. Furthermore, some parameter adjustments even gave misleading results. For example, increasing the floor height in a steel structure variant resulted in larger dimensioned columns and beams, which unexpectedly increased the BCI and DP scores. This happens because of the weighting process: as steel increases in volume, its MKI becomes higher relative to the other materials, causing the beneficial circularity attributes of steel to have more influence on the circularity scores. However, this doesn't necessarily mean that increasing the floor height is the optimal solution. Again, it is crucial to remain critical when interpreting these scores, as their weighting can lead to misleading conclusions. The goal should always be to use as little material as possible, so increasing material quantity to improve circularity scores is not a good approach.

Despite the successful optimisation simulations, a significant limitation must be addressed. A challenge in this research was to include material choice in the optimisation process. Grasshopper optimisation plugins require numerical sliders as genes, whereas materials are categorical variables. To work around this, *ReLifeCycle* uses an integer slider to select materials, which can be connected to the optimisation plugins. However, this causes the optimisation algorithms to assume there is a linear relationship between those numbers. For example, in a set of three materials, the algorithm might interpret material "2" as a midway between "1" and "3" even if that doesn't reflect the actual relationship between the materials. For the *ReLifeCycle* prototype, this was not a major issue, since each material set contained at most three options, but for a larger database, it could significantly skew the optimisation results. Addressing this challenge requires more research.

8.1.3 Reflection on Assessment Methods

In the literature review, the environmental impact, financial impact and circularity aspects of responsible material use were investigated by looking at LCA, LCC and the Circular Economy respectively. In the *ReLifeCycle* assessment framework in Section 5, several methods were selected for each of those aspects. After validation, we can now reflect on their usability and how well they represent LCA, LCC and the Circular Economy.

8.1.3.1 Environmental Impact

For environmental impact (LCA), three indicators were assigned: the MilieuPrestatie Gebouw (MPG), Paris Proof (PP) indicator and Construction Stored Carbon (CSC). An LCA evaluates the environmental impact of a building through multiple life cycle modules by using several environmental impact categories. Depending on data availability and design stage, LCAs can be classified as screening, simplified, or complete (Wittstock et al., 2012). This research uses the MPG and brand-independent data to consider a screening LCA for the early design stages. The MPG is calculated with the MKI which converts the 19 impact categories from the A2 set to monetised shadow cost values for each life cycle module (A-D). By using the A2 set, which is currently being adopted in practice, this research aligns with future LCA assessment regulations. It furthermore includes all life cycle modules and impact categories, considering many different impacts on the environment. However, the MPG has critical limitations. The MKI uses weighting factors to monetise all impact category emissions to a single financial value, which relies on assumptions and may obscure the meaning of the impact categories. For instance, effects such as biodiversity loss or ecosystem collapse cannot be accurately represented in financial costs.

To address this limitation, the PP indicator was included in the assessment framework, which calculates the GWP for the production and construction stages (modules A1-A5) to measure the direct effects of the building on climate change. During the exploration of different materialisation variants in the validation, we saw that a better MPG does not always result in a better PP. An SOO simulation on each indicator gave different results: PP optimisation favoured mostly biobased materials, whereas MPG optimisation also gave less sustainable choices, such as PVC for window frames. A potential reason for this is that the MPG calculation includes life cycle module D, which assigns negative shadow costs to materials with high reuse or recycling potential to apply benefits. However, it should be noted that in reality, this is only the case if the material is actually reused or recycled, meaning the MPG can overestimate environmental benefits. Therefore, it is important to consider both the MPG and PP for assessing environmental impact: the MPG accounts for multiple environmental effects, while the PP serves as a critical indicator that highlights the direct effect on climate change and ensures better alignment with the Paris Agreement. One limitation of the PP that should be acknowledged, is that it can give negative values when using the A2 dataset, which now includes negative biogenic GWP in the production stage for biobased materials. Ongoing discussions propose adjusting the official PP method to exclude biogenic GWP to prevent negative values (Nossek et al., 2023). If adopted, this change could affect the interpretation of PP results, potentially making those from this research outdated.

Finally, CSC was included to represent positive environmental impacts by considering carbon stored in biobased materials. Maximising CSC in the SOO simulation gave similar material choices as minimising the PP, making the CSC less relevant for optimisation. It therefore has more value for presentation, as it provides insight into environmental benefits and encourages the use of biobased materials.

8.1.3.2 Financial Impact

To measure financial impact, LCC was explored in the literature, which follows the same principles as LCA but focuses on costs rather than environmental impact. However, due to limited data availability, the assessment framework only includes material and labour costs, covering the product and construction stages (A1-A5). While it gives a good indication of the direct costs, it limits the integration between LCA and LCC, as the MPG considers all life cycle modules, whereas the direct costs exclude the use and end-of-life stages. To improve integration, the True Price was introduced. It combines the MKI from the environmental impact assessment with the direct costs to provide insight into the actual societal costs of the building. Although optimisation on the True Price in the SOO gave no different results compared to optimising direct costs, the True Price's primary goal is for a user to become conscious about the resulting financial consequences of the environmental damage of a design.

Furthermore, the financial impact assessment is limited in that it only provides insights into the direct costs of materials, while overlooking their potential value at the end of their life. As a result, sustainable and circular materials often perform worse than traditional materials on costs, making them less attractive from a financial viewpoint. To provide a more comprehensive perspective, the residual value should be included in the financial impact assessment to highlight the long-term economic benefits as well.

8.1.3.3 Circularity

To represent Circular Economy aspects, the Building Circularity Index (BCI) was used, along with material input and output flows and the Disassembly Potential (DP). This method was found to be the most comprehensive C-indicator compared to the circularity KPIs in Table 2.4, based on the C-indicator reviews of Khadim et al. (2022), Shivakumar (2021) and Zhai (2020). Only adaptability potential and use of renewable energy are not considered. The BCI addresses additional important circularity concepts introduced in the literature such as slowing, closing and narrowing the loop (Bocken et al., 2016) and the butterfly diagram (Ellen MacArthur Foundation, 2019). Slowing the loop involves keeping materials in use as long as possible, mainly through design for disassembly and reuse. This is reflected in the BCI by considering the reusing potential and the DP. Closing the loop focuses on recycling, which is represented by the recycled material input and recycling potential in the BCI. Narrowing the loop is about constructing more efficiently and minimising waste, which is captured by calculating the material output going to landfill or incineration. The biological cycle of the butterfly diagram is considered by calculating the percentage of biobased input, with higher percentages leading to higher circularity scores.

In essence, the BCI covers all circularity strategies and adopts the butterfly diagram concepts. However, the results from the validation should be viewed critically. For instance, the percentages of reused material input were always zero in the database, due to difficulties in determining the reuse source for materials. Since reusing is one of the most important circularity strategies, this is a significant limitation for the circularity assessment of this research, as it weakens the integration between environmental impact and circularity. To address this, users should be able to specify whether a material is reused. If this is the case, the percentage of reusable material input should increase, while environmental impact indicators, such as the MKI, should decrease. Nicholson et al. (2009) propose several methods for allocating environmental impact across multiple life cycles, which should be considered for further research.

Finally, it is important to discuss how the circularity scores are weighted for the total building. The literature review identified three potential weighting methods: volume, mass and MKI. This research uses both the mass and MKI methods. The BCI and DP scores are weighted by their MKI from the environmental impact assessment. This integrates environmental impact into the circularity assessment, ensuring that high-impact materials have a greater influence on the results. In contrast, mass-based weighting would cause the heaviest materials to have the most influence, regardless of their environmental impact. This research therefore favours weighting the BCI and DP by MKI, because addressing high-impact materials first is crucial for sustainability. However, it should be noted that the positive contribution of circular materials on the other hand, such as timber, is somewhat limited with this method. The material input and output flow percentages of the total building are weighted by mass, as this approach directly reflects the physical quantity of materials in the building, which is what the original percentages are based on.

8.1.4 Reflection on Data Management

Although the *ReLifeCycle* MySQL database links data from the NMD, ArchiCalc and NIBE databases, this data remains static as no direct connection is made with the source databases. Instead, CSV files are downloaded and imported into the MySQL database schema. As a result, data is not updated automatically, which can affect the accuracy and reliability. Additionally, the MySQL schema relies on the structure and attributes of the source databases. This means that adding new attributes to improve *ReLifeCycle's* functionality can be challenging. Moreover, any changes to the source database structures could potentially break the *ReLifeCycle* database, ultimately disrupting the tool's functionality.

8.1.5 User-Friendliness

User-friendliness of the *ReLifeCycle* prototype was tested by presenting it to experts in the field of parametric design. The experts found the overall prototype to be user-friendly, with an intuitive workflow that allowed them to complete tasks with limited guidance. Especially appreciated were intermediate data output parameters that extend the functionality of the tool beyond one fixed workflow, an appreciated feature among Grasshopper users. The *ReLifeCycle* user interface was praised for clearly visualising the assessment results in understandable graphs and charts, providing a more accessible alternative to viewing the results within Grasshopper "Panel" components. Its numerous functionalities and ability to view results on multiple levels allowed them to quickly see high-impact building elements and make adjustments to parameters and materials accordingly.

However, the test also highlighted the dependency on user input for accurate working of the tool. The *ReLifeCycle* components work together, so when they are connected in a different order or when intermediate data outputs are modified, this affects the assessment, leading to inaccurate results. This emphasises the need for clear documentation and implementation of warnings when incorrect inputs are given. Additionally, scrolling through materials with a slider was considered confusing and not user-friendly, posing a problem when the database is expanded with more materials.

Finally, the integration with Wallacei and the *ReLifeCycle* user interface was seen as an added value for the DSE process and supported the experts in selecting a suitable material variant. However, the limitation of the interface to Wallacei, excluding other optimisation plugins, was noted as a drawback for user-friendliness.

8.2 Comparison with Existing Digital Tooling

The literature review explored state-of-the-art digital tools related to responsible material use assessment. This was summarised in an evaluation of parametric design tools for LCA, LCC and circularity in Table 2.5 and the literature timeline in Figure 2.23. In the review, a distinction was made between general BIM tools and parametric design tools. The following paragraphs provide a critical comparison of the *ReLifeCycle* prototype with these tools, highlighting its unique contributions and limitations in the context of responsible material use assessment.

To begin, a summary of contributions from the literature is provided. In the field of BIM, tools such as MPG-ENVIE (van Gemert, 2019), the proof-of-concept from Röck et al. (2018) and CNET-DA & BEE (van den Biggelaar, 2022) focus mainly on integrating BIM with LCA, where van den Biggelaar did this in the field of refurbishment with a web-based application. Kaltenegger (2021) not only focused on LCA, but also added financial impact for refurbishment packages with the ROTUNDORO web-based tool and van Oeveren (2020) developed LEICAS, a tool for integrating LCA with LCC for IFC models. BIM tools for evaluating circularity are BCAS (Zhai, 2020), which uses an adjusted BCI method and BWPE (Akanbi et al., 2017) for assessing the salvage performance of structural materials. Shivakumar (2021) integrated both LCA with circularity in a BIM tool for Revit and Atta et al. (2021) integrated both in a material passport tool. The first to integrate all three aspects of responsible material use, LCA, LCC and circularity, was Karabinar (2021), who developed CECC for Revit.

In the field of parametric design, Hollberg (2016) was among the first to integrate LCA within a parametric workflow by developing CAALA, a Grasshopper tool for calculating embodied and operational environmental impact. The ZEB-tool from Lobaccaro et al. (2018) used a similar approach and used SOO and MOO plugins to optimise building geometry on energy and embodied impact. Säwén et al. (2022) and Dervishaj and Gudmundsson (2024) both did comparative studies of existing parametric tools for LCA, LCC and circularity, which were evaluated in Table 2.5. A promising tool is the Grasshopper plugin of One Click LCA (Apellániz et al., 2021), which calculates the GWP for a parametric building using a large variety of environmental databases. Apellániz et al. also integrated One Click LCA with SOO and MOO plugins to minimise material usage while considering the GWP, costs and structural integrity. Several Grasshopper plugins, such as Bombyx and Tortuga, extend on this plugin by performing a full LCA assessment, including impact categories beyond just GWP. However, most parametric tools focus primarily on LCA and lack the financial impact and circularity aspects of responsible material use. Therefore, a parametric tool that integrates all three aspects does not exist. Reisinger et al. (2022) did provide a parametric framework that covers LCA, LCC and circularity (including flexibility and recycling potential), which focused on structural design and the recommendation to apply the framework to whole building assessment.

Compared to these prior tools, *ReLifeCycle* is the first of its kind to integrate LCA, LCC and circularity for a whole building by using parametric design in the early design stages, bridging the research gap. This unique contribution is not found among existing Grasshopper plugins and studies, which focus mainly on LCA. Compared to the CECC BIM tool from Karabinar (2021), which does integrate LCA, LCC and circularity, *ReLifeCycle* offers a new perspective by using parametric design to support the DSE process, allowing a user to efficiently compare different design and materialisation variants already in the early design stages. It further builds upon the framework from Reisinger et al. (2022) by extending its use to a whole building assessment instead of a structure, and by integrating more circularity aspects, such as design for disassembly, reusing potential and amount of biobased input. Furthermore, while many LCA Grasshopper plugins have been integrated with MOO plugins (CAALA, ZEB-tool, One Click LCA), these primarily involve optimisation on geometry shape, structural dimensioning and building orientation, and do not address optimisation of material choices. This is a significant gap for optimising responsible material use and enabling a more material-driven design. *ReLifeCycle* bridges this gap by providing a smart filtering workflow that creates a set of suitable materials for a building element. Users can then select a material using an integer slider, which can be fed as a gene into optimisation plugins. This allows users to also include material choice as a decision variable, next to geometry parameters. Although using an integer slider to represent categorical variables presents challenges, as previously discussed in the reflection on optimisation methods, it still provides a new contribution to the field of responsible material use enhancement.

On the other hand, parametric design tools such as One Click LCA perform better in user-friendliness when it comes to material selection. They provide users with a clear list of materials to choose from, rather than a slider. The Grasshopper plugin Cardinal LCA enhances this even further by displaying a separate interface for viewing, filtering and selecting materials. Most Grasshopper LCA plugins also offer a user the ability to add custom materials, something that is lacking within *ReLifeCycle*. Additionally, Bombyx, CAALA and the ZEB-tool include operational environmental impact during the use stage, an important consideration for comprehensive assessments that *ReLifeCycle* does not currently address. Compared to the general BIM tools, one limitation of *ReLifeCycle* is its exclusive use within Grasshopper and Rhino, with no integration into the standard IFC format. This misses the opportunity to use *ReLifeCycle's* responsible material use assessment results to assign material passports to building elements, as Atta et al. (2021) did for a BIM model. Furthermore, where Kaltenegger (2021) and van den Biggelaar (2022) focus on refurbishment, *ReLifeCycle* focuses on new construction only. Refurbishment, however, is generally the better option in terms of environmental impact and circularity, highlighting a key difference between these tools.

9. CONCLUSION

This final section concludes the research on enhancing responsible material use in the early building design stages through parametric design. It begins by outlining the contributions of this research, followed by an elaboration on their significance and meaning and an answer to the research question. Finally, the limitations of this research are highlighted and recommendations for further research are given.

9.1 Contributions

The main contribution of this research is the development of a prototype for *ReLifeCycle*, a parametric Design Space Exploration (DSE) tool for enhancing responsible material use in the early design stages. This contribution can be divided into four key results of this research: (1) Integration Between LCA, LCC and Circularity for Assessing Responsible Material Use; (2) Relational Database Model for Linking Material Data; (3) Multi-Objective Optimisation (MOO) for Supporting DSE and (4) User-Centered Design for Effective Visualisation. The following sections will elaborate on these results and how *ReLifeCycle* achieves them.

9.1.1 Integration Between LCA, LCC and Circularity for Assessing Responsible Material Use

Responsible material use in this research is defined by the integration of three aspects: environmental impact, financial impact and circularity. *ReLifeCycle* assesses these aspects by facilitating an integration between LCA, LCC and circularity. The prototype achieves this with an integrated assessment framework of multiple indicators representing each aspect. For environmental impact (LCA), the MPG is used to consider various environmental impact categories across multiple life cycles, monetising them into a single score based on shadow costs, which facilitates comparison between building variants. However, since shadow costs do not always accurately reflect environmental impact, the Paris Proof indicator complements the MPG by specifically assessing the impact on climate change in the production and construction stages. Construction Stored Carbon is also included as a beneficial indicator for environmental impact, encouraging the use of biobased materials. Financial impact (LCC) is mainly represented by direct costs, which include material and labour costs, providing insight into price differences between materials. To further integrate environmental aspects, the True Price is included in the framework as well, which combines direct costs with shadow costs, helping users to become more conscious about the actual societal financial impact of a design and encouraging them to consider more sustainable materials. Circularity is measured through the Building Circularity Index (BCI) to express the circularity of a building in a single score that allows for efficient comparison of building variants. The BCI covers important circularity strategies such as reusing, recycling, the use of biobased materials, and design for disassembly. Acknowledging that the concept of circularity is too complex to be expressed in a single score, this research considers additional sub-indicators of the BCI, including material input and output flows and the Disassembly Potential (DP). Presenting these indicators together provides insight into circularity from multiple angles. To calculate the total building circularity scores, this research proposes using the MKI to weigh the BCI and DP indicators to integrate environmental impact and prioritise high-impact materials. For the material input and output flows, a mass-based weighting method is favoured as this directly reflects the physical quantity of materials in the building, aligning with their original data based on mass.

By combining these indicators, *ReLifeCycle* effectively integrates LCA, LCC and circularity, allowing users to explore the multi-objective design space of responsible material use and make informed trade-offs between different environmental, financial and circularity objectives. Additionally, this research incorporates performance levels for several indicators, allowing users to evaluate whether their designs align with sustainability and circularity goals, such as the carbon budget set by the Paris Agreement.

9.1.2 Relational Database Model for Linking Material Data

A robust assessment of responsible material use requires effective linking and management of environmental, financial and circularity data. *ReLifeCycle* addresses this need by implementing a relational database model in MySQL. This database model contains database tables for environmental impact, financial impact and circularity respectively. In the case of the *ReLifeCycle* prototype, the NMD is used for environmental data, ArchiCalc for financial data and NIBE for circularity data. These databases are linked by manually mapping closely related materials to a primary material in the NMD database, thereby enriching the material data. By hosting the MySQL database on a server, the *ReLifeCycle* Grasshopper plugin can establish a direct dynamic connection with the material database, ensuring any changes in data within the *ReLifeCycle* database are immediately reflected. However, it should be noted that this connection only applies to the *ReLifeCycle* database itself. Since no direct link with the source databases is established, any updates in source data are not automatically reflected and require manual updating. In terms of classification, the database model categorises materials according to the NL/SfB classification system, allowing *ReLifeCycle* to filter materials only suitable for specific building elements. This approach supports the material selection process and creates material sets, which are convenient for material choice optimisation. Ensuring accurate assessment results depends not only on the structure of the database model, but also relies heavily on the quality and availability of data, as well as careful mapping of materials. Inconsistencies or missing data can lead to misleading results.

9.1.3 Multi-Objective Optimisation for Supporting DSE

To support the DSE process and enhance responsible material use, the *ReLifeCycle* prototype was integrated with a Single-Objective Optimisation (SOO) and Multi-Objective Optimisation (MOO) plugin to optimise on material. Automated optimisation on geometry was not considered in this research, as this would always result in the smallest building possible within the design space parameters. Between SOO and MOO, the MOO approach stands out as the most promising for finding a balanced solution. In this research *ReLifeCycle* was integrated with the Wallacei MOO plugin for Grasshopper, which applies the genetic NSGA-II algorithm. The system design of *ReLifeCycle* enables this integration and makes it possible to optimise on material choice within Grasshopper. By creating material sets based on NL/SfB classes, *ReLifeCycle* ensures that only suitable materials are considered during optimisation. An MOO simulation on all objectives results in a Pareto front of optimised materialisation solutions that balance environmental, financial and circularity aspects. These solutions can be effectively explored by comparing their responsible material use assessment results side-by-side in the *ReLifeCycle* user interface. Validation with a case study showed that the MOO proved effective in finding design solutions that enhance responsible material use while remaining feasible within a user's constraints. Furthermore, the optimisation process greatly reduced the time needed to explore material choices compared to manually selecting materials. However, to come to a final variant, it remains important to think critically about the generated materialisations, as practical implementation and human expertise are not considered by the optimisation algorithm.

9.1.4 User-Centred Design for Effective Results Visualisation

Finally, to effectively present the assessment results to users, this research emphasises the importance of user-centred design. The *ReLifeCycle* prototype considers this by developing an intuitive user interface that can be connected to the assessment results of the Grasshopper plugin. This interface visualises the results on multiple levels: total results on the building level and detailed results on the building element and NL/SfB classification level. It uses different visualisation techniques including an overview of the most important results, bar charts for finding high-impact building elements that require attention, and the option to enable a colour override in the 3D model that visualises for different indicators, which elements in the model have the highest impact. After testing, experts in the field of parametric design and sustainability highly appreciated the interface for its ability to efficiently communicate the results. The various functions also allow the user to explore the design space in detail and respond to the results by changing parameters and material choices. This improves the otherwise flat data outputs in the Grasshopper interface. Additionally, a connection between the interface and the Wallacei MOO plugin was established and proved effective in supporting the DSE process even further, allowing users to make efficient trade-offs between material variants.

9.2 Findings

In the introduction of this research, four research problems were identified: (1) the neglect of responsible material use in building design due to a lack of knowledge among design-related decision-makers and a predominant focus on form- and cost-driven design; (2) the lack of integration between LCA, LCC and circularity in existing tools; (3) the tendency for assessments to occur in the final design stages, where material changes are difficult; and (4) the need for support in design space exploration of responsible material use. These problems were translated to the following research question:

"How can the responsible use of materials in a building be enhanced in the early design stages through parametric design?"

This research states four key findings to address this question: (1) Advancing Parametric Design for Responsible Material use; (2) Optimisation as a Means, Not an End; (3) Implementation Into Early-Stage Design Workflows; and (4) Shifting from Form and Cost-Driven to Material-Driven Design. The following sections discuss these findings and their significance and meaning for the scientific and practical fields.

9.2.1 Advancing Parametric Design for Responsible Material Use

This research acknowledges the existing literature and tooling regarding BIM-based LCA, LCC and circularity assessments, but argues that parametric design offers a more suitable method for the early design stages. *ReLifeCycle* contributes to this field by introducing a novel use of parametric design to enhance responsible material use. On one hand, it integrates LCA, LCC and circularity assessment methods into one comprehensive tool, addressing a gap in state-of-the-art tools, that tend to focus primarily on LCA, and therefore overlook complex trade-offs between environmental impact, financial costs and circularity. *ReLifeCycle* therefore contributes to this gap, and as the name suggests, Re-evaluates LCA by integrating LCC and circularity. However, *ReLifeCycle* goes beyond providing just integrating assessments. It incorporates material selection in the DSE process by embedding material choice directly as a parameter into the optimisation process itself, not just as a static input for assessment. So where most research and existing tools stop at assigning materials and calculating results, *ReLifeCycle* goes a step further and uses optimisation plugins to perform material-driven optimisation that supports the DSE process in finding balanced material combinations across the multiple objectives of responsible material use. Furthermore, the ability of parametric design to generate many design variants in a short time, makes the DSE process highly intuitive, allowing design-related decision-makers to become more conscious of the effect of various design changes on LCA, LCC and circularity, ultimately guiding them to use materials more responsibly. The scientific relevance of this lies in the novel application of parametric design to generate material-driven recommendations that, overall, improve sustainability and circularity from the earliest stages of design. *ReLifeCycle* therefore demonstrates that parametric design does not have to be limited to exploring form and geometry; it also has significant potential to enhance responsible material use, opening new doors for future research in this area.

9.2.2 Optimisation as a Means, Not an End

While this research shows that, in theory, optimisation algorithms have the potential to enhance responsible material use, they also raise a critical question: what are we truly trying to optimise for? The answer depends on the specific design context and requirements. Designers must ask themselves: do I primarily optimise for environmental impact, costs, circularity, or a balance of all three, and until what point should the optimisation continue? More importantly, does it result in an actual more circular and sustainable design in reality? This research emphasises that the outcome of an optimisation should not be seen as a perfect solution, but rather as a tool to support the DSE process until it provides an initial materialisation variant that users can further adjust. It will always remain essential to use human expertise to evaluate the optimisation results. As seen in the validation of *ReLifeCycle*, some material combinations generated by the optimisation were impractical. Critically looking at these combinations and adjusting such irregularities should always be an important step in the optimisation process. Furthermore, while the optimisation proved valuable in improving the assessment results, it remains a black box. Its success heavily relies on the quality of the material data and the assessment methods in reflecting real-world scenarios. Poor data quality can lead to misleading optimisation results. Simultaneously, concepts such as environmental impact and circularity are complex and not all aspects are measurable. Even with advanced optimisation, responsible material use cannot be reduced to a computational problem; it requires critical human judgement and a broader contextual understanding for making solid design decisions. This research therefore emphasises the importance of using optimisation as a means for enhancing responsible material use, and not as an end.

9.2.3 Implementation Into Early-Stage Design Workflows

Aside from contributions in the theoretical field, *ReLifeCycle* has significant practical implications for early-stage building design, from pre-design to sketch design. Its implementation at these stages is expected to enhance both responsible material use and the efficiency of the design process. By integrating LCA, LCC and circularity early on, *ReLifeCycle* can have a high influence on material decisions, ultimately leading to the use of more circular and sustainable materials before design changes become more difficult and expensive. Furthermore, the parametric way of designing lends itself perfectly to early-stage design processes, as a large variety of design variants can be quickly explored along with their responsible material use. This greatly enhances the efficiency of the design process as traditional LCA, LCC or circularity assessments often take weeks for one design variant. *ReLifeCycle* therefore would be most beneficial for decision-makers that have an influence on the materialisation of the design such as architects, engineers and consultants. The envisioned workflow begins with parametric design being used to generate a variety of design and material variants that can be discussed with the client or members of the design team. By integrating *ReLifeCycle* into this process, environmental, financial and circularity aspects of these variants are made visible. With the user interface, not only Grasshopper experts are able to interpret the results, but also users with no parametric design expertise, making it an effective means of communication. The design and objective spaces can then be explored, optionally with the help of MOO plugins, to come to an initial design and materialisation variant. Once a preferred variant is chosen, it can be further developed in the detailed and construction design stages. However, a challenge of implementing *ReLifeCycle* is the limited adoption of parametric design in practice. Parametric design skills with Grasshopper are a requirement for the correct use of the tool, which may be a barrier to decision-makers. To address this, *ReLifeCycle* should initially be implemented into the workflows from the early adopters, organisations in the field that already apply parametric design. By showcasing examples of successful implementations in projects, awareness can be raised about the benefits of parametric design for sustainability, potentially encouraging wider adoption across the industry.

9.2.4 Shifting from Form- and Cost-Driven to Material-Driven Design

The introduction highlights the primary focus of architects on form and contractors on costs during the early design stages, guided by the principle of 'sustainability follows form, follows costs'. With *ReLifeCycle*, this research emphasises the need for a paradigm shift toward a more material-driven approach in early design to enhance responsible material use. If we don't make this shift now, it will inevitably become a necessity due to resource scarcity, which must be avoided at all costs, as this could lead to negative environmental consequences that affect both the built environment and society at large, including environmental degradation and supply chain disruptions. We can avoid resource scarcity by actively addressing this issue and carefully considering the materials we use in the early design stages, their environmental impact, where we source them from and what we do with them at the end of a building's life. To establish this shift, this research advocates for the use of digital parametric tooling such as *ReLifeCycle* to evaluate, explore and optimise material variants on their environmental impact, financial impact and circularity during the early stages. These tools provide contractors with greater insight into the long-term benefits of sustainable and circular materials, including reduced environmental impact, reusability and disassembly potential, encouraging them to look further than costs. For architects, this requires a shift in mindset: designing with responsible materials as a foundation, allowing form to emerge from that base. Architects that already design with Grasshopper would benefit significantly from *ReLifeCycle*, which can be seamlessly integrated with their design process from the beginning, supporting this shift in mindset. Furthermore, to truly transition to a material-driven design approach, we must aim to include reused materials from demolished buildings in the early design stages. Achieving this requires better alignment between reused material demand and availability. Currently, material orders are typically made in the late design stages, making it difficult for contractors to reserve and reuse materials in time. Therefore, reused material reservations should be made possible in the early design stages, which can be achieved by establishing digital databases or platforms for material availability data. Finally, to further encourage contractors to adopt a material-driven approach, a cultural shift is needed, supported by stricter regulations about environmental impact and circularity in contractual agreements and tendering processes. This would urge contractors to already consider responsible material use early on.

9.3 Limitations

Throughout this research, various issues and difficulties were encountered, some of which could not be resolved at the present time. These limitations have been addressed in the discussion and this section highlights the five most significant ones.

Firstly, the accuracy and reliability of the assessments have a high dependency on the quality and completeness of the data and the calculation methodology. The results of the validation showed several issues with data quality. The most significant one is that the financial database lacked accurate cost-estimations of many sustainable and circular materials, as well as its limitation to residential construction, whereas the validation was done for utility construction, leading to high deviations from the benchmark calculation. Other encountered issues included missing data points and wrong material mapping between databases, also leading to inaccuracies. Additionally, several assessment indicators are weighted to come to single scores, which can obscure underlying trade-offs. Furthermore, it should be noted that the Paris Proof indicator method is currently under review for potential adjustments (Nossek et al., 2023), which could make the results of this research outdated in the future. So these factors highlight *ReLifeCycle's* dependency on data quality and the chosen assessment methods for providing accurate and reliable results.

Secondly, the accuracy of the assessment results in representing real-world scenarios is further affected by the simplification of the building model, particularly due to the exclusion of certain building elements. *ReLifeCycle* excludes several building element types from the database, including installations which have a major environmental impact. This results in lower scores than what would be in reality. It is also dependent on the amount of detail in the parametric model of the user. The fewer building elements are included, the more the results will deviate from realistic results. Furthermore, for simplification, it was chosen to assign a single standard thickness to each building element in the database that cannot be adjusted. Although this prevents users from having to manually change thickness per material, it will not always give a correct thickness for the actual building due to changes in spans, load-bearing capacities or insulation demands. So, due to both data inaccuracies and building model simplifications, it is important to note that *ReLifeCycle* is not a fully reliable tool for accurate real-world calculations. Instead, it primarily serves as a DSE tool, that is better suited for comparing variants.

Thirdly, a limitation in the circularity assessment is the insufficient consideration of reusability. Though *ReLifeCycle* provides insights into the disassembly and reusability potential for a material's output, it does not contain data about how much is reused of the material input, as this is not standardly included in circularity databases due to the unknown source of the material. This significantly reduces the circularity aspect of *ReLifeCycle* as reusing is one of the best strategies for achieving a Circular Economy.

Fourthly, *ReLifeCycle* uses numerical sliders to represent categorical material variables in the optimisation process. These sliders imply that there is a linear relationship between the materials, while the distance between the values is actually meaningless. This might have skewed the optimisation results and becomes an even more significant problem when a larger database is used with more material options per building element. This asks for additional research on how to represent categorical material variables with Grasshopper optimisation plugins.

Finally, although a dynamic MySQL data server is used to send material data to the *ReLifeCycle* Grasshopper plugin, the data itself remains static, as no direct link is made with the source databases (NMD, ArchiCalc and NIBE). This is a significant limitation in terms of data management, as data is not automatically updated when the source databases change, reducing data accuracy and reliability. To address this issue, *ReLifeCycle* should develop a more robust database model that makes a direct link with the source databases. Additionally, this database model should be designed to accommodate potential extra data attributes that are independent of the source databases, enabling future expansions of *ReLifeCycle's* functionality.

9.4 Recommendations

Based on the findings and limitations of this research, the following recommendations are made for further research and development.

One way to address the limited implementation of reusable material input in *ReLifeCycle's* circularity assessment, is to explore the integration of reused materials sourced from urban mining hubs and material banks. These collect usable construction materials from building demolition and redistribute them for reuse in new projects. To implement this, *ReLifeCycle* can be extended to allow users to add custom reused building elements, that they know are available from urban mining. This would require data such as dimensions, costs and LCA and circularity attributes on these elements. Best would be to investigate the possibility of integrating this data directly from digital material passports (Bnext.nl, nd; Madaster, nd). By including reused materials into *ReLifeCycle's* responsible material use assessment, their circularity scores can increase, while their environmental scores decrease. However, further research is required to determine exactly how much environmental impact can be reduced when reusing materials. One possible approach is to allocate the environmental impact over the total technical lifespan of a material. In this case, the impact of a reused material could be reduced in proportion to the remaining lifespan after its initial use.

Building on this, it is also worth exploring how parametric design can be used to its advantage for designing with reused materials. Suggested is to use the generative power of parametric design to develop a script or tool that checks if a building design variant is compatible with the dimensions and properties of selected reused building elements from urban mining hubs and material banks. If the design is not suitable, the tool could automatically generate alternative design configurations that fit these elements. This could further support the use of parametric design for responsible material use.

Another way to improve the reusability aspect of *ReLifeCycle* would be to assess the financial residual value of materials at the end of a building's lifespan. The residual value represents the estimated price at which materials can be sold for reuse or recycling. By including this in *ReLifeCycle*, a new perspective is offered on long-term cost savings, which is interesting for contractors to see a recovery of their initial material investments. This would further encourage cost-driven contractors to consider more sustainable and circular materials, which may require a higher initial investment but offer significant savings in the long term. This approach would also simultaneously promote the reuse of materials at the end of a building's lifespan.

Additionally, to enhance the implementation of *ReLifeCycle* in the design process, research into a BIM connection is recommended. In the introduction of this research, BIM tools were considered unsuitable for the early design stages due to their rare use in these phases. However, this makes them particularly suitable as a next step after *ReLifeCycle*. Beyond functioning as a design space exploration tool, *ReLifeCycle* could also be extended to generate material passports. These passports could be created directly from the assessment results and the Grasshopper model, which can then be converted to schema objects to ensure compatibility with BIM models. Highly recommended is to look into Speckle for this integration, an open-source BIM data platform developed especially for digital collaboration in the built environment and data exchange between software like Revit, AutoCAD and Rhino. Speckle provides a web-based environment for storing and retrieving data and has a Grasshopper plugin that facilitates both data retrieval from Speckle and uploading Grasshopper models. This plugin also enables the creation of generic BIM elements from Grasshopper geometry by assigning a Speckle schema to each object (Speckle, 2025). These BIM objects are automatically translated by Speckle Connectors to BIM-compatible software such as Revit, where they are converted to native elements. So potentially, by integrating *ReLifeCycle* with Speckle, material and geometry data could be converted into Speckle schemas and exported to the Speckle cloud, from where they can be accessed and used in BIM software. The advantage of this approach is that Grasshopper can be used to create an initial base geometry and materialisation variant, which can be developed in detail in BIM software, further enhancing the design process workflow. It would also expand *ReLifeCycle's* results beyond Grasshopper, by making it accessible within a web-based environment, increasing its potential for wider application in the design process.

Finally, *ReLifeCycle's* assessment can be extended beyond embodied impact to also include operational impact and energy aspects. For instance, operational impact during the use stage was out of scope for this research, while this can have a significant influence on the results. One approach to include these aspects would be to integrate third-party environmental analysis tools such as Ladybug. Ladybug is a collection of Grasshopper plugins that incorporate weather data, daylight simulations, building energy performance and indoor comfort aspects. Integrating this with *ReLifeCycle* could calculate the building's energy demand and operational impact, allowing assessment of environmental, financial and circularity impacts during the use stage, in addition to the production and end-of-life stages. Moreover, this integration would add new dimensions for MOO, as additional variables such as thermal mass, indoor comfort, solar gains and energy efficiency can be included. This would significantly enhance *ReLifeCycle's* assessment by providing a more comprehensive understanding of a building's impact throughout its entire life cycle.

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APPENDIX

A LIST OF INTERVIEWEES

Table A.1: List of interviewees

Name	Company	Function	Expertise	Date	Location
Erron Estrado	ABT	BIM Developer, data engineer	Parametric design, structural design, BIM	09/10/2024	Online
Jip Beijers	Alba Concepts	Consultant circularity and sustainability	Environmental impact	21/10/2024	Online
Sander van Gemert	Alba Concepts	Consultant circularity and sustainability	Environmental impact, costs	21/10/2024	‘s Hertogen-bosch
Damian van der Velden	Alba Concepts	Consultant circularity and sustainability	Environmental impact	21/10/2024	‘s Hertogen-bosch
Rick Titulaer	Arup	Sr. Strucural Engineer, computational designer	Parametric design, structural design	25/10/2024	Online
Mike van Vliet	BCI Gebouw	Consultant circularity and sustainability	BCI, circularity, sustainability	21/10/2024	‘s Hertogen-bosch
Thimo Hilenius	BCI Gebouw	Ontwerper, technical specialist built environment	BCI, circularity, sustainability	27/09/2024	‘s Hertogen-bosch
Gijs Joosen	Royal Haskoning DHV	Architect, leading professional parametric design	Parametric design, architectural design	10/10/2024	Online
Prethvi Manoharan	UN Studio	Sustainability Engineering Lead	Climate and façade engineering, parametric design	11/10/2024	Online

B USE CASES

B.1 Model Linking & Material Mapping

UC_1.01: Link building element geometry from Grasshopper model

Goal:	The user links Grasshopper geometry to ReLifeCycle.
Actor:	User, Grasshopper 3D Building Model.
Precondition:	The user has made a Grasshopper script for a 3D building model.
Postcondition:	The user has extracted a building element from Grasshopper geometry and linked this to ReLifeCycle.
Requirements:	FR_1.01, NFR_1.05.
Priority:	Must have.

UC_1.02: Assign name to building element

Goal:	The user assigns a custom name to a building element.
Actor:	User.
Precondition:	The user has linked a Grasshopper building element geometry to ReLifeCycle.
Postcondition:	The user has a building element with a name.
Requirements:	FR_1.06, NFR_1.16.
Priority:	Should have.

UC_1.03: Assign classification to building element

Goal:	The user assigns a classification to a building element.
Actor:	User, MySQL Database.
Precondition:	The user has linked a Grasshopper building element geometry to ReLifeCycle.
Postcondition:	The user has a building element with an NL/SfB classification.
Requirements:	FR_1.02, NFR_1.06, NFR_1.07.
Priority:	Must have.

UC_1.04: Create material set

Goal: The user creates a material set for a building element classification.

Actor: User, MySQL Database.

Precondition: The user has selected an NL/SfB classification.

Postcondition: The user has a material set with suitable materials for the chosen NL/SfB classification.

Requirements: FR_1.03, FR_1.05, NFR_1.01, NFR_1.02, NFR_1.08.

Priority: Must have.

UC_1.05: Verify geometry type

Goal: The user sees if the inserted geometry type is correct.

Actor: User.

Precondition: The user has linked a Grasshopper building element geometry to ReLifeCycle and has assigned a classification.

Postcondition: The user sees the required geometry type for the selected material. If this does not match the inserted geometry, the user receives a warning message.

Requirements: FR_1.04, NFR_1.06, NFR_1.10.

Priority: Must have.

UC_1.06: Assign material to building element

Goal: The user assigns a material to a building element.

Actor: User, MySQL Database.

Precondition: The user has linked a Grasshopper building element geometry to ReLifeCycle, has assigned a classification and has created a material set.

Postcondition: The user has a building element with a material.

Requirements: FR_1.03, FR_1.05, NFR_1.09, NFR_1.11.

Priority: Must have.

B.2 Responsible Material Use Assessment

UC_2.01: Set calculation variables

Goal: The user sets calculation variables for the assessment (building lifespan, function, GFA).

Actor: User.

Precondition: The user has completed the model linking & material mapping steps for at least one building element.

Postcondition: The user has set the calculation variables for the assessment.

Requirements: FR_2.02, NFR_2.05.

Priority: Must have.

UC_2.02: Assess responsible material use

Goal: The user sees responsible material use results.

Actor: User, MySQL Database.

Precondition: The user has completed the model linking & material mapping steps for at least one building element and has set the calculation variables.

Postcondition: The user sees the results of the responsible material use assessment (environmental impact, circularity and/or financial impact).

Requirements: FR_2.01, NFR_2.01, NFR_2.06, NFR_07.

Priority: Must have.

UC_2.03: Calculate environmental impact

Goal: The user sees the environmental impact results.

Actor: User, MySQL Database.

Precondition: The user has completed the model linking & material mapping steps for at least one building element and has set the calculation variables.

Postcondition: The user sees the results of the environmental impact assessment.

Requirements: FR_2.01, NFR_2.02.

Priority: Must have.

UC_2.04: Calculate circularity

Goal: The user sees the circularity results.

Actor: User, MySQL Database.

Precondition: The user has completed the model linking & material mapping steps for at least one building element and has set the calculation variables.

Postcondition: The user sees the results of the circularity assessment.

Requirements: FR_2.01, NFR_2.03.

Priority: Must have.

UC_2.05: Calculate financial impact

Goal: The user sees the financial impact results.

Actor: User, MySQL Database.

Precondition: The user has completed the model linking & material mapping steps for at least one building element and has set the calculation variables.

Postcondition: The user sees the results of the financial impact assessment.

Requirements: FR_2.01, NFR_2.04.

Priority: Must have.

B.3 Responsible Material Use Enhancement

UC_3.01: Generate set of material-optimised variants

Goal: The user sees a set of material-optimised variants.

Actor: User, Optimisation Plugin.

Precondition: The user has assessed the environmental impact, circularity and/or financial impact of a building design.

Postcondition: The user has generated a set of material-optimised building design variants.

Requirements: FR_3.01, NFR_3.01, NFR_3.07.

Priority: Must have.

UC_3.02: Set decision variables

Goal: The user sets decision variables for the optimisation process.

Actor: User.

Precondition: The user has assessed the environmental impact, circularity and/or financial impact of a building design.

Postcondition: The user has set the decision variables for the optimisation process.

Requirements: FR_3.02, NFR_3.03.

Priority: Must have.

UC_3.03: Set objectives

Goal: The user sets objectives for the optimisation process.

Actor: User.

Precondition: The user has assessed the environmental impact, circularity and/or financial impact of a building design.

Postcondition: The user has set the objectives for the optimisation process.

Requirements: FR_3.03, NFR_3.04.

Priority: Must have.

UC_3.04: Set constraints

Goal: The user sets constraints for the optimisation process.

Actor: User.

Precondition: The user has assessed the environmental impact, circularity and/or financial impact of a building design.

Postcondition: The user has set the constraints variables for the optimisation process.

Requirements: FR_3.04, NFR_3.05.

Priority: Must have.

UC_3.05: Choose variant

Goal: The user chooses between the material-optimised variants.
Actor: User.
Precondition: The user has generated a set of material-optimised variants.
Postcondition: The user has chosen a material-optimised variant.
Requirements: FR_3.06, NFR_3.10.
Priority: Must have.

UC_3.06: Name and store variant

Goal: The user names and stores the chosen variant.
Actor: User.
Precondition: The user has chosen a material-optimised variant.
Postcondition: The user has named and stored the chosen variant.
Requirements: FR_3.06, NFR_3.09, NFR_3.10.
Priority: Should have.

B.4 Results Interface

UC_4.01: Visualise responsible material use assessment results

Goal: The user explores the responsible material use assessment results displayed in an interface.
Actor: User.
Precondition: The user has linked the responsible material use assessment results to the interface script.
Postcondition: The user has made a direct link between the interface and the responsible material use assessment results.
Requirements: FR_4.01 - FR_4.06, NFR_4.01 - NFR_4.08.
Priority: Must have.

UC_4.02: Export results to PDF, Excel

Goal: The user exports the results from ReLifeCycle to PDF or Excel.
Actor: User.
Precondition: The user has linked the responsible material use assessment results to the interface script.
Postcondition: The user has obtained a PDF and/or Excel file with the responsible material use assessment results.
Requirements: FR_4.09, FR_4.10, NFR_4.13 - NFR_4.15.
Priority: Should have.

UC_4.03: Compare optimised variants

Goal:	The user compares optimised material variants by setting baseline variant next to a comparison variant.
Actor:	User.
Precondition:	The user has linked the responsible material use assessment results and the optimisation output to the interface script.
Postcondition:	The user sees the results of two optimised variants next to each other.
Requirements:	FR_4.08, NFR_4.10 - NFR_4.12.
Priority:	Should have.

C SYSTEM DIAGRAMS

C.1 Detailed System Architecture

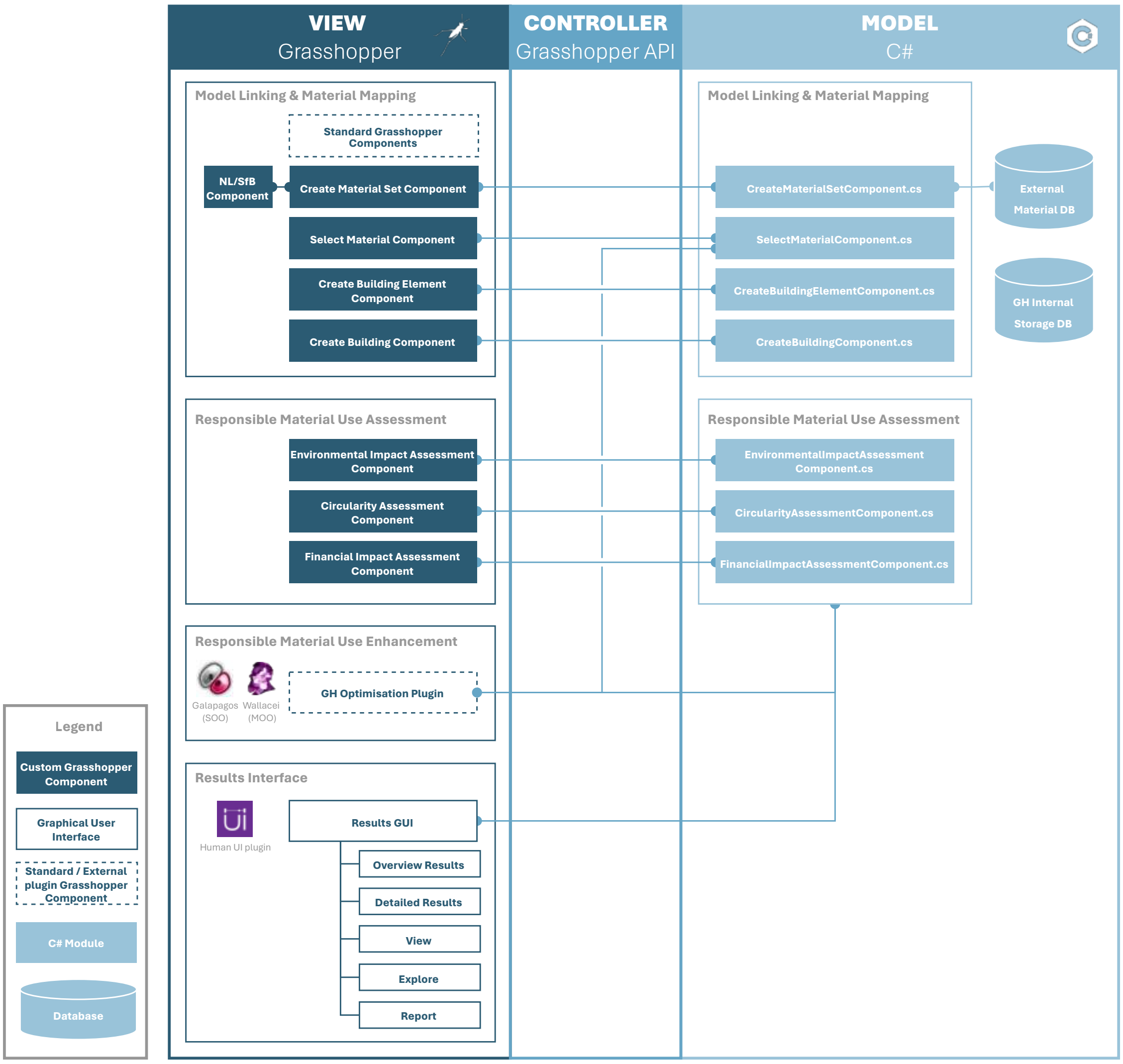

Figure C.1: *ReLifeCycle* detailed system architecture

C.2 Sequence Diagrams

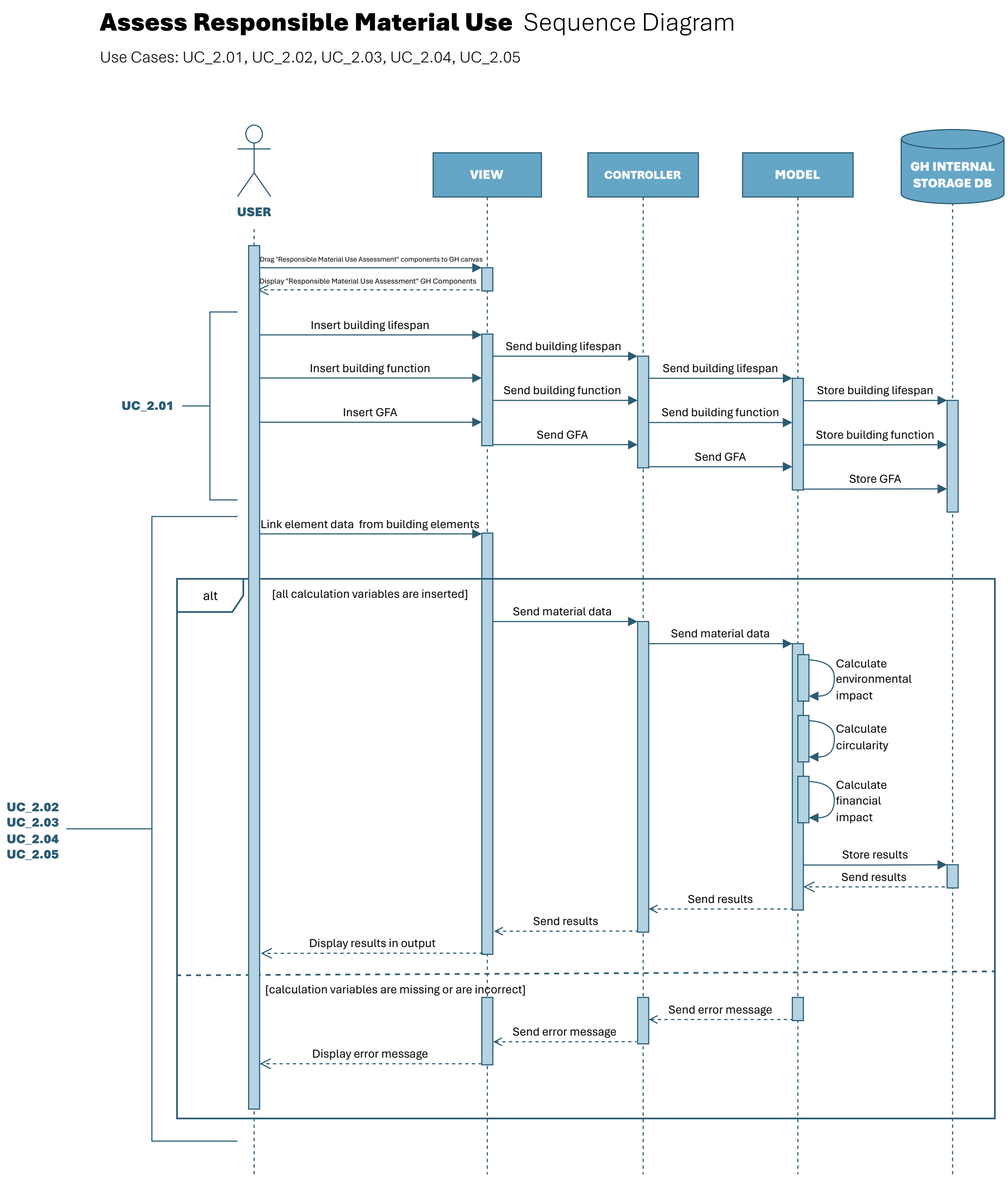

Figure C.2: Sequence diagram for the "Responsible Material Use Assessment" package

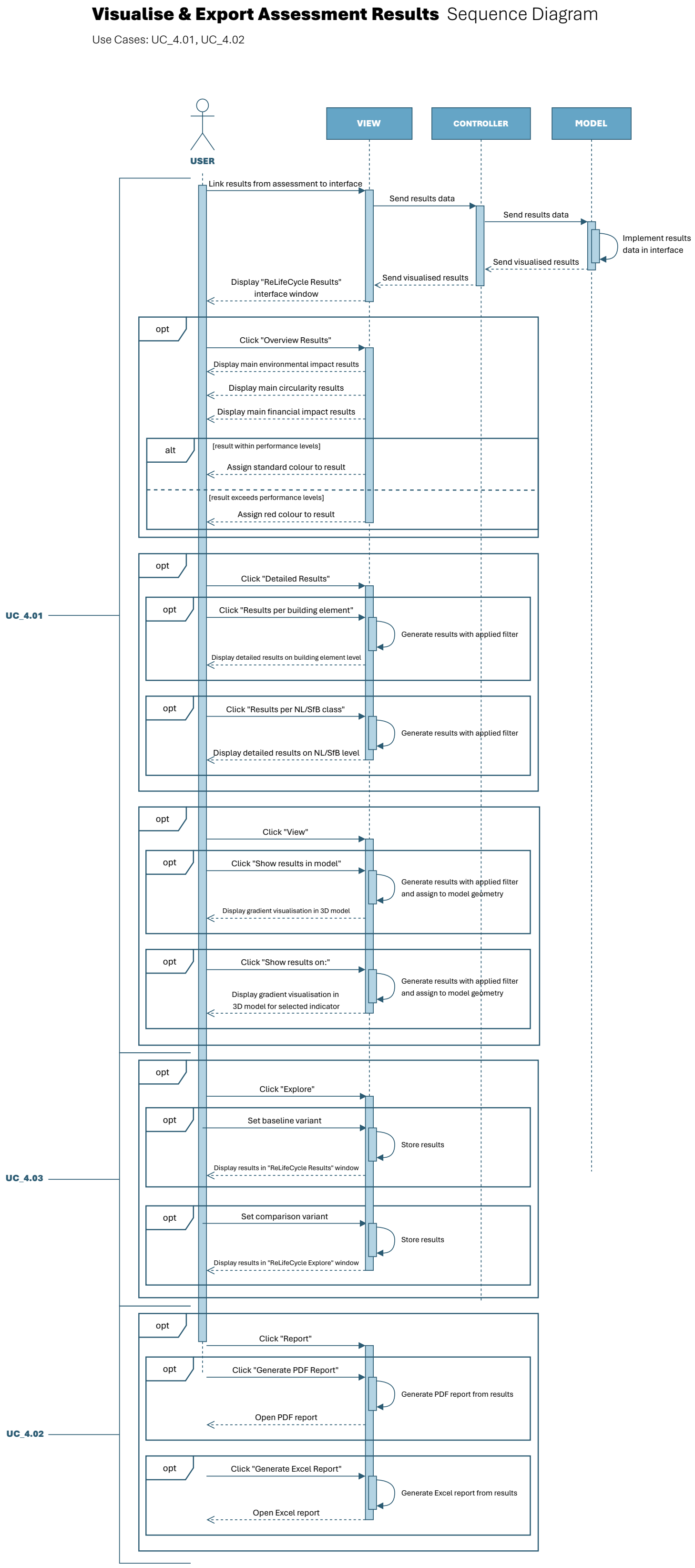

Figure C.3: Sequence diagram for the "Results Interface" package

D ASSESSMENT METHODS

D.1 Example Assessment Case

To explain the assessment methods and also validate them during the development process of *ReLifeCycle*, an example case has been made. This case, illustrated in Figure D.1, consists of two simple floor slabs, one made from timber and one from concrete.

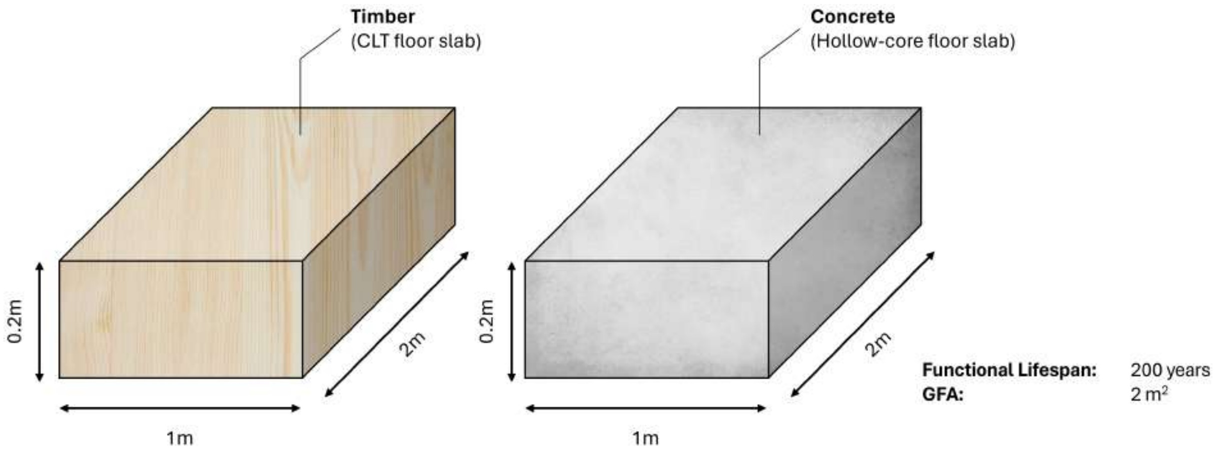

Figure D.1: Example case

D.2 Environmental Impact

D.2.1 MilieuPrestatie Gebouwen

The MilieuPrestate Gebouwen (MPG) method is set up by the National Environmental Database (NMD) in the Netherlands (Stichting Nationale MilieuDatabase, 2022a) and is based on the EN 15804. It calculates the MilieuKostenIndicator (MKI), a combination of all environmental impact categories into one score. In this research, the 19 environmental impact categories from set A2 (Table 2.2) are used. The MKI is calculated by expressing the impact categories with shadow costs, theoretical costs a government should have to pay to prevent the environmental impact caused by the building. To convert the impact categories to shadow costs, weighting factors are derived (Table D.1), which are based on the report "Toxicity has its price: shadow pricing for ecotoxicity and other toxicity and depletion of abiotic raw materials within DuboCalc" (Broers et al., 2004).

Table D.1: Weighting factors for the environmental impact categories from the A2 set (Broers et al., 2004)

Environmental Impact Category	Unit	Weighting factor
Climate change - total	€ / kg CO2-eq.	0.116
Climate change - fossil	€ / kg CO2-eq.	0.116
Climate change - biogenic	€ / kg CO2-eq.	0.116
Climate change - land use	€ / kg CO2-eq.	0.116
Ozone Depletion	€ / kg CFC11-eq.	32
Acidification	€ / mol H+-eq	0.39
Eutrophication aquatic freshwater	€ / kg P-eq.	1.96
Eutrophication aquatic marine	€ / kg N-eq.	3.28
Eutrophication terrestrial	€ / mol N-eq.	0.36
Photochemical ozone formation	€ / kg NMVOC-eq.	1.22
Depletion of abiotic resources - minerals	€ / kg Sb-eq.	0.3
Depletion of abiotic resources - fossil fuels	€ / MJ, net cal. val.	0.00033
Water use	€ / m³ world eq. deprived	0.00506
Particulate Matter emissions	€ / Health incidences	549750
Ionizing radiation, human health	€ / kBq U235-eq.	0.049
Eco-toxicity (freshwater)	€ / CTUh	0.00013
Human toxicity, cancer effects	€ / CTUh	1096368
Human toxicity, non-cancer effects	€ / CTUh	147588
Land use-related impacts / Soil quality	Pt / m^2.year	0.000087

By converting all impact categories to shadow costs and summing those shadow costs, the MKI for a material can be calculated. Figure D.2 gives an example of this calculation for a few impact categories.

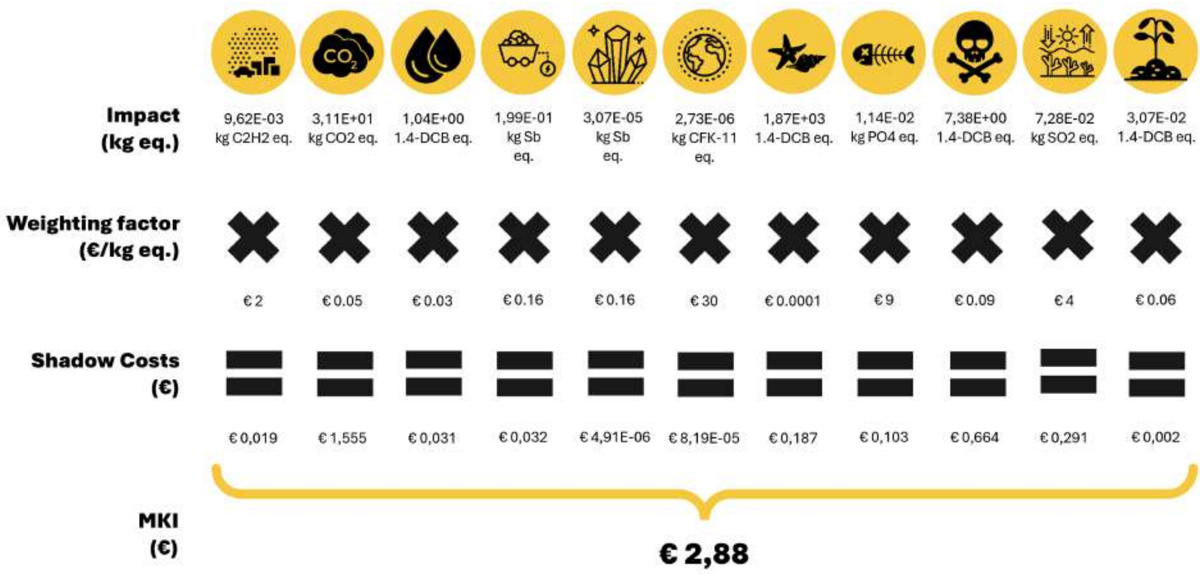

Figure D.2: MKI calculation explained (van Gemert, 2019)

In this research, MKI data per life cycle stage of a material is directly derived from the database sources. The MKI for each life cycle stage of a building element is then calculated by multiplying the MKI per life cycle stage by the quantity of the element, based on the functional unit specified in the database (m^3, m^2, m, kg or piece). The total MKI is then determined by summing the MKI values across all life cycle stages. Equation D.1 shows the formula for calculating the total MKI of a building element.

$$MKI_{e,total} = \sum_{lcs} MKI_{e,lcs} * Q \tag{D.1}$$

where:

$MKI_{e,total}$	is the total MKI of a building element in €
lcs	is the life cycle stage
$MKI_{e,lcs}$	is the MKI for each life cycle stage per functional unit of the building element in € / unit
Q	is the quantity of the building element in m^3, m^2, m, kg or piece

---

Equation D.1 Assessment Example - Total MKI of building element
1x2x0.2m concrete hollow-core floor slab (unit m^2)

$$\begin{aligned} MKI_{e,total} &= (MKI_{e,A1-A3} + MKI_{e,A4} + MKI_{e,A5} + MKI_{e,B1} + MKI_{e,B2} + MKI_{e,B3} + MKI_{e,B4} \\ &\quad + MKI_{e,B5} + MKI_{e,C1} + MKI_{e,C2} + MKI_{e,C3} + MKI_{e,C4} + MKI_{e,D}) * Q \\ &= (5.021 + 0.412 + 0.305 + 0 + 0 + 0 + 0 \\ &\quad + 0 + 0.055 + 0.378 + 0.101 + 0.004 - 0.513) * 2 \\ &= €\,11.526 \end{aligned}$$

An important addition to the total MKI is the consideration of possible replacements. When the functional lifespan of a building is longer than the technical lifespan of a material, the material likely has to be replaced. The impact of replacements is calculated with Equation D.2 by multiplying the sum of each MKI per life cycle stage by the number of replacements minus one (which cannot be smaller than zero). This MKI is added to the MKI of life cycle stage B4 "Replacements".

$$MKI_{e,B4} = \sum_{lcs} MKI_{lcs} * max(0; \frac{L_f}{L_t} - 1) \tag{D.2}$$

where:

$MKI_{e,B4}$	is the MKI of replacements of a building element, adopted in life cycle stage B4
L_f	is the functional lifespan of the building in years
L_t	is the technical lifespan of the material in years

Equation D.2 Assessment Example - Replacements
1x2x0.2m concrete hollow-core floor slab (unit m^2)

$$\begin{aligned} MKI_{e,B4} &= 11.526 * max(0; \frac{200}{100} - 1) = €\,11.526 \\ MKI_{e,total} &= \sum_{lcs} MKI_{lcs} + MKI_{e,B4} = 11.526 + 11.526 = €\,23.052 \end{aligned}$$

The total MKI of each building element is finally combined into a single score: the MPG. The MPG is calculated by dividing the sum of all building element MKIs by the gross floor area and building functional lifespan according to Equation D.3.

$$MPG = \frac{\sum MKI_{e,total}}{A_{GFA} * L_f} \tag{D.3}$$

where:

MPG is the MPG in € / m^2 GFA / year
A_{GFA} is the Gross Floor Area of the building in m^2

Equation D.3 Assessment Example - MPG
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

$$MPG = \frac{(23.052 + 8.225)}{2 * 200} = \text{€}\, 0.0782/m^2GFA/year$$

D.2.2 Paris Proof Indicator

The Paris Proof Indicator is calculated with the method described in the Dutch Green Building Council report "Paris Proof Embodied Carbon: Calculation Protocol" (Spitsbaard and Leeuwen, 2021). It is calculated by dividing the total Global Warming Potential (GWP) for life cycle stages A1-A5 by the gross floor area of the building (Equation D.4).

$$Paris\ Proof\ Indicator = \frac{\sum GWP_{e,A1-A5}}{GFA} \tag{D.4}$$

where:

$Paris\ Proof\ Indicator$ is the Paris Proof Indicator in kg CO_2 eq. / m^2 GFA
$GWP_{e,A1-A5}$ is the Global Warming Potential of a building element for life cycle stages A1-A5 in kg CO_2 eq.

Equation D.4 Assessment Example - Paris Proof Indicator
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

$$Paris\ Proof\ Indicator = \frac{(74.455 + -263.012)}{2} = -94.278\ kgCO_2/m^2GFA$$

D.2.3 Construction Stored Carbon

The Construction Stored Carbon (CSC) method calculates the total weight of biogenic carbon that is physically stored in biobased materials in buildings. The adopted method for this research is based on the report "Proposed calculation method to assess carbon storage in biobased building materials" (SGS Search, 2021) which proposes an assessment method for converting biogenic carbon to its equivalent

Global Warming Potential in kilograms of CO_2 equivalent. In this research, the CSC is already calculated and directly available as raw data from the data sources. However, Equation D.5 illustrates the workings of this method. To compare the CSC of materials or buildings, a 100-year storage timescale is introduced as T_{kp}. This aligns with the standard timescale used in LCA practices to compare the effects of different greenhouse gases on global warming.

$$CSC = \left(V_1 * C_b * \frac{44}{12}\right) * \frac{L_{p1} + (V_2 * L_{p2})}{T_{kp}} \tag{D.5}$$

where it holds that $\frac{L_{p1}+(V_2*L_{p2})}{T_{kp}} = 1$ if $L_{p1} + (V_2 * L_{p2}) > T_{kp}$.

and where:

W_{cb} is the effect of biogenic carbon on Global Warming Potential in kg CO_2 eq.
V_1 is variable 1, uncertainty factor for the effects of material production (see SGS Search (2021) for calculation)
$\frac{44}{12}$ is the weight ratio of CO_2 to carbon (1 kg biogenic carbon is $\frac{44}{12}$ kg CO_2)
C_b is the biogenic carbon in kg
L_{p1} is the material lifespan for first application in years
V_2 is variable 2, uncertainty factor for the effects of end-of-life scenarios (see SGS Search (2021) for calculation)
L_{p2} is the material lifespan after the first application in years
$T_{kp]}$ is the timespan extending beyond the 'critical' period, which is set at 100 years

However, the formula used in the development of *ReLifeCycle* is given in Equation D.6.

$$CSC = W_{cb} * Q \tag{D.6}$$

where:

CSC is the Construction Stored Carbon of a building element in kg CO_2 eq.
Q is the quantity of the building element in m^3, m^2, m, kg or piece

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Equation D.6 Assessment Example - Construction Stored Carbon
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

$$CSC_{concrete} = 0 * 2 = 0\ kgCO_2eq.$$
$$CSC_{clt} = 75.22 * 2 = 150.44\ kgCO_2eq.$$

$$CSC_{total} = 0 + 150.44 = 150.44\ kgCO_2eq.$$

D.3 Financial Impact

D.3.1 Direct Costs

The direct costs of a material are calculated by summing the material costs and the labour costs to produce and construct the building material. This is done according to Equation D.7.

$$C_d = (C_m + C_l) * Q \tag{D.7}$$

where:

C_d is the direct costs of a building element in €
C_m is the material costs in €
C_l is the labour costs in €
Q is the quantity of the building element in m^3, m^2, m, kg or piece

---

Equation D.7 Assessment Example - Direct Costs
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

$$C_{d,concrete} = (38.84 + 3.06) * 2 = €\,83.80$$
$$C_{d,clt} = (161.96 + 2.94) * 2 = €\,329.80$$

$$C_{d,total} = 83.80 + 329.80 = €\,413.60$$

D.3.2 True Pricing

The True Pricing method calculates the true price of a material by combining financial costs with environmental impact costs. Currently, no standardised method exists for the built environment. However, in this research, the calculation is based on the fundamentals of the report "Principles For True Pricing" (Impact Economy Foundation, 2020) and will be calculated by adding the direct costs to the total MKI shadow costs, as defined in Equation D.8.

$$True\ Price = C_d + MKI_{total} \tag{D.8}$$

where:

$True\ Price$ is the true price of a building element in €
MKI_{total} is the total MKI of a building element of all its life cycle stages in €

Equation D.8 Assessment Example - True Price
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

$$True\ Price_{\ concrete} = 83.80 + 23.052 = €\,106.85$$
$$True\ Price_{\ clt} = 329.80 + 8.22 = €\,338.02$$

$$True\ Price_{\ total} = 106.85 + 338.02 = €\,444.88$$

D.4 Circularity

D.4.1 Building Circularity Index

The Building Circularity Index (BCI) measures the circularity level of a complete building and its calculation follows the method from the "User Manual BCI Gebouw" (BCI Gebouw, 2024). The calculation is performed using a stepwise procedure which includes the following intermediate results (Figure D.3):

1. Material Circularity Index (MCI)
2. Disassembly Potential (DP)
3. Product Circularity Index (PCI)
4. Element Circularity Index (ECI)
5. Building Circularity Index (BCI)

The MCI calculates the circularity index at the material level. Afterwards, the DP is calculated to determine the disassembly potential of that material. Combining the MCI and DP gives the PCI. The ECI calculates the circularity level of an element, defined as a composition of materials that cannot be separated individually, but can be separated as a whole. However, elements are outside the scope of this research, so the ECI is excluded from the assessment. Finally, the BCI is calculated by combining the PCIs of all building materials and converting them to a single score. The assessment methods for each step are elaborated in the next sections.

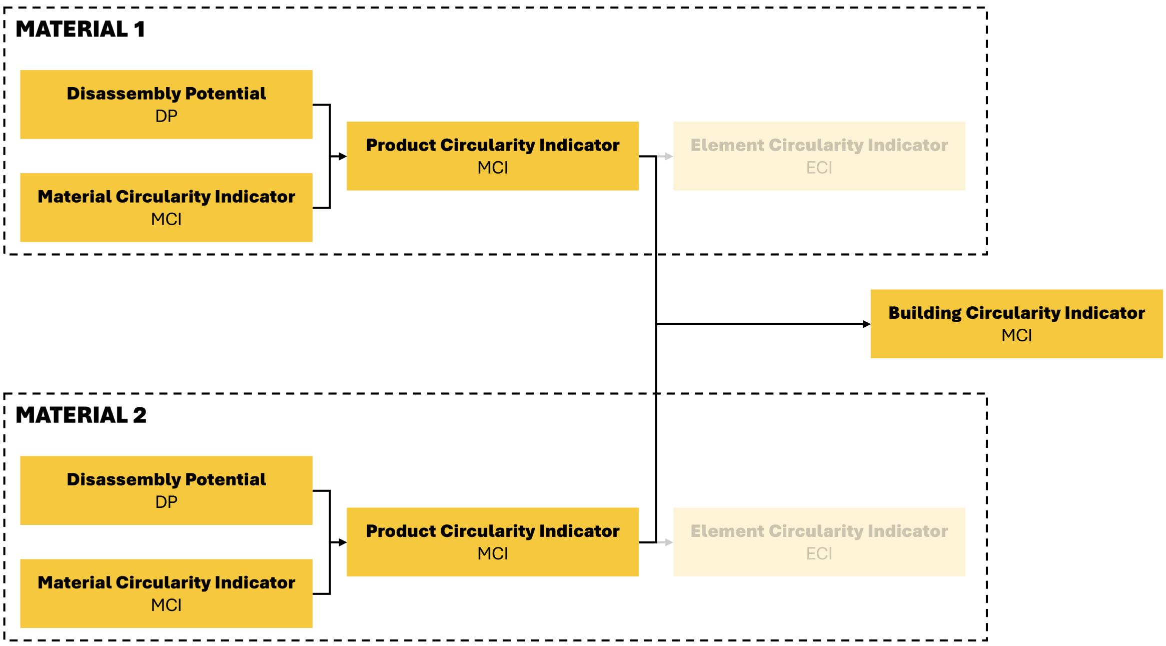

Figure D.3: BCI assessment method explanation

Material Circularity Index

To calculate the Material Circularity Index (MCI), the material input and output flows are used. These are percentages of the mass of a material that explain the origin and future scenarios of the material sources. In this research, these are defined as follows:

Material input flows
- % new
- % biobased
- % recycled
- % reused

Material output flows
- % landfill
- % burning
- % recycling
- % reusing

It should be acknowledged that the inclusion of "% biobased" represents a different category compared to the other input flows, as biobased materials can simultaneously be classified as new, recycled or reused. Nevertheless, its inclusion is important, since it highlights an important distinction: biobased materials are sourced from renewable sources that align with the biological cycle of the butterfly diagram (Figure 2.6), and thus have a different impact on circularity. While it would be best to have additional input and output flows such as "% new biobased" and "% reused biobased", the absence of such data limits this possibility. Therefore, this limitation is accepted.

The input and output flows are used first to calculate the total amount of unrecoverable waste that is burned or sent to the landfill. This calculation is performed using Equations D.9 through D.12.

$$W_t = W_0 + \frac{W_f + W_c}{2} \tag{D.9}$$

$$W_0 = M\,(1 - C_{Rw} - C_{Uw}) \tag{D.10}$$

$$W_f = M\frac{(1 - E_f)\,F_{Ro}}{E_F} \tag{D.11}$$

$$W_c = M\,(1 - E_c)\,C_{Rw} \tag{D.12}$$

where:

W_t is the total amount of unrecoverable waste in kg
W_0 is the amount of direct waste in kg
W_f is the amount of recycling waste during production
W_c is the amount of recycling waste during waste processing
M is the mass of the building element in kg
C_{Rw} is the recycling output ratio in %
C_{Uw} is the reusing output ratio in %
E_f is the recycling efficiency during production, set standard at 80%
E_c is the recycling efficiency during waste processing, set standard at 80%
F_{Ro} is the recycled input ratio in %

Equations D.9-D.12 Assessment Example - Total amount of unrecoverable waste
1x2x0.2m concrete hollow-core floor slab (unit m^2)

$$W_0 = 611.72 * (1 - 1 - 0) = 0\ kg$$
$$W_f = 611.72 * \frac{(1 - 0.8)\,0.28}{0.8} = 42.82\ kg$$
$$W_c = 611.72 * (1 - 0.8) * 1 = 122.34\ kg$$

$$W_t = 0 + \frac{42.82 + 122.34}{2} = 82.85\ kg$$

The next step involves calculating the Linear Flow Index (LFI), a factor between zero and one that indicates a material's level of linearity by using the total amount of virgin material and unrecoverable waste. This is performed with Equation D.13 and D.14. The higher the LFI, the more linear the material.

$$V_0 = M * F_{Vo} \tag{D.13}$$

$$LFI = \frac{V_o + W_t}{2M + \frac{W_f - W_c}{2}} \tag{D.14}$$

where:

V_0 is the total amount of virgin material in kg
LFI is the Linear Flow Index

Equations D.13-D.14 Assessment Example - Linear Flow Index
1x2x0.2m concrete hollow-core floor slab (unit m²)

$$V_0 = 611.72 * 0.72 = 440.44\ kg$$

$$LFI = \frac{440.44 + 82.85}{2 * 611.72 + \frac{42.82 - 122.34}{2}} = 0.44$$

The LFI is then used together with the utility factor $F(X)$ to calculate the MCI with Equations D.15 and D.16. The utility factor is calculated by comparing the technical lifespan of a material against its functional lifespan. Because the functional lifespan is often difficult to determine in practice, it is decided to always keep the technical lifespan and functional lifespan the same so the $F(X)$ becomes 0.9 for all materials. The MCI results in a score between zero and one, zero meaning a fully linear material and one a fully circular material.

$$MCI = \max(0; 1 - LFI * F(X)) \tag{D.15}$$

$$F(X) = \frac{0.9}{\frac{FL}{AL}} \tag{D.16}$$

where:

MCI is the Material Circularity Index
$F(X)$ is the utility factor, standard set at 0.9

Equations D.15-D.16 Assessment Example - Material Circularity Index
1x2x0.2m concrete hollow-core floor slab (unit m²)

$$F(X) = \frac{0.9}{\frac{100}{100}} = 0.9$$

$$MCI = \max(0; 1 - 0.44 * 0.9) = 0.60$$

The assessment examples of the MCI are given to illustrate the method. The MCI itself is already calculated internally in the *ReLifeCycle* database.

Disassembly Potential

The Disassembly Potential (DP) is based on the report "Circular Buildings: Disassembly Potential Measurement Method Version 2.0" (van Vliet et al., 2021) and measures the disassembly potential of a building element. It is calculated with four disassembly factors:

- Type of connection
- Accessibility of connection
- Edge restraint
- Intersections

Each disassembly factor is given a score between 0.1 and 1.0 based on the descriptions in Table D.2.

Table D.2: Scoring table for disassembly factors (BCI Gebouw, 2024)

Type of Connection (TC)	Accessibility of Connection (AoC)	Edge Restraint (ER)	Intersections (IS)
Dry connection (1.0)	Freely accessible without additional actions (1.0)	Open - no obstruction to (intermediate) removal of products or elements (1.0)	No intersections - modular zoning of products or elements from different layers (1.0)
Connection with added elements (0.8)	Accessible with extra actions that cause no damage (0.8)	Overlapping - partial obstruction to (intermediate) removal of products or elements (0.4)	Incidental intersections of products or elements from different layers (0.4)
Direct integral connection (0.6)	Accessible with extra actions with fully repairable damage (0.6)	Closed - complete obstruction to (intermediate) removal of products or elements (0.1)	Full integration of products or elements from different layers (0.1)
Soft chemical connection (0.2)	Accessible with extra actions with partially repairable damage (more than 20% of value) (0.4)		
Hard chemical connection (0.1)	Not accessible - irreparable damage to the product or surrounding products (0.1)		

The disassembly factors are used first to calculate the DP of the connection DP_c and the composition DP_co, after which the DP of the material DP_m is calculated. Equations D.17 through D.19 give the formulas for these calculations. The DP results in a score between 0.1 and 1, where a higher score means that the material is easier to disassemble.

$$DP_m = \frac{2}{\frac{1}{DP_c} + \frac{1}{DP_{co}}} \tag{D.17}$$

$$DP_c = \frac{2}{\frac{1}{IS} + \frac{1}{ER}} \tag{D.18}$$

$$DP_{co} = \frac{2}{\frac{1}{TC} + \frac{1}{AoC}} \tag{D.19}$$

where:

DP_m	is the Disassembly Potential of the material
DP_c	is the Disassembly Potential of the connection
DP_{co}	is the Disassembly Potential of the composition
IS	is the Intersections score for the material
ER	is the Edge Restraint score for the material
TC	is the Type of Connection score for the material
AoC	is the Accessibility of Connection score for the material

---

Equations D.17-D.19 Assessment Example - Disassembly Potential
1x2x0.2m concrete hollow-core floor slab (unit m^2)

$$DP_c = \frac{2}{\frac{1}{0.4} + \frac{1}{0.1}} = 0.16$$
$$DP_{co} = \frac{2}{\frac{1}{0.1} + \frac{1}{0.4}} = 0.16$$

$$DP_m = \frac{2}{\frac{1}{0.16} + \frac{1}{0.16}} = 0.16$$

Similar to the MCI, the DP is already calculated internally in the *ReLifeCycle* database.

Product Circularity Index

The Product Circularity Index is calculated with Equation D.20 by integrating the MCI with the DP. Similar to the MCI, it gives a score between zero and one, where a higher score indicates a more circular product.

$$PCI = \sqrt{MCI * DP} \tag{D.20}$$

where:

PCI	is the Product Circularity Index

Equation D.20 Assessment Example - Product Circularity Index
1x2x0.2m concrete hollow-core floor slab (unit m^2)

$$PCI = \sqrt{0.60 * 0.16} = 0.31$$

Similar to the MCI and DP, the PCI is already calculated internally in the *ReLifeCycle* database.

Building Circularity Index

The Building Circularity Index (BCI) is finally calculated according to Equation D.21 by weighting the PCIs of all building elements with their corresponding MKI value. It results in a single score between 10 and 100%, where 10% indicates the lowest circularity level of a building and 100% the highest.

$$BCI = \frac{1}{\sum_{i=1}^{n} MKI_e} * \sum_{i=1}^{n} (MKI_e * PCI_e) \tag{D.21}$$

where:

BCI is the Building Circularity Index of the building in %
MKI_e is the total MilieuKostenIndicator of a building element in €
PCI_e is the Product Circularity Index of a building element

Equation D.21 Assessment Example - Building Circularity Index
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

$$BCI = \frac{1}{23.052 + 8.225} * (23.052 * 0.31 + 8.225 * 0.75) = 43\%$$

D.4.2 Total Disassembly Potential of Building

We have already seen the assessment method for calculating the DP for a material. However, the DP can also be given for the complete building. This is done by weighting the DPs of all building elements with their MKI, similar to the BCI weighting method. Equation D.22 gives the formula for this method.

$$DP_b = \frac{1}{\sum_{i=1}^{n} MKI_e} * \sum_{i=1}^{n} (MKI_e * DP_e) \tag{D.22}$$

where:

DP_b is the total Disassembly Potential of the building in %
MKI_e is the total MilieuKostenIndicator of a building element in €
DP_e is the Disassembly Potential of a building element

Equation D.22 Assessment Example - Total Disassembly Potential of Building
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

$$DP_b = \frac{1}{23.052 + 8.225} * (23.052 * 0.16 + 8.225 * 0.81) = 33\%$$

D.4.3 Total Material Input & Output Flows of Building

The material input and output flows can also be calculated on the building levels. However, in contrast to the BCI and DP methods, the total material input and output flows are weighted on mass (Equation D.23).

$$MF_b = \frac{1}{\sum_{i=1}^{n} M_e} * \sum_{i=1}^{n} (M_e * MF_e) \tag{D.23}$$

where:

MF_b is a total material input or output flow ratio in % for the building
MF_e is a material input or output flow ratio in % for a building element

Equation D.23 Assessment Example - Total Material Input & Output Flows of Building
1x2x0.2m concrete hollow-core floor slab (unit m^2)
1x2x0.2m CLT floor slab (unit m^2)

Material Input Flows

$$\%\ new\ _b = \frac{1}{611.72 + 188} * (611.72 * 0.72 + 188 * 0) = 55\%$$
$$\%\ biobased\ _b = \frac{1}{799.72} * (611.72 * 0 + 188 * 1) = 24\%$$
$$\%\ recycled\ _b = \frac{1}{799.72} * (611.72 * 0.28 + 188 * 0) = 21\%$$
$$\%\ reused\ _b = \frac{1}{799.72} * (611.72 * 0 + 188 * 0) = 0\%$$

Material Output Flows

$$\%\ landfill\ _b = \frac{1}{799.72} * (611.72 * 0 + 188 * 5) = 1\%$$
$$\%\ burning\ _b = \frac{1}{799.72} * (611.72 * 0 + 188 * 95) = 22\%$$
$$\%\ recycling\ _b = \frac{1}{799.72} * (611.72 * 1 + 188 * 0) = 76\%$$
$$\%\ reusing\ _b = \frac{1}{799.72} * (611.72 * 0 + 188 * 0) = 0\%$$

E PERFORMANCE LEVELS

Indicator	Categorie	Prestatieniveaus: HNN Gebouw 1.1 Nieuwbouw					Eenheid	Methode
		Woningbouw grondgebonden	Woningbouw gestapeld	Utiliteitsbouw kantoren	Utiliteitsbouw Onderwijs	Utiliteits-bouw Zorg		
Milieu-impact								
Milieuprestatie Gebouw (MPG)[1,2]	Standaard	≤0,45	≤0,50	≤0,70	-	-	€MKI / m² BVO / jaar	Bepalingsmethode Milieuprestatie Bouwwerken
Materiaalgebonden CO_2-uitstoot[3]	Standaard	≤200	≤240	-	-	-	kg CO_2-eq / m² BVO	Rekenmethodiek *Paris Proof*
Materiaalgebonden CO_2-opslag	Begrip	-	-	-	-	-	ton CO_2-eq	Bepalingsmethode *koolstofvastlegging biobased materialen*
Materiaalgebruik								
Herkomst materialen	Standaard	≥25%	≥20%	≥25%	-	-	%massa biobased, hergebruikt, gerecycled	*Material Circularity Indicator* (MCI). EllenMacArthur Foundation
Gezonde materialen	Begrip	-	-	-	-	-	Aantal gecertificeerde producten	Certificaten (o.a. *Material Health Certificate, Natureplus*)
Omgang restmateriaal bouw	Begrip	-	-	-	-	-	-	Inventarisatie materiaalstromen & aantoonbare afspraken
Waardebehoud								
Adaptief vermogen	Indicatie	-	-	≥40%	-	-	%	*Methode Adaptief Vermogen Gebouwen 2.0*
Losmaakbaarheid	Standaard	≥55%	≥50%	≥55%	-	-	%	*Circular Buildings - een meetmethodiek voor losmaakbaarheid* (v2.0)
Hergebruikpotentie	Indicatie	-	-	-	-	-	% massa recycling, hergebruik	Verwerkingsscenario einde levensduur (EPD, fase C3 - C4)

1. Let op: MPG-prestaties op basis van EN-15804:A1. Vanaf januari 2026 wijzigt deze naar EN-15804+A2.
2. Voor kleinere woningen (< 80 m² BVO) is het lastiger om de MPG-prestatie uit HNN raamwerk te halen. Voor deze woningen geldt een indicatief prestatieniveau van ≤0,55.
3. Voor Materiaalgebonden CO_2-uitstoot is de methodiek 'Rekenmethodiek Paris Proof'. De HNN prestaties zijn gebaseerd op leerervaringen uit evaluaties en aanvullende databronnen ('Wat is er op dit moment haalbaar én ambitieus?). De daadwerkelijk benodigde CO_2-grenswaarde conform Paris Proof ligt lager. Het doel is dat deze waarde en het prestatieniveau HNN steeds dichter naar elkaar toe komen.

Figure E.1: 'Het Nieuwe Normaal' performance levels (Het Nieuwe Normaal, 2023)

F DATA

F.1 Overview of LCA, LCC and circularity databases

Table F.1: Overview of existing LCA, LCC and circularity databases

Name	Data category	Region	Description	Open access	Data type
NMD (Nationale Milieu Database) (Dutch Environmental Database)	LCA	Netherlands	Largest Dutch environmental database with data on many materials. Designed for building products. This database is obligated by law to use for professional MPG calculations in the Netherlands.	✗ / ✓ (limited online viewer)	Generic, specific
NIBE (Nederlands Instituut voor Bouwbiologie en Ecologie) (Dutch Institution for Building Biology and Ecology)	LCA Circularity	Netherlands	Dutch database that provides mainly circularity data for building products. It also contains limited LCA data as well as data on construction stored carbon. Limited version available to the general public through an online viewer.	✗ / ✓ (limited online viewer)	Generic, specific
Madaster	Circularity	Netherlands	Database used for Madaster CI. Specific database is paid, but two generic Excel databases for circularity data are publicly accessible: "Madaster Material List" and "EPEA Generic Database".	✗ / ✓ (two generic databases)	Generic, specific
ÖKOBAUDAT	LCA Circularity	Germany	German environmental database by the Federal Ministry of Housing, Urban Development and Building. Provides data on individual building materials and products.	✓	Generic, specific
InData (International Open Data Network for Sustainable Construction)	LCA Circularity	Europe	A new initiative that is a combination of multiple international databases including the ÖKOBAUDAT.	✓	Generic, specific
ECO PORTAL	LCA Circularity	Europe	Initiative in collaboration with InData that also combines multiple international databases.	✓	Generic, specific
ICE (Inventory of Carbon Energy database)	LCA	UK	Open-source Excel database that provides data on total embodied carbon (GWP, kg CO2) for building materials.	✓	Generic
2050 Materials	LCA Circularity	Worldwide	International database providing embodied carbon and circularity data for different products and life cycle stages.	✓	Specific
Ecoinvent	LCA	Worldwide	Largest international LCA database designed for all sectors with more than 20,000 datasets.	✗ (license required)	Generic, specific
Bouwkostenkompas	LCC	Netherlands	Building cost database that gives average data for total costs of building elements per m^2 GFA based on building type and location.	✗ / ✓ (limited online viewer)	Generic
ArchiCalc	LCC	Netherlands	Desktop software that provides generic up-to-date cost data on material and labour costs for building materials. Limited data can be seen in an online viewer. A student license is available for the premium version.	✗ / ✓ (student license)	Generic
RSMeans	LCC	North-America	Contains current cost estimate data books of building materials as well as an online database for construction costs in North-America.	✗ (license required)	Generic
Casadata	LCC	Netherlands	Dutch database that provides estimates for direct and indirect costs for complete buildings as well as building elements.	✗ (license required)	Generic

F.2 ReLifeCycle Classification System

Table F.2: Modified NL/SfB classification system (exlcuded classifications are made grey)

NL/SfB Code	NL/SfB Class (EN)	NL/SfB Class (NL)
1	**Ground, Substructure**	**Funderingen**
11	ground	bodemvoorzieningen
13A	floors on the ground - structure	vloeren op grondslag - constructie
13B	floors on the ground - insulation	vloeren op grondslag - isolatie
16	foundation	funderingsconstructies
17	pile foundations	paalfunderingen
2	**Primary elements, Carcass**	**Ruwbouw**
21A	external walls - structure	buitenwanden - constructie
21B	external walls - insulation	buitenwanden - isolatie
22A	internal walls - structure	binnenwanden - constructie
22B	internal walls - insulation	binnenwanden - isolatie
23A	floors - structure	vloeren - constructie
23B	floors - insulation	vloeren - isolatie
24	stairs and ramps	trappen en hellingen
27A	roofs - structure	daken - constructie
27B	roofs - insulation	daken - isolatie
28A	load-bearing structures - general	hoofddraagconstructies - algemeen
28B	load-bearing structures - reinforcement	hoofddraagconstructies - bewapening
3	**Secondary elements**	**Afbouw**
31A	external wall openings - windows (frames)	buitenwandopeningen - ramen (kozijnen)
31B	external wall openings - windows (glazing)	buitenwandopeningen - ramen (beglazing)
31C	external wall openings - doors	buitenwandopeningen - deuren
32A	internal wall openings - windows (frames)	binnenwandopeningen - ramen (kozijnen)
32B	internal wall openings - windows (glazing)	binnenwandopeningen - ramen (beglazing)
32C	internal wall openings - doors	binnenwandopeningen - deuren
33A	floor openings - windows (frames)	bloeropeningen - ramen (kozijnen)
33B	floor openings - windows (glazing)	bloeropeningen - ramen (beglazing)
34	stair balustrades and handrails	balustrades en leuningen
37A	roof openings - windows (frames)	bakopeningen - ramen (kozijnen)
37B	roof openings - windows (glazing)	bakopeningen - ramen (beglazing)
4	**Finishes**	**Afwerkingen**
41	external wall finishes	buitenwandafwerkingen
42	internal wall finishes	binnenwandafwerkingen
43	floor finishes	vloerafwerkingen
44	stair and ramp finishes	Trap- en hellingafwerkingen
45	ceiling finishes	Plafondafwerkingen
47	roof finishes	Dakafwerkingen
5	**Services mainly piped and ducted**	**Installaties werktuigbouwkundig**
52	waste disposal	afvoeren
53	liquids supply	water
54	gasses supply	gassen
55	cooling	koeling
56	heating	verwarming
57	air conditioning	luchtbehandeling
6	**Services mainly electrical**	**Installaties elektrotechnisch**
61	electrical supply	centrale elektrotechnische voorzieningen
62	energy supply user connections	energievoorziening gebruikersaansluitingen
63	lighting	verlichting
66	transport	transport
7	**Fittings**	**Vaste voorzieningen**
73	culinary fittings	vaste keukenvoorzieningen
74	sanitary fittings	vaste sanitaire voorzieningen
9	**Terrain**	**Terrein**
90	terrain	terrein

F.3 Prototype Database Entries

Table F.3: Prototype Database Entries

NL/SfB Class	Product description	Example
13A floors on the ground - structure	C30/37 reinforced concrete floor	
13B floors on the ground - insulation	EPS floor insulation	
	Cork floor insulation	
	Rock wool insulation	
16 foundation	C30/37 concrete foundation	
21A external walls - structure	C30/37 concrete external wall	
	Calcium silicate external wall	
	Timber external wall frame	
21B external walls - insulation	EPS external wall insulation	
	Cork external wall insulation	

	Cellulose external wall insulation	
22A internal walls - structure	Calcium silicate internal wall	
	Timber internal wall frame	
	Steel internal wall frame	
22B internal walls - insulation	Wood fibre insulation	
	Rock wool insulation	
	Cellulose internal wall insulation	
23A floors - structure	CLT floor slab	
	Timber floor frame	
	Concrete hollow-core floor slab	
23B floors - insulation	Cork floor insulation	

	Wood fibre insulation	
	Rock wool insulation	
27A roofs - structure	CLT floor slab	
	Timber roof frame	
	Concrete hollow-core floor slab	
27B roofs - insulation	EPS roof insulation	
	Cork roof insulation	
	Wood fibre insulation	
28A load-bearing structures - general	Timber structure	
	Concrete structure (no reinforcement)	
	Steel structure	

28B load-bearing structures - reinforcement	Reinforcement steel	
31A external wall openings - windows (frames)	Timber window frame	
	PVC window frame	
	Aluminum window frame	
31B external wall openings - windows (glazing)	Double glazing glass	
32B internal wall openings - windows (glazing)	Double glazing glass	
33B floor openings - windows (glazing)	Double glazing glass	
37A roof openings - windows (frames)	Timber window frame	
	PVC window frame	
	Aluminum window frame	
37B roof openings - windows (glazing)	Double glazing glass	

41 external wall finishes	Brick strips	
	Steel plate cladding	
	Timber cladding	
42 internal wall finishes	Gypsum fibreboard	
	Multiplex sheet	
	Plasterboard	
43 floor finishes	Cast biobased floor	
	Ceramic floor tiles	
	Timber cladding	
45 ceiling finishes	Mineral fibre ceiling tiles	
	Plasterboard ceiling	

	Timber ceiling cladding	
47 roof finishes	Recycled bitumen roofing	
	Bitum roofing	
	Recycled plastic waste roofing	

G CODE

G.1 Grasshopper Component C# Template

```
using System;
using System.Collections.Generic;

using Grasshopper.Kernel;
using Rhino.Geometry;

namespace ReLifeCycleGHPlugin
{
    public class MyComponent1 : GH_Component
    {
        /// <summary>
        /// Initializes a new instance of the MyComponent1 class.
        /// </summary>
        public MyComponent1()
          : base("MyComponent1", "Nickname",
              "Description",
              "Category", "Subcategory")
        {
        }

        /// <summary>
        /// Registers all the input parameters for this component.
        /// </summary>
        protected override void RegisterInputParams(GH_Component.
            GH_InputParamManager pManager)
        {
        }

        /// <summary>
        /// Registers all the output parameters for this component.
        /// </summary>
        protected override void RegisterOutputParams(GH_Component.
            GH_OutputParamManager pManager)
        {
        }

        /// <summary>
        /// This is the method that actually does the work.
        /// </summary>
        /// <param name="DA">The DA object is used to retrieve from inputs and store
             in outputs.</param>
        protected override void SolveInstance(IGH_DataAccess DA)
        {
        }

        /// <summary>
        /// The Exposure property controls where in the panel a component icon
        /// will appear. There are seven possible locations (primary to septenary),
        /// each of which can be combined with the GH_Exposure.obscure flag, which
        /// ensures the component will only be visible on panel dropdowns.
        /// </summary>
```

```
        public override GH_Exposure Exposure => GH_Exposure.primary;

        /// <summary>
        /// Provides an Icon for the component.
        /// </summary>
        protected override System.Drawing.Bitmap Icon
        {
            get
            {
                //You can add image files to your project resources and access them like this:
                // return Resources.IconForThisComponent;
                return null;
            }
        }

        /// <summary>
        /// Gets the unique ID for this component. Do not change this ID after release.
        /// </summary>
        public override Guid ComponentGuid
        {
            get { return new Guid("D2E08562-627C-4101-A369-D0BF3869DB6D"); }
        }
    }
}
```

Listing 2: Empty Grasshopper C# component template

G.2 Pseudocode

Algorithm 7 Financial Impact Assessment Component

procedure FINANCIALIMPACTASSESSMENTCOMPONENT(BuildingData)
    Calculate Detailed Results: Group $buildingData$ by main path index
    for each building element group in $buildingData$ **do**
        Initialise $directCostsElement$, $materialCostsElement$, $labourCostsElement$, $truePriceElement$, $totalMKIElement$
        for each subbranch in group **do**
            if description starts with "MKI", "Material Costs", "Labour Costs" **then**
                Add value to $totalMKIElement$, $materialCostsElement$, $labourCostsElement$
            end if
        end for
        Calculate $directCostsElement$, $truePriceElement$
        Update Results: Append results to $detailedResults$
    end for
    Calculate Total Results:
    Calculate $totalMKI$, $totalMaterialCosts$, $totalLabourCosts$, $totalDirectCosts$, $totalTruePrice$
    Update Results: Append results to $totalResults$
    Set Outputs: Set $totalResults$ (as tree), $detailedResults$ (as tree)
end procedure

Algorithm 8 Circularity Assessment Component

```
procedure CircularityAssessmentComponent(BuildingData)
    Calculate Detailed Results: Group buildingData by main path index
    for each building element group in buildingData do
        Initialise totalMKIElement, totalMassElement, weightedPCIElement,
  weightedDPElement, weightedInputandOutputFlows
        for each subbranch in group do
            Retrieve description and value
            if description starts with "MKI", "Total Mass" then
                Add value to totalMKIElement, totalMassElement
            end if
            Calculate Weighted Circularity Indicators:
            for each subbranch in group do
                Retrieve PCIElement, DPElement, inputandOutputFlows
                Calculate weighted values based on totalMKIElement or totalMassElement
            end for
        end for
        Update Results: Append results to detailedResults
    end for
    Calculate Total Results:
    Calculate totalBCI, totalDP, totalNewIn, totalBioIn, totalRecIn, totalReuIn
  totalLanOut, totalBurOut, totalRecOut, totalReuOut
    Update Results: Append results to totalResults
    Set Outputs:
    Set totalResults (as tree), detailedResults (as tree)
end procedure
```

H GRASSHOPPER SCRIPTS

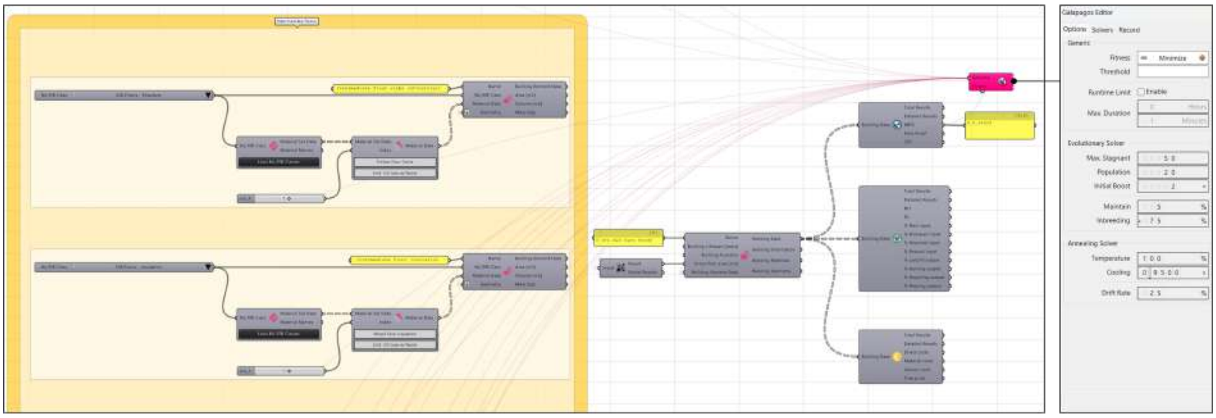

Figure H.1: Grasshopper script for integrating Galapagos with *ReLifeCycle*

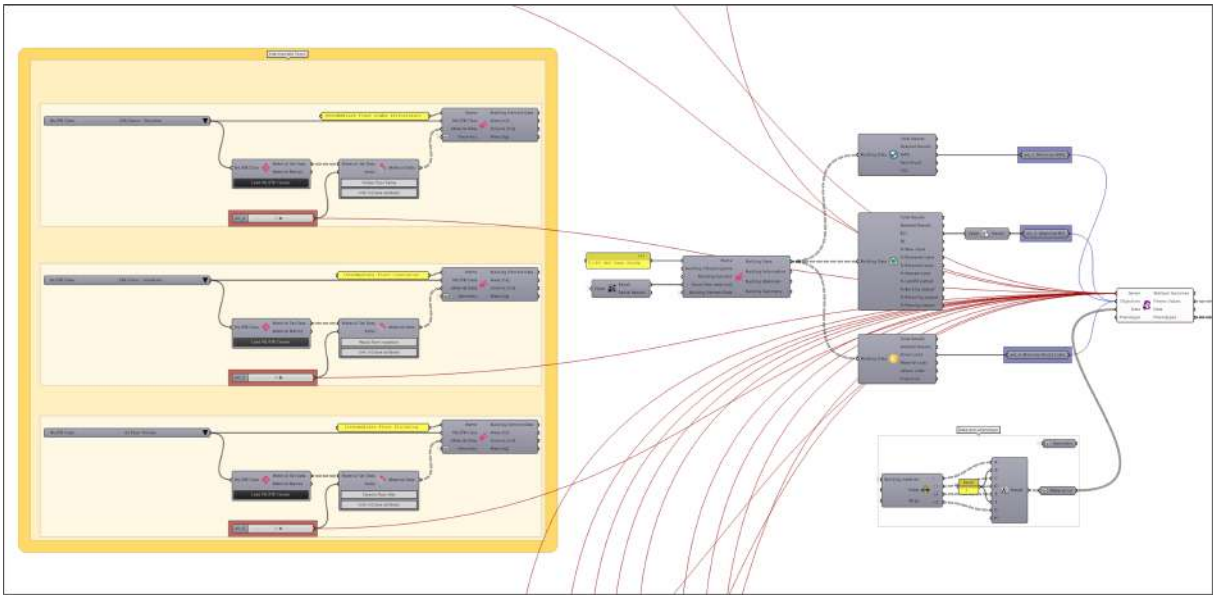

Figure H.2: Grasshopper script for integrating Wallacei with *ReLifeCycle* for MOO simulation 1

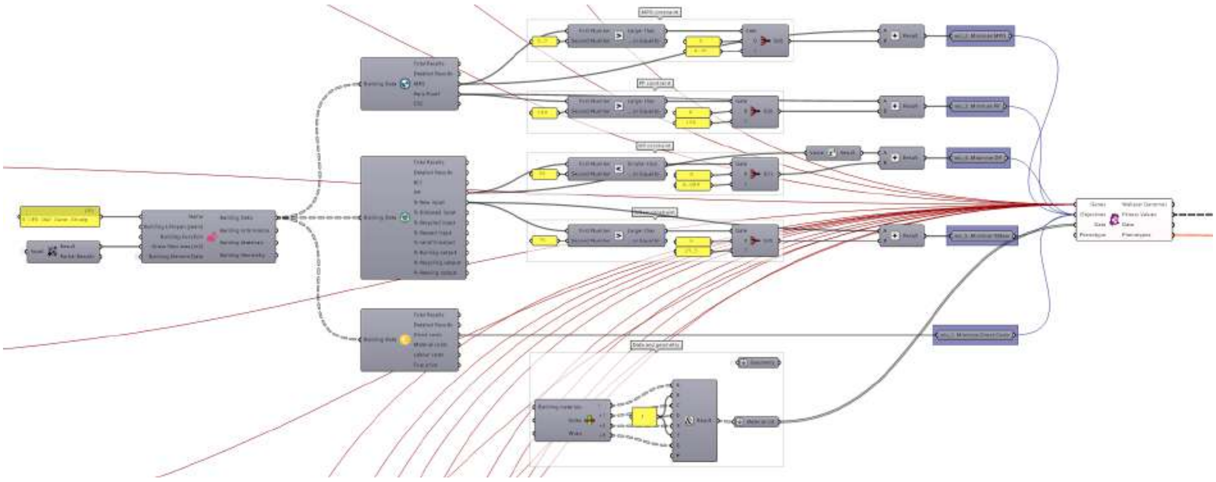

Figure H.3: Grasshopper script for integrating Wallacei with *ReLifeCycle* for MOO simulation 2

I APPLICATION RESULTS

I.1 Case Study Assessment Results

Table I.1: Assessment results of the benchmark comparison

Indicator	ReLifeCycle Result	Benchmark Result	Deviation
Environmental impact			
MPG [€ / m^2 GFA / year]	0.565	0.526	7.41%
PP [kg CO2 eq. / m^2 GFA]	90.26	86.56	4.27%
CSC [tonnes CO2]	37.32	39.14	-4.66%
Total MKI [€]	104199	101245.24	2.92%
Total GWP [kg CO2 eq.]	574452	560505.21	2.49%
Circularity			
BCI [%]	38	39	-1.00%
DP [%]	40	40	0%
Material input			
New [%]	86	85	1.00%
Biobased [%]	4	4	0%
Recycled [%]	11	11	0%
Reused [%]	0	0	0%
Material output			
Landfill [%]	13	13	0%
Burning [%]	7	7	0%
Recycling [%]	80	80	0%
Reusing [%]	0	0	0%
Financial impact			
Direct costs per NL/SfB Class			
13 Floors on the ground	€ 167,130	€ 146,704	14%
21 External walls	€ 69,423	€ 306,357	-77%
23 Floors	€ 114,225	€ 700,909	-84%
27 Roofs	€ 69,338	€ 500,486	-86%
28 Load-bearing structures	€ 163,547	€ 288,014	-43%
31 External wall openings	€ 215,783	€ 437,702	-51%
41 External wall finishes	€ 94,998	€ 195,440	-51%
42 Internal wall finishes	€ 20,740	€ 51,365	-60%
43 Floor finishes	€ 122,834	€ 78,089	57%
47 Roof finishes	€ 49,338	€ 34,528	43%
Total direct costs	**€ 1,087,356**	**€ 2,739,594**	**-60%**

Table I.2: Assessment results of the SOO simulations on environmental impact

Indicator	Minimise MPG	Minimise PP	Maximise CC
Environmental impact			
MPG [€ / m^2 GFA / year]	0.311	0.366	0.354
PP [kg CO2 eq. / m^2 GFA]	-62.53	-310.77	-192.22
CSC [tonnes CO2]	267.58	520.48	569.32
Total MKI [€]	57118	67164	65046
Total GWP [kg CO2 eq.]	316048	417008	370693
Circularity			
BCI [%]	40	42	42
DP [%]	45	39	45
Material input			
New [%]	81	58	57
Biobased [%]	18	42	43
Recycled [%]	1	1	1
Reused [%]	0	0	0
Material output			
Landfill [%]	17	6	6
Burning [%]	1	39	4
Recycling [%]	66	54	52
Reusing [%]	0	0	0
Financial impact			
Total direct costs [€]	1,278,320	2,360,588	1,827,925
Total true price [€]	1,335,439	2,427,752	1,892,971
Direct costs per m^2 GFA [€]	348	642	497
True price per m^2 GFA [€]	363	661	515
Material costs per m^2 GFA [€]	228	534	392
Labour costs per m^2 GFA [€]	120	109	105
Shadow costs per m^2 GFA [€]	16	18	18

Table I.3: Assessment results of the SOO simulations on circularity

Indicator	Maximise BCI	Maximise DP	Minimise %New
Environmental impact			
MPG [€ / m^2 GFA / year]	0.377	0.377	0.312
PP [kg CO2 eq. / m^2 GFA]	-104.14	-104.14	-194.94
CSC [tonnes CO2]	459.7	459.7	569.32
Total MKI [€]	69401	69401	57255
Total GWP [kg CO2 eq.]	402035	402035	336756
Circularity			
BCI [%]	55	55	47
DP [%]	60	60	49
Material input			
New [%]	57	57	56
Biobased [%]	37	37	43
Recycled [%]	6	6	1
Reused [%]	0	0	0
Material output			
Landfill [%]	6	6	6
Burning [%]	36	36	41
Recycling [%]	58	58	53
Reusing [%]	0	0	0
Financial impact			
Total direct costs [€]	1,709,015	1,709,015	1,841,141
Total true price [€]	1,778,417	1,778,417	1,898,396
Direct costs per m^2 GFA [€]	464	464	501
True price per m^2 GFA [€]	482	482	517
Material costs per m^2 GFA [€]	347	347	392
Labour costs per m^2 GFA [€]	117	117	109
Shadow costs per m^2 GFA [€]	19	19	16

Table I.4: Assessment results of the SOO simulations on financial impact

Indicator	**Minimise Direct Costs**	**Minimise True Price**
Environmental impact		
MPG [€ / m^2 GFA / year]	0.464	0.477
PP [kg CO2 eq. / m^2 GFA]	39.27	48.64
CSC [tonnes CO2]	100.46	69.89
Total MKI [€]	85431	86835
Total GWP [kg CO2 eq.]	466466	481271
Circularity		
BCI [%]	32	31
DP [%]	32	32
Material input		
New [%]	93	94
Biobased [%]	5	4
Recycled [%]	2	2
Reused [%]	0	0
Material output		
Landfill [%]	14	15
Burning [%]	7	5
Recycling [%]	79	79
Reusing [%]	0	0
Financial impact		
Total direct costs [€]	900,537	900,537
Total true price [€]	992,291	985,968
Direct costs per m^2 GFA [€]	245	245
True price per m^2 GFA [€]	270	268
Material costs per m^2 GFA [€]	135	135
Labour costs per m^2 GFA [€]	110	110
Shadow costs per m^2 GFA [€]	25	23

Table I.5: Assessment results of MOO simulation 1

Indicator	Gen 99 ind. 7 (Lowest direct costs)	Gen 99 ind. 8 (Highest direct costs)	Gen 99 ind. 26 (High BCI, low MPG)	Gen 99 ind. 26 (Balanced)
Environmental impact				
MPG [€ / m^2 GFA / year]	0.48	0.349	0.392	0.351
PP [kg CO2 eq. / m^2 GFA]	56.2	-138.34	-29.24	5.44
CSC [tonnes CO2]	91.55	419.84	202.17	211.03
Total MKI [€]	88283	64189	72179	64553
Total GWP [kg CO2 eq.]	477003	374633	409646	352149
Circularity				
BCI [%]	34	45	49	40
DP [%]	36	47	53	48
Material input				
New [%]	93	65	78	85
Biobased [%]	5	34	15	14
Recycled [%]	2	1	7	1
Reused [%]	0	0	0	0
Material output				
Landfill [%]	13	8	13	16
Burning [%]	8	3	1	1
Recycling [%]	79	59	71	69
Reusing [%]	0	0	0	0
Financial impact				
Total direct costs [€]	967,909	1,690,277	1,444,039	1,145,697
Total true price [€]	1,056,192	1,754,465	1,516,218	1,210,250
Direct costs per m^2 GFA [€]	263	460	392	312
True price per m^2 GFA [€]	287	477	411	329
Material costs per m^2 GFA [€]	144	340	258	182
Labour costs per m^2 GFA [€]	119	120	134	130
Shadow costs per m^2 GFA [€]	24	17	20	18

Table I.6: Assessment results of MOO simulation 2

Indicator	**Gen 99 ind. 11 (Lowest direct costs)**	**Gen 99 ind. 6 (Medium direct costs)**	**Gen 99 ind. 12 (Highest costs)**
Environmental impact			
MPG [€ / m^2 GFA / year]	0.396	0.38	0.4
PP [kg CO2 eq. / m^2 GFA]	-74.45	-100.94	-133.38
CSC [tonnes CO2]	390.91	443.6	411.59
Total MKI [€]	73003	70005	73674
Total GWP [kg CO2 eq.]	419514	407043	435509
Circularity			
BCI [%]	51	54	52
DP [%]	55	57	55
Material input			
New [%]	62	59	60
Biobased [%]	31	35	34
Recycled [%]	6	6	6
Reused [%]	0	0	0
Material output			
Landfill [%]	8	6	6
Burning [%]	3	3	3
Recycling [%]	62	60	61
Reusing [%]	0	0	0
Financial impact			
Total direct costs [€]	1,558,772	1,680,785	1,818,988
Total true price [€]	1,631,774	1,750,790	1,892,663
Direct costs per m^2 GFA [€]	423	456	493
True price per m^2 GFA [€]	443	475	513
Material costs per m^2 GFA [€]	305	340	373
Labour costs per m^2 GFA [€]	117	116	120
Shadow costs per m^2 GFA [€]	20	19	20

Table I.7: Assessment results of the tweaked MOO solution and the final solution after geometry optimisation

Indicator	Tweaked final MOO solution	Geometry optimisation (final solution)
Environmental impact		
MPG [€ / m^2 GFA / year]	0.395	0.397
PP [kg CO2 eq. / m^2 GFA]	-49.68	-54.19
CSC [tonnes CO2]	338.88	303.6
Total MKI [€]	72741	63564
Total GWP [kg CO2 eq.]	414046	361620
Circularity		
BCI [%]	51	51
DP [%]	55	55
Material input		
New [%]	66	65
Biobased [%]	27	28
Recycled [%]	7	7
Reused [%]	0	0
Material output		
Landfill [%]	9	10
Burning [%]	2	2
Recycling [%]	64	63
Reusing [%]	0	0
Financial impact		
Total direct costs [€]	1,459,143	1,279,755
Total true price [€]	1,531,884	1,343,318
Direct costs per m^2 GFA [€]	396	400
True price per m^2 GFA [€]	416	420
Material costs per m^2 GFA [€]	276	280
Labour costs per m^2 GFA [€]	120	120
Shadow costs per m^2 GFA [€]	20	20

I.2 Case Study Materialisation Results

Table I.8: Initial materialisation for the O&O case study. Excluded NL/SfB classifications have been greyed out

NL/SfB class	Building element	Material
11 Ground	-	-
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	EPS floor insulation
16 Foundation	-	-
17 Pile foundations	-	-
21A External walls - Structure	Facade walls structure	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	Cellulose external wall insulation
22A Internal walls - Structure	-	-
22B Internal walls - Insulation	-	-
23A Floors - Structure	Intermediate floor slabs (structural)	Timber floor frame
	Gym floor slab (structural)	Concrete hollow-core floor slab
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation
	Gym floor insulation	Rock wool insulation
24 Stairs and ramps	-	-
27A Roofs - Structure	Roof slabs (structural)	Timber roof frame
27B Roofs - Insulation	Roof insulation	EPS roof insulation
28A Load-bearing structures - General	Structural skeleton	Steel structure
28B Load-bearing structures - Reinforcement	-	-
31A External wall openings - Windows (frames)	Window frames	Aluminum window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass
31C External wall openings - Doors	-	-
32A Internal wall openings - Windows (frames)	-	-
32B Internal wall openings - Windows (glazing)	-	-
32C Internal wall openings - Doors	-	-
33A Floor openings - Windows (frames)	-	-
33B Floor openings - Windows (glazing)	-	-
34 Stair balustrades and handrails	-	-
37A Roof openings - Windows (frames)	-	-
37B Roof openings - Windows (glazing)	-	-
41 External wall finishes	Facade walls cladding	Brick strips
42 Internal wall finishes	Façade walls interior finishing	Gypsum fibreboard
43 Floor finishes	Ground floor finishing	Cast biobased floor
	Intermediate floor finishing	Cast biobased floor
	Gym floor finishing	Cast biobased floor
44 Stair and ramp finishes	-	-
45 Ceiling finishes	-	-
47 Roof finishes	Roof finishing	Bitum roofing

Table I.9: Overview of materialisations from the SOO simulations (one indicator per responsible material use aspect)

NL/SfB class	Building element	Material (Minimise MPG)	Material (Maximise BCI)	Material (Minimise Direct Costs)
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	Cork floor insulation	EPS floor insulation	EPS floor insulation
21A External walls - Structure	Facade walls structure	Timber external wall frame	Tiber external wall frame	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	Cellulose external wall insulation	Cellulose external wall insulation	EPS external wall insulation
23A Floors - Structure	Intermediate floor slabs (structural)	Timber floor frame	CLT floor slab	Timber floor frame
	Gym floor slab (structural)	Timber floor frame	CLT floor slab	Timber floor frame
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
	Gym floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
27A Roofs - Structure	Roof slabs (structural)	Timber roof frame	CLT floor slab	Timber roof frame
27B Roofs - Insulation	Roof insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
28A Load-bearing structures - General	Structural skeleton	Timber structure	Steel structure	Concrete structure
28B Load-bearing structures - Reinforcement	-	-	-	Reinforcement steel
31A External wall openings - Windows (frames)	Window frames	PVC window frame	Aluminum window frame	PVC window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass	Double glazing glass	Double glazing glass
41 External wall finishes	Facade walls cladding	Timber cladding	Timber cladding	Brick strips
42 Internal wall finishes	Façade walls interior finishing	Plasterboard	Multiplex sheet	Gypsum fibreboard
43 Floor finishes	Ground floor finishing	Timber cladding	Timber cladding	Cast biobased floor
	Intermediate floor finishing	Timber cladding	Timber cladding	Cast biobased floor
	Gym floor finishing	Timber cladding	Timber cladding	Cast biobased floor
47 Roof finishes	Roof finishing	Recycled bitumen roofing	Recycled plastic waste roofing	Bitumen roofing

Table I.10: Materialisations for the SOO simulations on environmental impact

NL/SfB class	Building element	Material (Minimise MPG)	Material (Minimise PP)	Material (Maximise CC)
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	Cork floor insulation	Cork floor insulation	Cork floor insulation
21A External walls - Structure	Facade walls structure	Timber external wall frame	Timber external wall frame	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	Cellulose external wall insulation	Cork external wall insulation	Cellulose external wall insulation
23A Floors - Structure	Intermediate floor slabs (structural)	Timber floor frame	CLT floor slab	CLT floor slab
	Gym floor slab (structural)	Timber floor frame	CLT floor slab	CLT floor slab
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation	Cork floor insulation	Wood fibre insulation
	Gym floor insulation	Wood fibre insulation	Cork floor insulation	Wood fibre insulation
27A Roofs - Structure	Roof slabs (structural)	Timber roof frame	CLT floor slab	CLT floor slab
27B Roofs - Insulation	Roof insulation	Wood fibre insulation	Cork roof insulation	Wood fibre insulation
28A Load-bearing structures - General	Structural skeleton	Timber structure	Timber structure	Timber structure
28B Load-bearing structures - Reinforcement	-	-	-	-
31A External wall openings - Windows (frames)	Window frames	PVC window frame	Timber window frame	Timber window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass	Double glazing glass	Double glazing glass
41 External wall finishes	Facade walls cladding	Timber cladding	Timber cladding	Timber cladding
42 Internal wall finishes	Façade walls interior finishing	Plasterboard	Multiplex sheet	Multiplex sheet
43 Floor finishes	Ground floor finishing	Timber cladding	Timber cladding	Timber cladding
	Intermediate floor finishing	Timber cladding	Timber cladding	Timber cladding
	Gym floor finishing	Timber cladding	Timber cladding	Timber cladding
47 Roof finishes	Roof finishing	Recycled bitumen roofing	Recycled plastic waste roofing	Bitumen roofing

Table I.11: Materialisations for the SOO simulations on circularity

NL/SfB class	Building element	Material (Maximise BCI)	Material (Maximise DP)	Material (Minimise %New)
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	EPS floor insulation	EPS floor insulation	Cork floor insulation
21A External walls - Structure	Facade walls structure	Tiber external wall frame	Tiber external wall frame	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	Cellulose external wall insulation	Cellulose external wall insulation	Cellulose external wall insulation
23A Floors - Structure	Intermediate floor slabs (structural)	CLT floor slab	CLT floor slab	CLT floor slab
	Gym floor slab (structural)	CLT floor slab	CLT floor slab	CLT floor slab
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
	Gym floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
27A Roofs - Structure	Roof slabs (structural)	CLT floor slab	CLT floor slab	CLT floor slab
27B Roofs - Insulation	Roof insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
28A Load-bearing structures - General	Structural skeleton	Steel structure	Steel structure	Timber structure
28B Load-bearing structures - Reinforcement	-	-	-	-
31A External wall openings - Windows (frames)	Window frames	Aluminum window frame	Aluminum window frame	Timber window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass	Double glazing glass	Double glazing glass
41 External wall finishes	Facade walls cladding	Timber cladding	Timber cladding	Timber cladding
42 Internal wall finishes	Façade walls interior finishing	Multiplex sheet	Multiplex sheet	Multiplex sheet
43 Floor finishes	Ground floor finishing	Timber cladding	Timber cladding	Timber cladding
	Intermediate floor finishing	Timber cladding	Timber cladding	Timber cladding
	Gym floor finishing	Timber cladding	Timber cladding	Timber cladding
47 Roof finishes	Roof finishing	Recycled plastic waste roofing	Recycled plastic waste roofing	Recycled plastic waste roofing

Table I.12: Materialisations for the SOO simulations on financial impact

NL/SfB class	Building element	Material (Minimise Direct Costs)	Material (Minimise True Price)
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	EPS floor insulation	EPS floor insulation
21A External walls - Structure	Facade walls structure	Timber external wall frame	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	EPS external wall insulation	EPS external wall insulation
23A Floors - Structure	Intermediate floor slabs (structural)	Timber floor frame	Timber floor frame
	Gym floor slab (structural)	Timber floor frame	Timber floor frame
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation	Wood fibre insulation
	Gym floor insulation	Wood fibre insulation	Wood fibre insulation
27A Roofs - Structure	Roof slabs (structural)	Timber roof frame	Timber roof frame
27B Roofs - Insulation	Roof insulation	Wood fibre insulation	Wood fibre insulation
28A Load-bearing structures - General	Structural skeleton	Concrete structure	Concrete structure
28B Load-bearing structures - Reinforcement	-	Reinforcement steel	Reinforcement steel
31A External wall openings - Windows (frames)	Window frames	PVC window frame	PVC window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass	Double glazing glass
41 External wall finishes	Facade walls cladding	Brick strips	Brick strips
42 Internal wall finishes	Façade walls interior finishing	Gypsum fibreboard	Gypsum fibreboard
43 Floor finishes	Ground floor finishing	Cast biobased floor	Cast biobased floor
	Intermediate floor finishing	Cast biobased floor	Cast biobased floor
	Gym floor finishing	Cast biobased floor	Cast biobased floor
47 Roof finishes	Roof finishing	Bitumen roofing	Recycled bitumen roofing

Table I.13: Materialisations for the selected solutions of MOO simulation 1

NL/SfB class	**Building element**	**Material** **Gen 99 ind. 7 (Lowest direct costs)**	**Material** **Gen 99 ind. 8 (Highest direct costs)**	**Material** **Gen 99 ind. 26 (High BCI, low MPG)**	**Material** **Gen 99 ind. 26 (Balanced)**
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	Rock wool insulation	Cork floor insulation	Cork floor insulation	Rock wool insulation
21A External walls - Structure	Facade walls structure	Timber external wall frame	Timber external wall frame	Timber external wall frame	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	EPS external wall insulation	Cellulose wall insulation	EPS external wall insulation	Cellulose external wall insulation
23A Floors - Structure	Intermediate floor slabs (structural)	Timber floor frame	CLT floor slab	Timber floor frame	Timber floor frame
	Gym floor slab (structural)	Timber floor frame	Timber floor frame	CLT floor slab	Timber floor frame
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
	Gym floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
27A Roofs - Structure	Roof slabs (structural)	Timber roof frame	CLT floor slab	Timber roof frame	Timber roof frame
27B Roofs - Insulation	Roof insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
28A Load-bearing structures - General	Structural skeleton	Concrete structure	Timber structure	Steel structure	Timber structure
28B Load-bearing structures - Reinforcement	Structural skeleton - reinforcement	Reinforcement steel	-	-	-
31A External wall openings - Windows (frames)	Window frames	Aluminum window frame	PVC window frame	Aluminum window frame	PVC window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass	Double glazing glass	Double glazing glass	Double glazing glass
41 External wall finishes	Facade walls cladding	Steel plate cladding	Steel plate cladding	Timber cladding	Steel plate cladding
42 Internal wall finishes	Façade walls interior finishing	Multiplex sheet	Multiplex sheet	Multiplex sheet	Multiplex sheet
43 Floor finishes	Ground floor finishing	Cast biobased floor	Timber cladding	Timber cladding	Timber cladding
	Intermediate floor finishing	Cast biobased floor	Ceramic floor tiles	Ceramic floor tiles	Ceramic floor tiles
	Gym floor finishing	Ceramic floor tiles	Ceramic floor tiles	Ceramic floor tiles	Ceramic floor tiles
47 Roof finishes	Roof finishing	Recycled bitumen roofing	Recycled bitumen roofing	Recycled plastic waste roofing	Recycled bitumen roofing

Table I.14: Materialisations for the selected solutions of MOO simulation 2

NL/SfB class	Building element	Material Gen 99 ind. 11 (Lowest direct costs)	Material Gen 99 ind. 6 (Medium direct costs)	Material Gen 99 ind. 12 (Highest costs)
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	EPS floor insulation	EPS floor insulation	EPS floor insulation
21A External walls - Structure	Facade walls structure	Timber external wall frame	Timber external wall frame	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	EPS external wall insulation	EPS external wall insulation	Cork external wall insulaiton
23A Floors - Structure	Intermediate floor slabs (structural)	CLT floor slab	CLT floor slab	CLT floor slab
	Gym floor slab (structural)	Timber floor frame	CLT floor slab	CLT floor slab
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
	Gym floor insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
27A Roofs - Structure	Roof slabs (structural)	CLT floor slab	CLT floor slab	CLT floor slab
27B Roofs - Insulation	Roof insulation	Wood fibre insulation	Wood fibre insulation	Wood fibre insulation
28A Load-bearing structures - General	Structural skeleton	Steel structure	Steel structure	Steel structure
28B Load-bearing structures - Reinforcement	Structural skeleton - reinforcement	-	-	-
31A External wall openings - Windows (frames)	Window frames	PVC window frame	PVC window frame	PVC window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass	Double glazing glass	Double glazing glass
41 External wall finishes	Facade walls cladding	Timber cladding	Timber cladding	Timber cladding
42 Internal wall finishes	Façade walls interior finishing	Multiplex sheet	Multiplex sheet	Multiplex sheet
43 Floor finishes	Ground floor finishing	Timber cladding	Timber cladding	Ceramic floor tiles
	Intermediate floor finishing	Timber cladding	Timber cladding	Timber cladding
	Gym floor finishing	Cast biobased floor	Ceramic floor tiles	Ceramic floor tiles
47 Roof finishes	Roof finishing	Recycled plastic waste roofing	Recycled plastic waste roofing	Recycled plastic waste roofing

Table I.15: Materialisations for the final MOO solution and its tweaked variant with the adjusted materials in bold

NL/SfB class	Building element	Material Final MOO solution	Material Tweaked final MOO solution
13A Floors on the ground - Structure	Ground floor slab	C30/37 reinforced concrete floor	C30/37 reinforced concrete floor
13B Floors on the ground - Insulation	Ground floor insulation	EPS floor insulation	EPS floor insulation
21A External walls - Structure	Facade walls structure	Timber external wall frame	Timber external wall frame
21B External walls - Insulation	Facade walls insulation	EPS external wall insulation	EPS external wall insulation
23A Floors - Structure	Intermediate floor slabs (structural)	CLT floor slab	CLT floor slab
	Gym floor slab (structural)	Timber floor frame	**CLT floor slab**
23B Floors - Insulation	Intermediate floor insulation	Wood fibre insulation	Wood fibre insulation
	Gym floor insulation	Wood fibre insulation	Wood fibre insulation
27A Roofs - Structure	Roof slabs (structural)	CLT floor slab	**Timber roof frame**
27B Roofs - Insulation	Roof insulation	Wood fibre insulation	Wood fibre insulation
28A Load-bearing structures - General	Structural skeleton	Steel structure	Steel structure
28B Load-bearing structures - Reinforcement	Structural skeleton - reinforcement	-	-
31A External wall openings - Windows (frames)	Window frames	PVC window frame	PVC window frame
31B External wall openings - Windows (glazing)	Window glass	Double glazing glass	Double glazing glass
41 External wall finishes	Facade walls cladding	Timber cladding	Timber cladding
42 Internal wall finishes	Façade walls interior finishing	Multiplex sheet	Multiplex sheet
43 Floor finishes	Ground floor finishing	Timber cladding	Timber cladding
	Intermediate floor finishing	Timber cladding	Timber cladding
	Gym floor finishing	Cast biobased floor	Cast biobased floor
47 Roof finishes	Roof finishing	Recycled plastic waste roofing	Recycled plastic waste roofing

I.3 Wallacei Analytics

I.3.1 MOO Simulation 1: Optimise MPG, BCI, Direct Costs

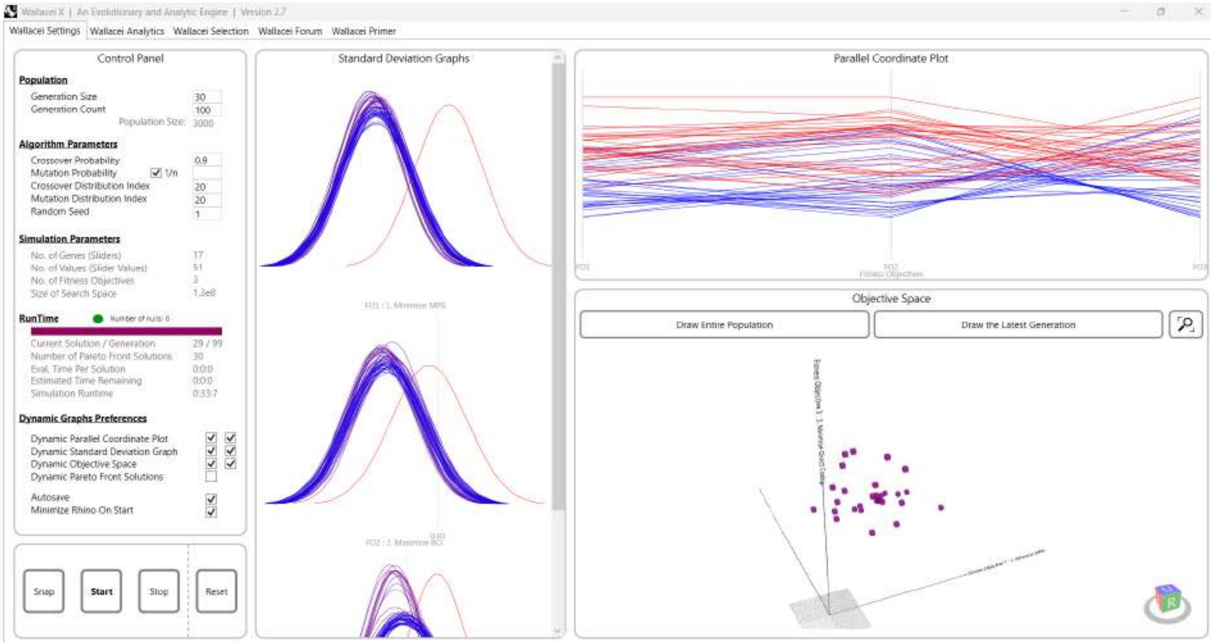

Figure I.1: Parameters and results for the final 50 solutions of MOO simulation 1

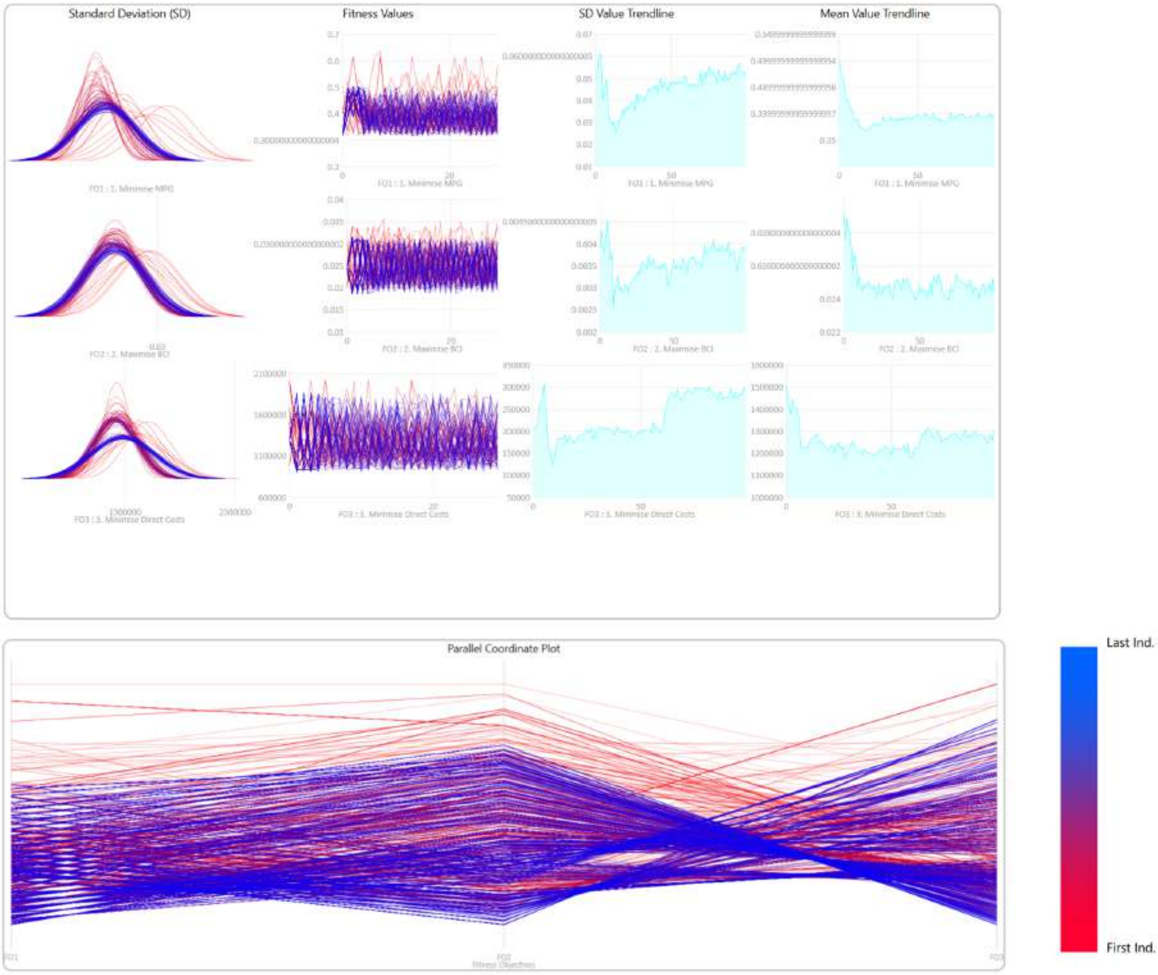

Figure I.2: Analytics of MOO simulation 1

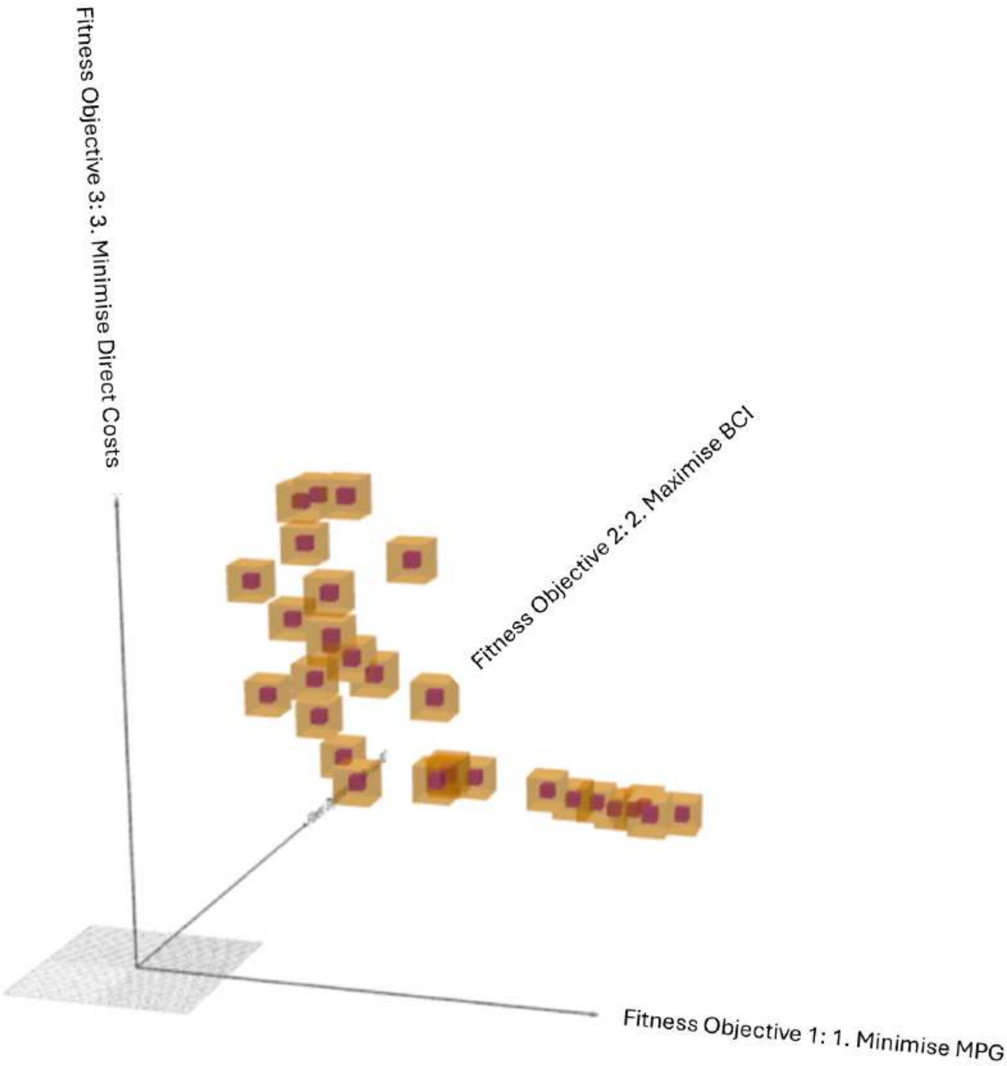

Figure I.3: 3D Pareto front of MOO simulation 1

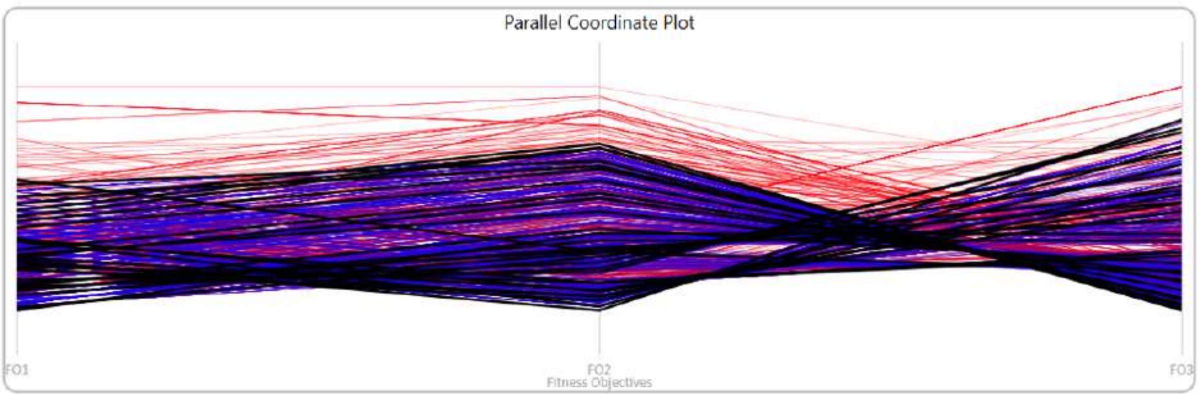

Figure I.4: Pareto front shown on the parallel coordinate plot of MOO simulation 1

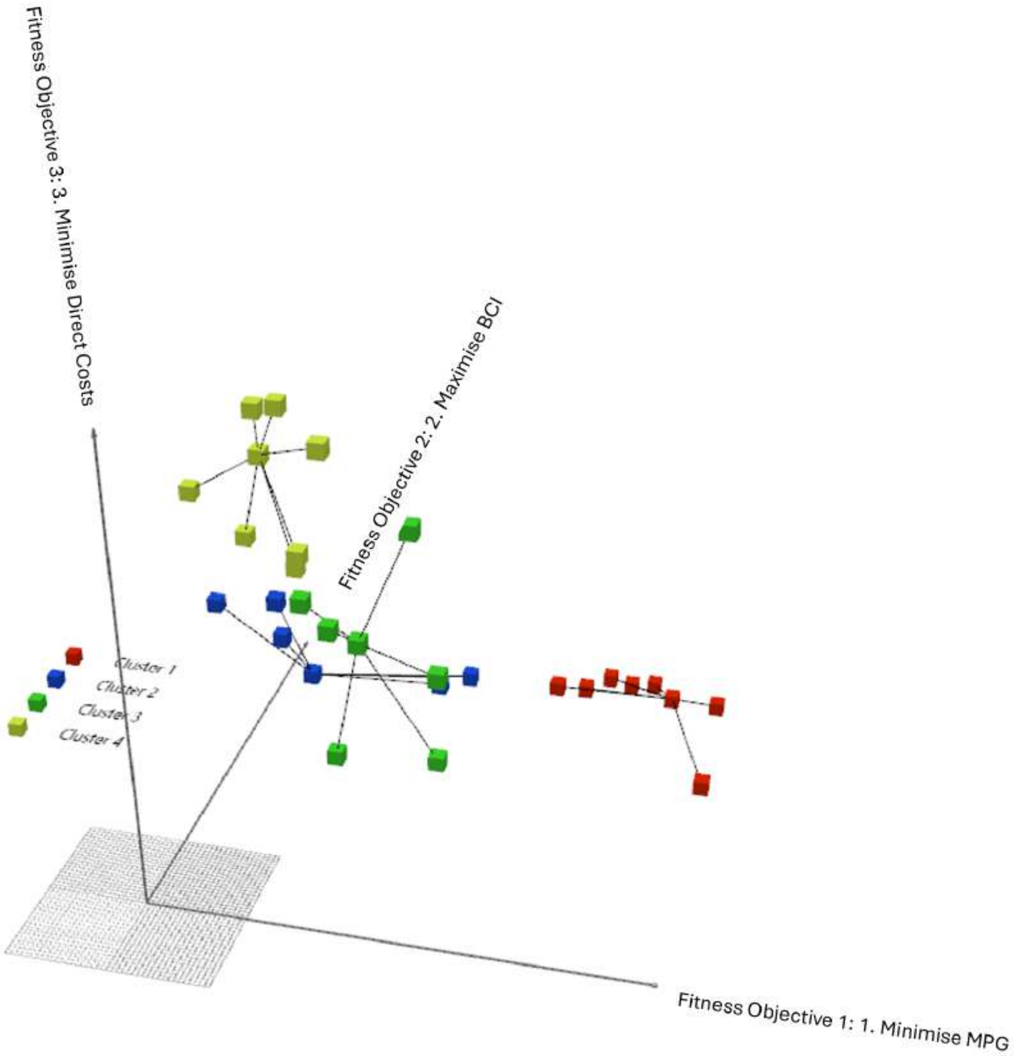

Figure I.5: Clusters for final generation of MOO simulation 1

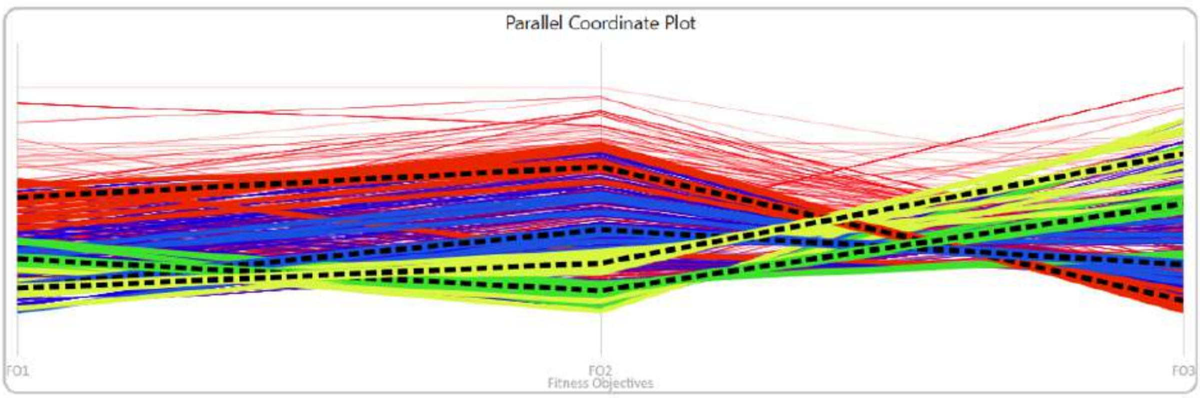

Figure I.6: Clusters shown on the parallel coordinate plot of MOO simulation 1

Figure I.7: Diamond fitness charts of the selected solutions from MOO simulation 1

I.3.2 MOO Simulation 2: Optimise Direct Costs, Case study requirements

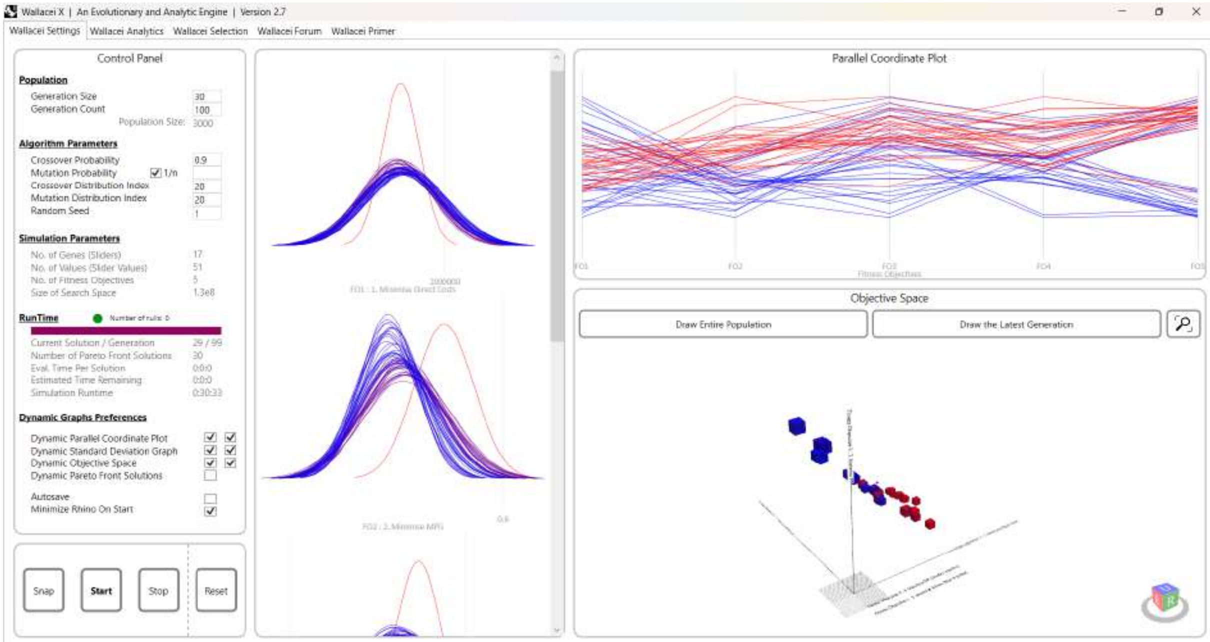

Figure I.8: Parameters and results for the final 50 solutions of MOO simulation 2

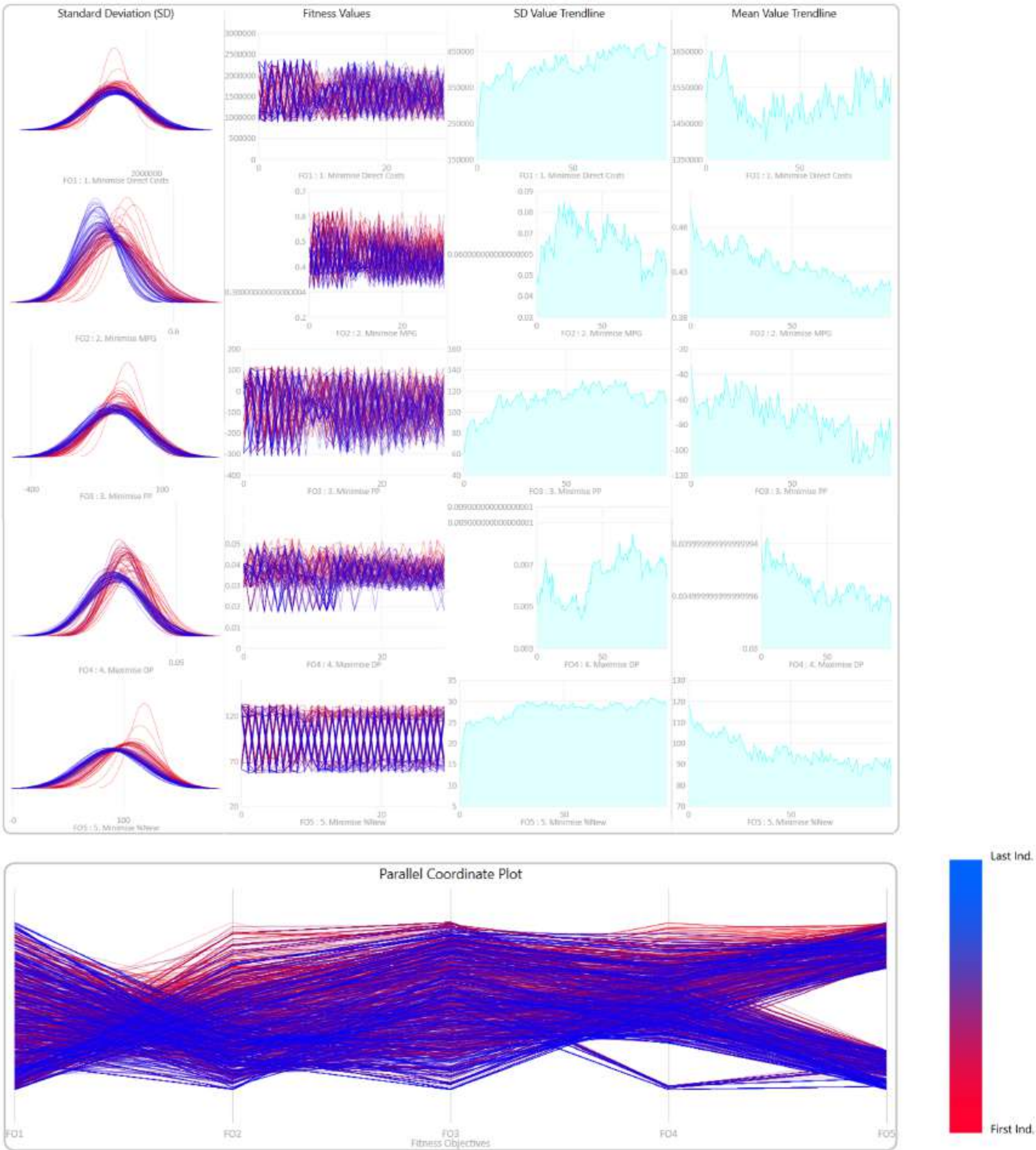

Figure I.9: Analytics of MOO simulation 2

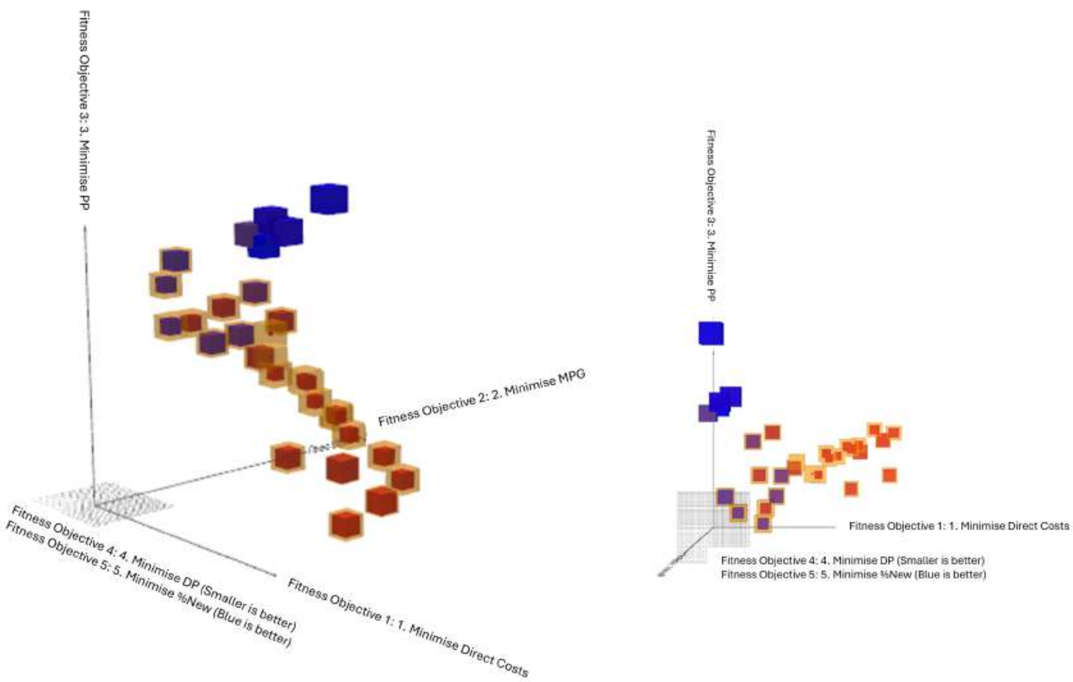

Figure I.10: 3D Pareto front of MOO simulation 2

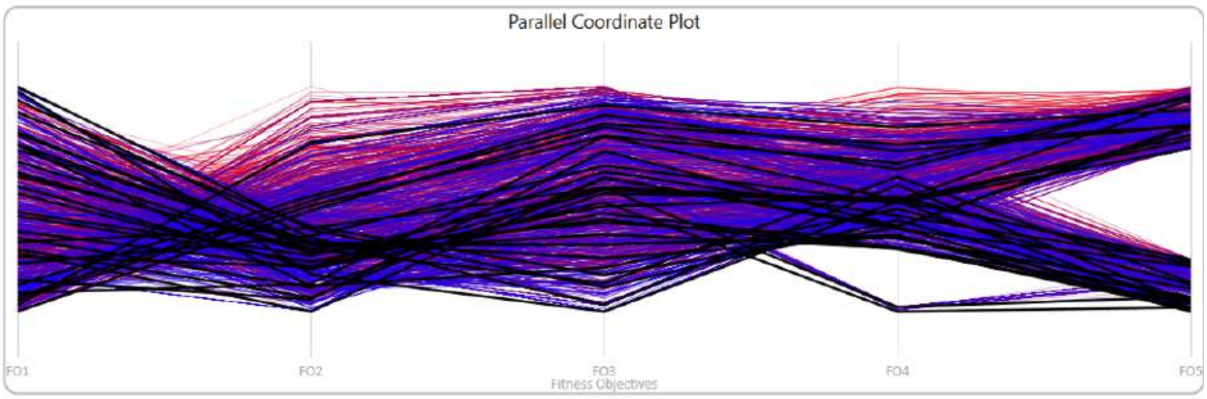

Figure I.11: Pareto front shown on the parallel coordinate plot of MOO simulation 2

Figure I.12: Diamond fitness charts of the final generation of MOO simulation 2

J REQUIREMENTS EVALUATION

Table J.1: Non-Functional Requirements Evaluation

ID	Requirement	Priority	Status
	1. Model Linking & Material Mapping		
NFR_1.01	The system must be able to store general, environmental, circularity, and cost-related data of materials in a relational MySQL database	MUST	Completed
NFR_1.02	The system must be able to process data stored in an external MySQL database	MUST	Completed
NFR_1.03	The system won't have more than one database for each aspect of responsible material use (environmental impact, financial impact, circularity)	WON'T	-
NFR_1.04	The system won't have a direct connection with the original environmental, circularity and cost databases	WON'T	-
NFR_1.05	The system must allow the user to link building element Grasshopper geometry to the system with a custom Grasshopper component	MUST	Completed
NFR_1.06	The system must present the user with an overview of geometry input requirements	MUST	Completed
NFR_1.07	The system must be able to classify a building element from the model with an NL/SfB code	MUST	Completed
NFR_1.08	The system must be able to create a material set with suitable materials for each NL/SfB classification	MUST	Completed
NFR_1.09	The system must be able to link material data to building element Grasshopper geometry	MUST	Completed
NFR_1.10	The system must display an error when the building element geometry does not match the functional unit of the material	MUST	Completed
NFR_1.11	The material list should contain general environmental, circularity and cost information	SHOULD	Partially completed
NFR_1.12	The system could present the material list as a separate pop-up window	COULD	Not completed
NFR_1.13	The material list could have a search function	COULD	Not completed
NFR_1.14	The material list could have a filter function	COULD	Not completed
NFR_1.15	The system should be able to assign a name to a building element	SHOULD	Completed
NFR_1.16	The system could include automatic structural dimensioning	COULD	Not completed
NFR_1.17	The system could include automatic insulation dimensioning based on R-value	COULD	Not completed
NFR_1.18	The system won't be able to process IFC data from a BIM model	WON'T	-
NFR_1.19	The system won't be able to link an imported BIM model by mapping the IFC categories to NL/SfB codes	WON'T	-
NFR_1.20	The system could be able to create a custom material based on data delivered by the user	COULD	Not completed
NFR_1.21	The system could link a simple building mass with a custom Grasshopper component	COULD	Not completed
NFR_1.22	The system could classify a simple building mass with general building information	COULD	Not completed

Continued on next page

ID	Requirement	Priority	Status
NFR_1.23	The system must include a demo Grasshopper script that explains the workings of the tool with a case study	MUST	Completed
2. Responsible Material Use Assessment			
NFR_2.01	The system must be able to perform a responsible material use assessment for the linked building elements with a custom Grasshopper component for each responsible material use aspect (environmental impact, circularity, financial impact)	MUST	Completed
NFR_2.02	The system must be able to perform an environmental impact calculation by considering the MPG, Paris Proof and Construction Stored Carbon	MUST	Completed
NFR_2.03	The system must be able to perform a circularity calculation by considering the Building Circularity Index (BCI), Disassembly Potential (DP), material input flows and material output flows	MUST	Completed
NFR_2.04	The system must be able to perform a financial impact calculation by considering the material costs, labour costs and true pricing	MUST	Completed
NFR_2.05	The system must allow the user to set the following calculation variables: - Building lifespan [years] - Building function - GFA [m^2]	MUST	Completed
NFR_2.06	The system must measure the quantity of a building component used in the calculation according to the functional unit of the selected material (m, m^2, m^3, piece)	MUST	Completed
NFR_2.07	The system must be capable of processing design changes and parameter adjustments in real-time, updating results and visualisations immediately	MUST	Completed
NFR_2.08	The system should provide a text with documentation on the used assessment methods and databases	SHOULD	Not completed
NFR_2.09	The system should give a user the option to choose if a material is new or reused with a toggle	SHOULD	Not completed
NFR_2.10	The system should apply extra benefits for the circularity and environmental impact assessments when a reused material is selected	SHOULD	Not completed
NFR_2.11	The system could give the user freedom to include or exclude specific life cycle stages with a multiple value list	COULD	Not completed
NFR_2.12	The system could set a reference date and consistently retrieve the data used for the assessment on that date	COULD	Not completed
NFR_2.13	The system will not give the user freedom to change the calculation methods	WON'T	-
NFR_2.14	The system will not consider the Element Circularity Index (ECI) in the BCI calculation	WON'T	-
3. Responsible Material Use Enhancement			
NFR_3.01	The system must include an optimisation functionality by facilitating an integration with an external multi-objective optimisation Grasshopper plugin	MUST	Completed
NFR_3.02	The integration between the system and the multi-objective optimisation plugin must be explained in an example script with a simple building case	MUST	Completed
NFR_3.03	The system must be able to process decision variables (genome)	MUST	Completed
NFR_3.04	The system must be able to process objective functions	MUST	Completed
NFR_3.05	The system must be able to process constraints	MUST	
NFR_3.06	The system must be able to set a count for the amount of design variations	MUST	Completed

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ID	Requirement	Priority	Status
NFR_3.07	The system must be able to perform an optimisation on material choices	MUST	Completed
NFR_3.08	The system could be able to perform an optimisation on geometry	COULD	Partially completed
NFR_3.09	The system must assign a unique name to each design variant	MUST	Partially completed
NFR_3.10	The system should be able to name, store and load variants generated during the optimisation process by storing their parameters and material choices	SHOULD	Completed
NFR_3.11	The system could set the standards from “Het Nieuwe Normaal” as objectives for the optimisation process	COULD	Not completed
NFR_3.12	The system could integrate a Multi-Criteria Analysis into the optimisation process to assist a user in choosing one optimal variant based on their own weights of priority for each objective	COULD	Not completed
4. Results Interface			
NFR_4.01	The results interface must include an "Overview Results" menu that visualises the most important results of the responsible material use assessment with graphs and charts	MUST	Completed
NFR_4.02	The results must be updated in real-time when parameters or material choices are adjusted by linking the results interface directly to the Grasshopper script	MUST	Completed
NFR_4.03	The results interface should compare the outcomes to performance levels set by "Het Nieuwe Normaal" and relevant benchmark studies	SHOULD	Completed
NFR_4.04	The results interface should be able to calculate indirect and additional costs based on percentages of direct costs, in order to calculate investment costs	SHOULD	Completed
NFR_4.05	The results interface should give the user control over the percentages for indirect and additional costs variables	SHOULD	Completed
NFR_4.06	The results interface should include a "Detailed Results" menu with results on the building element level and classification level	SHOULD	Completed
NFR_4.07	The system should be able to categorise the results on the building element level	SHOULD	Completed
NFR_4.08	The system should be able to categorise the results on the classification level	SHOULD	Completed
NFR_4.09	The system could categorise the results on the layers of Brand	COULD	Not completed
NFR_4.10	The results interface should include an "Explore" menu that visualises the materialisation variants and results from the optimisation process by linking directly to the output from the external multi-objective optimisation Grasshopper plugin	SHOULD	Completed
NFR_4.11	The "Explore" menu should allow users to compare different design variants based on their performance results and material selections	SHOULD	Completed
NFR_4.12	When a user has chosen a final variant, the system should select this variant and update the results in the "Overview Results" accordingly	SHOULD	Completed
NFR_4.13	The results interface should include a "Report" menu for reporting the results to PDF and Excel	SHOULD	Not completed
NFR_4.14	The system should transform internal Grasshopper data to PDF format	SHOULD	Not completed
NFR_4.15	The system should transform internal Grasshopper data to Excel format	SHOULD	Not completed